APPLIED ECOLOGY

Improvements in reports of species redistribution under climate change are required

Copyright © 2021 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).

Shirin Taheri[1,2]*, Babak Naimi[3], Carsten Rahbek[4,5,6], Miguel B. Araújo[1,7]*

Studies have documented climate change–induced shifts in species distributions but uncertainties associated with data and methods are typically unexplored. We reviewed 240 reports of climate-related species-range shifts and classified them based on three criteria. We ask whether observed distributional shifts are compared against random expectations, whether multicausal factors are examined on equal footing, and whether studies provide sufficient documentation to enable replication. We found that only ~12.1% of studies compare distributional shifts across multiple directions, ~1.6% distinguish observed patterns from random expectations, and ~19.66% examine multicausal factors. Last, ~75.5% of studies report sufficient data and results to allow replication. We show that despite gradual improvements over time, there is scope for raising standards in data and methods within reports of climate-change induced shifts in species distribution. Accurate reporting is important because policy responses depend on them. Flawed assessments can fuel criticism and divert scarce resources for biodiversity to competing priorities.

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

INTRODUCTION

As climate changes, so do species distributions. Evidence is mounting that ongoing climate changes are causing species to redistribute globally (*1*, *2*). The magnitude of distributional shifts is now estimated to be 2.5 times greater than originally thought (*3*). While many studies have uncovered the existence of nonrandom latitudinal or altitudinal shifts in species distributions (*3*–*5*), consistent with the hypothesis that climate change is driving them, others found that shifts can lag behind climate change owing to physiological plasticity, microclimate buffering, and delayed responses (*6*–*8*). These lags can lead to nondetection of ongoing distributional changes and failures to detect the mechanisms underpinning them. Observational studies have also detected species redistributions not following clear climatic gradients (*9*–*11*). These seemingly idiosyncratic responses to climate change could be related to complex interactions among temperature, precipitation (*12*), land-use change (*13*), species climatic tolerances (*14*), and biotic interactions (*15*). Complex nonlinear species responses to climate change can also limit the ability to detect distributional changes. This is particularly true with approaches assuming simple, often linear, relationships between temperature and species distributions (*10*). Measuring range dynamics along spatial gradients, such as latitude or altitude, can also mask complex biological responses to climate change because these gradients are not precise surrogates for temperature gradients, let alone for multiple climate dimensions (*16*, *17*).

Unlike the literature involving modeling of future climate change effects on species distributions, where several studies have examined uncertainties and addressed questions related to the minimum standards that should be required to make statements about modeled patterns (*18*, *19*), there is an unexpected lack of analyses evaluating the quality of observational inferences regarding climate change effects on past species distributions. As a first step toward weighting the strength of the observational evidence provided by these studies, we review the literature involving the analysis of multiple species responses to climate change (see Materials and Methods; fig. S1) in light of three important criteria: (i) pattern detection, which is the ability to discern signal from noise in patterns of species distributional shifts; (ii) causality, which is the ability to attribute climate change as the most plausible driver of observed distributional shifts given alternative mechanisms; and (iii) reproducibility, which is the ability to replicate studies given the information provided.

Each one of these criteria is assessed by a simple "yes" or "no" answer to six questions linked with the three criteria (Table 1). Stronger support to the conclusions in the reviewed studies is expected for those comparing distributional changes across multiple geographical directions, investigating multiple alternative causal mechanisms potentially driving distributional changes, and describing results with enough detail to enable replication and reanalysis.

RESULTS

Using extensive search of the literature (see Materials and Methods), we identified 240 studies examining the effects of climate change on the distributions of multiple species. Existing research is strongly biased toward the Northern Hemisphere (78.9%) and terrestrial ecosystems (80.4%) (Fig. 1A). Specifically, studies predominate in North America and Europe, mainly western Europe and within the United Kingdom, with notable knowledge gaps emerging in South America, Africa, Asia, and the Middle East [see also (*20*)]. We also found that evidence of climate change effects on species distribution has been examined for ≤2% of reptiles, insects, plants, algae, crustacean, and mollusca; 2.9% of mammals; 2.3% of fishes; and 23.47% of bird species (Fig. 1B).

When examining how the different studies characterize the direction of species distributional shifts, we found that only ~12.1% (n = 29)

[1]Department of Biogeography and Global Change, National Museum of Natural Sciences, CSIC, Calle Jose Gutierrez Abascal, 2, 28006 Madrid, Spain. [2]Departamento de Biología y Geología, Física y Química Inorgánica, Área de Biodiversidad y Conservación, Escuela Superior de Ciencias Experimentales y Tecnología, Universidad Rey Juan Carlos, c/Tulipán s/n, Móstoles 28933, Spain. [3]Department of Geosciences and Geography, University of Helsinki, P.O. Box 64, 00014 Helsinki, Finland. [4]Center for Macroecology, Evolution and Climate, GLOBE Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark. [5]Danish Institute for Advanced Study, University of Southern Denmark, 5230 Odense M, Denmark. [6]Institute of Ecology, Peking University, Beijing 100871, China. [7]Rui Nabeiro Biodiversity Chair, MED Institute, University of Évora, Largo dos Colegiais, 7000 Évora, Portugal.
*Corresponding author. Email: taheri.shi@gmail.com (S.T.); maraujo@mncn.csic.es (M.B.A.)

Table 1. Checklist used to measure the strength of evidence about species distributional shifts and their link with climate.

Evaluation criteria
Question of interest: Are distributional changes different from that expected in the absence of major external drivers, that is, by chance?
I. Pattern detection
a. Are range changes analyzed simultaneously across all possible directions of change? Yes = 1, No = 0
b. If so, are the obtained results compared against a null model expectation enabling distinguishing the observed patterns from chance expectation? Yes = 1, No = 0
Question of interest: Are potential causal factors rather than temperature examined in equal footing?
II. Attribution
a. Are explanatory causes of range changes investigated? Yes = 1, No = 0
b. If so, are alternative causal explanations compared on equal footing? Yes = 1, No = 0
Question of interest: Are distributional changes described with sufficient details to enable replication and reanalysis of the results?
III. Reproducibility
a. Are results presented for each individual species? Yes = 1, No = 0
b. If not, is variation among range dynamics of different sets of species described? Yes = 1, No = 0

compare shifts simultaneously across all possible geographical directions (*21*–*23*). That is, they generally investigate the species range changes across the expected direction of climate change (typically temperature change) while ignoring comparison with distributional changes across alternative directions (Fig. 2, A and B). Of the 29 studies that examine distributional changes across multiple directions, just four tested whether observed distribution shifts could have arisen by chance by comparison with a suitable null model (*8*, *24*–*26*). Analyses of species distributional shifts across multiple directions were mostly conducted with animals (n = 25). Plants feature in just four assessments (*27*–*30*). Unlike studies addressing distributional changes in a single dimension (e.g., latitude or altitude), studies examining range shifts in multiple directions typically found shifts to be idiosyncratic while being difficult to ascribe a clear direction of change [e.g., (*12*, *31*, *32*)].

When investigating links between species distributions and climate change, ~59% (n = 142) of the studies explicitly examine how temperature change covaries with species distributional changes. However, most studies disregard other environmental drivers, such as precipitation change, land-use change, or the interactions among them. Of the reviewed studies investigating the causes of distribution shifts other than temperature change (36.4%; n = 87), only 19.66% (n = 47) have tested alternative causal factors on equal footing (Fig. 2A). Complex interactions among temperature and precipitation change, and species-specific tolerances intervening on species responses to climate changes, were examined in a few studies so far [e.g., (*10*, *33*)].

When examining the reproducibility of studies, we found that ~25.5% (n = 59) did not report data at the individual species level; a requirement for full reanalysis and replication of the studies (Fig. 2A).

The degree to which studies met our criteria also varied among regions: Australia, northern Europe, and a few studies in North America were generally more proficient (Fig. 2, B and C). For example, among 40 papers that received a score of 4 in our criteria scoring, 42.5% (n = 17) are in Europe and 37.5% (n = 15) are in North America. In total, only 6 studies of 240 received a score of 5, in which two of them are in Europe, three of them in North America, and one in Africa. Great Britain, although with the highest number of species distributional change studies (n = 37), had an average (median) of just two subcriteria met. China with three studies reviewed averaged three subcriteria met (*34*–*36*), all reporting heterogeneous and diverse responses of species to climate change (Fig. 2, B and C).

Overall, studies performed poorly against the three criteria (six subcriteria) used (see Table 1). Of the 240 papers reviewed, only 11 (4.5%) met the three criteria, i.e., detected changes in all possible directions, considered at least one other causal factors rather than temperature, and presented the results for individual species meeting all the three main criteria (Fig. 3). Just 16.6% (n = 40) met four subcriteria, and only 2.5% (n = 6) met five subcriteria [e.g., (*23*, *34*)]. In general, studies conducted for terrestrial ecosystems achieved greater performance according to the subcriteria used (Fig. 2B), although the sample size of studies in terrestrial ecosystems (n = 193; 80.4%) is much larger than in marine ones (n = 47).

We analyzed how the different aspects reflecting the quality of studies evolved through time given the criteria. We found that the studies' performances had a tendency to increase across all criteria (Fig. 4). For example, among studies that measured multidirectionality of range shifts (n = 29), 26 were published from 2011 onward. Likewise, in this period, 60 of 87 studies investigated multiple causal factors, while 116 of 181 met our criteria for reproducibility.

DISCUSSION

Species adapt to changes in climate by moving to more suitable locations (*37*). Alternatively, some species might be able to persist throughout their known distributions because of phenotypic plasticity or adaptive genetic modification (*38*, *39*). When neither of these options are available, species perish (*40*). The combined adaptive responses of species to climate change leads to changes in species ranges. Detecting changes using fragmented samples of data and identifying potential causes for those changes is particularly challenging.

There are considerable uncertainties regarding the speed of distributional shifts (*41*–*43*), particularly along rear (contracting) edges (*44*, *45*), the accelerating or mitigating effects of biotic interactions (*46*, *47*), the capacity to adapt in situ associated with expressions of phenotypic plasticity (*38*, *39*) or genetic modification (*48*), and the effects of interactions among multiple climate drivers of change (*49*). The tolerances of species to climate extremes are generally inferred with statistical approaches (*50*–*52*). However, circumstantial evidence suggests that inferred tolerances are narrower than real ones (*15*, *53*). Combined, these biological and environmental effects can truncate the pace and direction of biological responses to climate change. Delayed responses are common (*54*), resilience to changes (*55*) has been observed, and the unknown consequences of novel climates are hard to anticipate (*56*).

In addition, current estimates of climate change effects on species distributions are severely hampered by geographic and taxonomic biases in the underlying data [Fig. 1; see also (*20*)]. Most data come from species-poor, mostly temperate, regions. In sharp contrast, the tropics hosting the vast majority the planet's biological diversity (*57*) scarcely have any study assessing climate change effects on species. A range of factors affects the availability of biodiversity-related information. The knowledge gap in tropics, for example, is related to insufficient funding, inadequate infrastructure, and scarce local

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

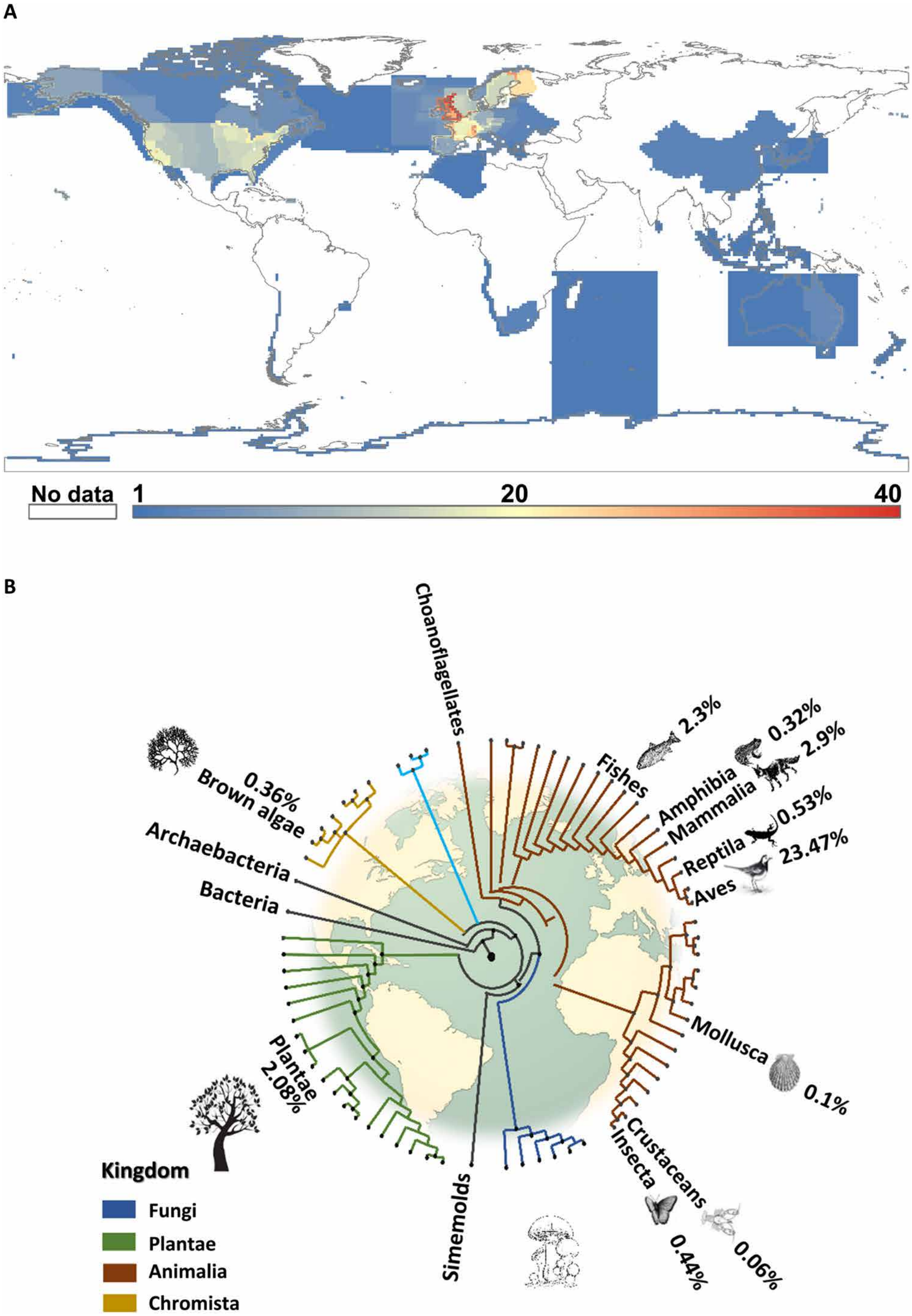

Fig. 1. Geographic and taxonomic coverage of climate related range shifts studies. (**A**) Geographical coverage across terrestrial and marine realms with 82% of the studies being in the Northern Hemisphere while 80.4% covering terrestrial ecosystems. (**B**) Taxonomic coverage with ≤2% including studies with amphibians, insects, reptiles, algae, crustaceans, and mollusca; 2.3% including fish; 2.9% mammals; and 23.47% birds.

expertise for data collection and identification, inaccessibility to research sites because of the political upheaval, and difficulties in getting data published or public (*58*). In addition, geopolitics (*59*), regional democracy (*60*), socioeconomic, history, culture, scientific interest (*61*), and unwillingness of sharing the data play an important role in biodiversity data collections and publishing bias.

While the impact of climate change on the future of biodiversity has been assessed for a wide range of taxonomic groups, the total number of empirical studies remains relatively low. One important reason for this is the lack of replicable historical surveys [but see (*62*)] that limit the reliability of the assessed empirical relationships between species distributional changes and environmental changes (*63*).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

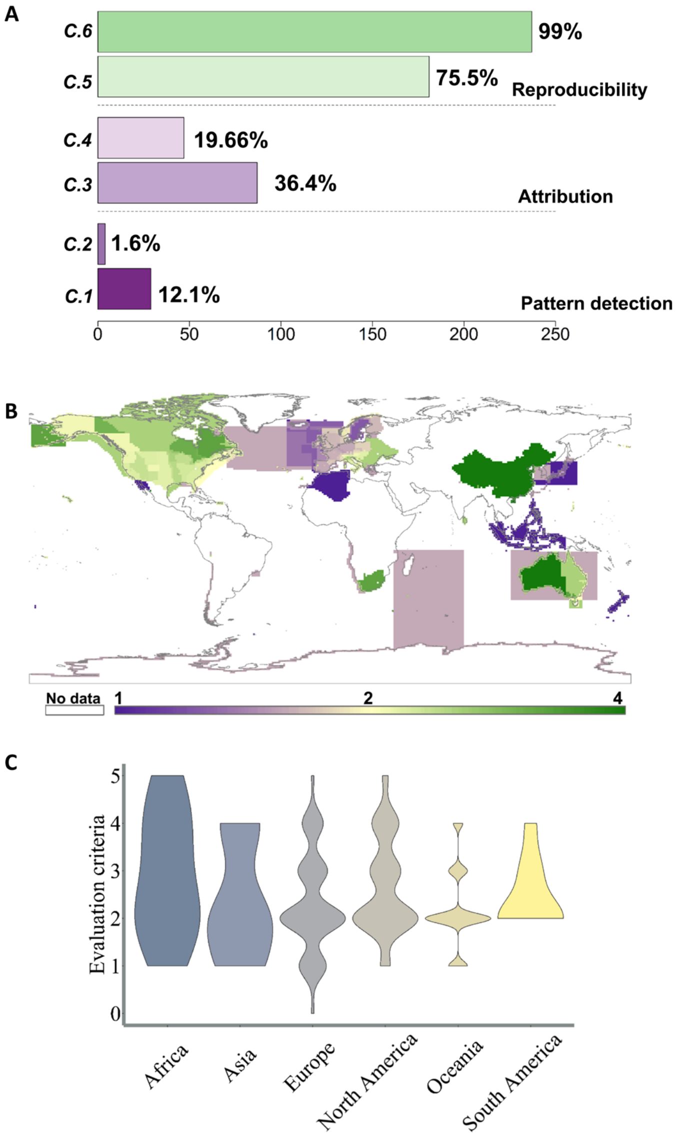

Fig. 2. The quality assessment in climate-related range shifts reports. (**A**) The proportion of reports for six subcriteria. The plot shows the proportion of each study met each criterion (C.1 and C.2, pattern detection; C.3 and C.4, attribution; and C.5 and C.6, reproducibility). (**B**) Assessed quality of the reports of species redistribution under climate change across marine and terrestrial ecosystems. Shows the geographical distribution of studies investigating climate change effects on species distributions ranked by the overall (median) benchmark score achieved through summation of individual ranks in the three evaluation criteria. Values in the map range from 1 (only one of the evaluation subcriteria met) to 4 (four of the evaluation subcriteria met). Higher scores are colored green and lower scores are colored violet. (**C**) Sum of the evaluation subcriteria in each continent. Shows the number of evaluation subcriteria met by each study across continents.

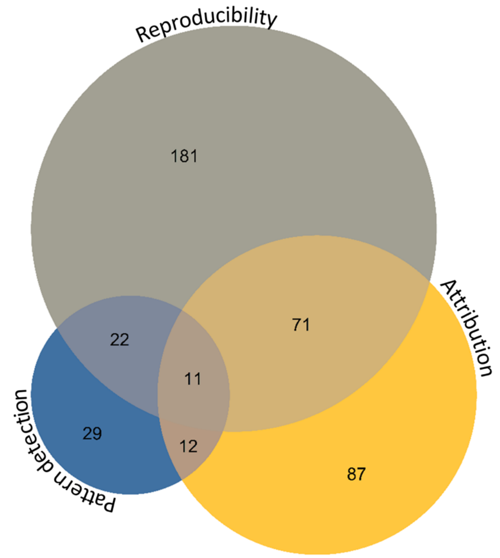

Fig. 3. Cross-examination of the subcriteria used to evaluate reports of species redistribution under climate change. Shows the multiple overlapping among the three main criteria. Each circle corresponds to one of the main evaluation criteria. The size of the circles represents the number of reports met each main criterion (pattern detection, causality, and reproducibility). The Reuleaux triangle in the center shows the intersection between three circles, and it means only 4.5% ($n = 11$) of the studies met these three main criteria.

Studied clades also represent an extremely small fraction of the world's life forms: insects, by far the most specious group in the world, are almost not covered by assessments, and most studies are based on trees and vertebrates with 23% conducted on birds alone. Any conclusion drawn from existing data is thereby regional, taxonomically biased, and hardly transferable globally. Possible generalizations are, therefore, limited.

Adding to the limitations of the data, we found that most studies underperform on the methodological standards of analysis. These are, however, more easily circumvented than the limitations of data. To ascertain whether a distributional shift occurs in response to a given environmental driver, one needs to assess changes not only along the expected gradient but also along alternative gradients (*22*). That is, if species are expected to change along a south to north gradient, for example, then one needs to measure whether the changes along latitude are significantly different from the changes along longitude. If not, then it will be difficult to ascertain that changes are not a consequence of natural population dynamics of range expansion and contraction (*64*). Even when distributional changes are examined across multiple directions, one might still ask if observed patterns could not have arisen by chance given geometrical constrains for dispersal or alternative environmental driver dynamics (*26*). Addressing these questions requires the use of null models of distributional change, but although null models have made their way into ecology (*65*, *66*) and biogeography (*67*), they are still hard to find in studies of climate change effects on biodiversity.

That correlation does not imply that causation is well known. Nevertheless, when a good mechanistic hypothesis exists linking a pattern and the potential underlying mechanisms, and when expected relationships are observed repeatedly across different regions and times, accumulation of evidence can be interpreted as supporting hypothesized causal links between pattern and mechanism (*18*). This is the logic linking elevation and latitudinal shifts with climate change: As temperature increases, higher latitudes and elevations are expected to warm, hence receiving more warm tolerant species while losing cold tolerant ones. Such is an observation dating as far as the classic observations of A. von Humboldt in the Chimborazo Mountain of Ecuador (*62*, *68*). However, climatic gradients do not always follow geographical gradients linearly (*12*), and most often there are

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

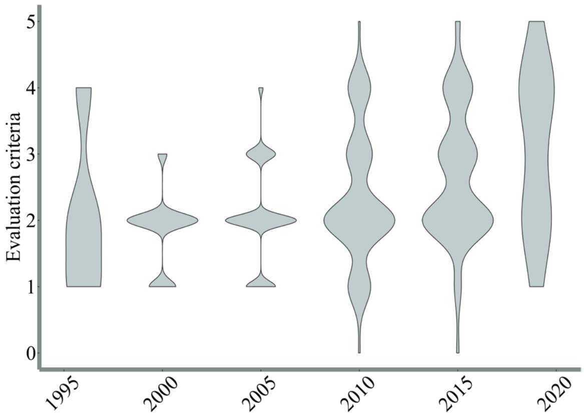

Fig. 4. Distribution of studies by evaluation subcriteria over time. Shows a general trend of improvement of reports of climate-related range shifts over time across the six subcriteria. Higher values in the *y* axis mean that more of the established evaluation criteria were met.

feedbacks between temperature and other climatic variables (e.g., humidity and wind) that further affect the expected relationship between temperature and geographic gradients (*69*). Seeking to attribute climate change to a given distributional shift is thus better achieved by relating species range changes with climate variables instead of geographical proxies, such as latitude and elevation. This point has been made several times for studies examining diversity gradients along elevation gradients (*70*) and latitude (*17*), but as our review shows, it has not been fully appreciated and integrated in assessments of climate change effects on biodiversity.

In addition, even when climate change variables are used, instead of geographical proxies, to examine relationships with species distributional shifts, there are occasions when distributional shifts respond not only to climate but also to other environmental changes, such as spread of disease (*71*) or land-use change (*49*, *72*, *73*). Attributing a mechanism to an observed pattern thus benefits from examination of multiple alternative hypotheses on equal footing. Nevertheless, multimodal inference (*74*) was found to be extremely rare in the reviewed literature.

Last, a critical feature of science-based assessments is the ability to reproduce and build upon each other's published results. Unfortunately, many findings cannot be reproduced. Our review reveals that ~25% of the reports on distributional changes under climate change do not provide full access to the data and detailed results. Reproducibility contains several elements such as selective reporting, methods and availability of codes, statistical power, experimental design, and availability of raw data. In this review, we focused on selective reporting. However, we notice that considering other factors of reproducibility could markedly affect our assessment of published studies. Recently, a study (*75*) carried out by 1500 scientists from different disciplines (e.g., chemistry, physics, medicine, and biology) showed that most of the scientific articles are not fully reproducible; our review corroborates their findings in the subfield of climate change ecology and biogeography.

Moving forward in the capacity to assess the where, when, and why of climate change effects on biodiversity is crucial to guide the timing and magnitude of human adaptation strategies for biodiversity. In our scan of the literature, we asked very simple questions that enable establishing inferences about the quality of the underlying data and methods. We demonstrate that substantial improvements should be considered in assessments. Most of them do not require reinventing concepts or methods. Questions about the need for null models to discriminate expected directional patterns from stochastic (or more complex) ones (*65*, *76*), or the disadvantages of using indirect proxies as opposed to direct variables with proven mechanistic links to the patterns (*17*, *70*), are well established in the ecological literature. Somehow, these debates and the associated recommendations have not percolated through studies examining climate change effects on species distributions.

Our study provides a hint of the best-practice standards needed for assessments of climate change effects on a specific facet of biodiversity change: species range change. Other biodiversity change facets, such as local patterns of colonization and extinction, or abundance changes, or changes in community composition are not covered by our analysis, partly because very few of these studies exist across multiple species. Future investigations should seek to expand the facets of biodiversity change considered in quality assessments and strive to build consensus on the standards required to increase the strength of evidence of climate change impacts on biodiversity while developing detailed guidelines to help increase the robustness, transparency, and reproducibility of the assessments.

MATERIALS AND METHODS

Literature review

We identified papers by screening published reviews (*20*) and meta-analyses (*1*, *2*) and by searching the primary literature using engines such as Google Scholar, ISI Web of Science, Scopus, and Wiley Online Library. We used a combination of the following keywords in our search: "climate change" or "climate warming," "range" or "distribution," and "poleward/northward shift" or "upslope/altitudinal shift" or expansion/contraction (fig. S1). We then filtered the records by using some inclusion and exclusion criteria. These criteria comprised references that assessed distributional changes based on species occurrence data over at least two historical periods. Since our focus was on the empirically observed distributional shifts, we excluded papers that used abundance or richness data alone or those that used modeling and/or predictions to quantify "future" or "potential" changes. Our search criteria provided a set of 240 publications.

Data mining

Following the literature search, we extracted the relevant data to be structured in a suitable database (table S1). For each publication, we recorded the following information: (i) study year, (ii) spatial scale (e.g., local, regional, and continental), (iii) geographic region as reported in the study, (iv) ecosystem type (terrestrial versus marine), (v) climate zone, (vi) magnitude and direction of distributional shifts, (iv) total number of taxa and their identity (taxonomic group and species names), (vi) time period, and (vii and viii) the general methodology used by the study (table S1).

In the database, a unique code was assigned to each article reviewed and its geographic location was also recorded. To effectively visualize the spatial coverage of the reports, we digitized the geographical boundaries of all the studies reviewed as a set of either spatial polygons or points depending on the geographical extent of the study. We then used a regular 2-degree (2 × 69 miles) grid cells covering the world's land and sea areas in ArcMap software

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

(version 10.1) to aggregate the digitized points and polygons into the grid cells and quantify the frequency of the studies at each cell.

We used the Köppen climate classification (*77*) to group the studies into the climate zones. In addition, we aggregated the spatial boundaries of the studies within the five major climatic zones defined by the Köppen climate classification based on seasonal temperature and precipitation patterns. The five climatic zones are (i) tropical, (ii) dry, (iii) temperate, (iv) continental/cold, and (v) polar.

To sort the taxonomic coverage of the data used in the studies, we first extracted the number of species and their scientific names for the given taxonomic group in each article (table S3). We added the names of species to the database, and after removing duplicate records, we calculated the proportion of species considered in studies (fig. S1).

Assessment criteria

The assessment of published studies was made following a simple set of criteria as described in Table 1. For pattern detection, we focused on the methodological aspects of the studies. We explored how the species distributional shifts were measured. Specifically, we asked whether distribution shifts were analyzed across all potential directions (e.g., latitude, longitude, and elevation), and whether the null expectation regarding distributional changes (likelihood of changes derived from patterns shifted by chance because of internal variability) was determined. Therefore, scientific publications that assessed distributional shifts within all the possible directions, rather than only along a single elevation or latitudinal axis, and also compared the results against the patterns expected by chance (null distribution) received the maximum score for the pattern detection group benchmark.

For attribution, we asked whether studies examined potential causal links between observed distributional changes and environmental predictors (e.g., climate, precipitation, and land use). We carefully reviewed the studies' methods sections to assess how (if at all) they attributed observed shifts in species distributions to climate change and what approaches were used to perform the task. The papers that investigated multiple alternative causal factors on equal footing, rather than simply examining patterns against a single predictor (e.g., temperature), received maximum score for the attribution criteria.

For reproducibility, we examined the results sections of the studies. A study received the full score for this group if the results were available for each individual species analyzed and if the divergence responses among species were fairly reported.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/15/eabe1110/DC1

REFERENCES AND NOTES

1. C. Parmesan, Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.* **37**, 637–669 (2006).
2. I.-C. Chen, J. K. Hill, R. Ohlemüller, D. B. Roy, C. D. Thomas, Rapid range shifts of species associated with high levels of climate warming. *Science* **333**, 1024–1026 (2011).
3. C. Parmesan, G. Yohe, A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37–42 (2003).
4. C. D. Thomas, J. J. Lennon, Birds extend their ranges northwards. *Nature* **399**, 213 (1999).
5. C. Parmesan, N. Ryrholm, C. Stefanescu, J. K. Hill, C. D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, W. J. Tennent, J. A. Thomas, M. Warren, Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* **399**, 579–583 (1999).
6. J. A. Pounds, M. P. L. Fogden, J. H. Campbell, Biological response to climate change on a tropical mountain. *Nature* **398**, 611–615 (1999).
7. V. Devictor, R. Julliard, D. Couvet, F. Jiguet, Birds are tracking climate warming, but not fast enough. *Proc. R. Soc. B Biol. Sci.* **275**, 2743–2748 (2008).
8. G. Forero-Medina, J. Terborgh, S. J. Socolar, S. L. Pimm, Elevational ranges of birds on a tropical montane gradient lag behind warming temperatures. *PLOS ONE* **6**, e28535 (2011).
9. F. E. Bedford, R. J. Whittaker, J. T. Kerr, Systemic range shift lags among a pollinator species assemblage following rapid climate change. *Botany* **90**, 587–597 (2012).
10. J. VanDerWal, H. T. Murphy, A. S. Kutt, G. C. Perkins, B. L. Bateman, J. J. Perry, A. E. Reside, Focus on poleward shifts in species' distribution underestimates the fingerprint of climate change. *Nat. Clim. Change* **3**, 239–243 (2013).
11. F. Archaux, Breeding upwards when climate is becoming warmer: No bird response in the French Alps. *Ibis* **146**, 138–144 (2004).
12. M. W. Tingley, M. S. Koo, C. Moritz, A. C. Rush, S. R. Beissinger, The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Glob. Chang. Biol.* **18**, 3279–3290 (2012).
13. S. M. Crimmins, S. Z. Dobrowski, J. A. Greenberg, J. T. Abatzoglou, A. R. Mynsberge, Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science* **331**, 324–327 (2011).
14. M. S. Warren, J. K. Hill, J. A. Thomas, J. Asher, R. Fox, B. Huntley, D. B. Roy, M. G. Telfer, S. Jeffcoate, P. Harding, G. Jeffcoate, S. G. Willis, J. N. Greatorex-Davies, D. Moss, C. D. Thomas, Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature* **414**, 65–69 (2001).
15. M. B. Araújo, F. Ferri-Yáñez, F. Bozinovic, P. A. Marquet, F. Valladares, S. L. Chown, Heat freezes niche evolution. *Ecol. Lett.* **16**, 1206–1219 (2013).
16. P. Hersteinsson, D. W. MacDonald, Interspecific competition and the geographical distribution of red and arctic foxes vulpes vulpes and alopex lagopus. *Oikos* **64**, 505–515 (1992).
17. B. A. Hawkins, J. A. Felizola Diniz-Filho, 'Latitude' and geographic patterns in species richness. *Ecography* **27**, 268–272 (2004).
18. M. B. Araújo, R. P. Anderson, A. M. Barbosa, C. M. Beale, C. F. Dormann, R. Early, R. A. Garcia, A. Guisan, L. Maiorano, B. Naimi, R. B. O'Hara, N. E. Zimmermann, C. Rahbek, Standards for distribution models in biodiversity assessments. *Sci. Adv.* **5**, eaat4858 (2019).
19. D. Zurell, J. Franklin, C. König, P. J. Bouchet, C. F. Dormann, J. Elith, G. Fandos, X. Feng, G. Guillera-Arroita, A. Guisan, J. J. Lahoz-Monfort, P. J. Leitão, D. S. Park, A. T. Peterson, G. Rapacciuolo, D. R. Schmatz, B. Schröder, J. M. Serra-Diaz, W. Thuiller, K. L. Yates, N. E. Zimmermann, C. Merow, A standard protocol for reporting species distribution models. *Ecography* **43**, 1261–1277 (2020).
20. J. Lenoir, J. C. Svenning, Climate-related range shifts – a global multidimensional synthesis and new research directions. *Ecography* **38**, 15–28 (2015).
21. S. Gillings, D. E. Balmer, R. J. Fuller, Directionality of recent bird distribution shifts and climate change in Great Britain. *Glob. Chang. Biol.* **21**, 2155–2168 (2015).
22. S. Taheri, B. Naimi, M. B. Araújo, Did British breeding birds move north in the late 20th century? *Clim. Chang. Respon.* **3**, 5 (2016).
23. P. A. R. Hockey, C. Sirami, A. R. Ridley, G. F. Midgley, H. A. Babiker, Interrogating recent range changes in South African birds: Confounding signals from land use and climate change present a challenge for attribution. *Divers. Distrib.* **17**, 254–261 (2011).
24. A. Wolf, N. B. Zimmerman, W. R. L. Anderegg, P. E. Busby, J. Christensen, Altitudinal shifts of the native and introduced flora of California in the context of 20th-century warming. *Glob. Ecol. Biogeogr.* **25**, 418–429 (2016).
25. L. Boisvert-Marsh, C. Périé, S. de Blois, Divergent responses to climate change and disturbance drive recruitment patterns underlying latitudinal shifts of tree species. *J. Ecol.* **107**, 1956–1969 (2019).
26. S. Taheri, D. García-Callejas, M. B. Araújo, Discriminating climate, land-cover and random effects on species range dynamics. *Glob. Chang. Biol.* **27**, 1309–1317 (2020).
27. B. B. Hanberry, M. H. Hansen, Latitudinal range shifts of tree species in the United States across multi-decadal time scales. *Basic Appl. Ecol.* **16**, 231–238 (2015).
28. Q. J. Groom, Some poleward movement of British native vascular plants is occurring, but the fingerprint of climate change is not evident. *PeerJ.* **1**, e77 (2013).
29. S. B. Rumpf, K. Hülber, G. Klonner, D. Moser, M. Schütz, J. Wessely, W. Willner, N. E. Zimmermann, S. Dullinger, Range dynamics of mountain plants decrease with elevation. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 1848–1853 (2018).
30. S. Fei, J. M. Desprez, K. M. Potter, I. Jo, J. A. Knott, C. M. Oswalt, Divergence of species responses to climate change. *Sci. Adv.* **3**, e1603055 (2017).
31. K. C. Rowe, K. M. C. Rowe, M. W. Tingley, M. S. Koo, J. L. Patton, C. J. Conroy, J. D. Perrine, S. R. Beissinger, C. Moritz, Spatially heterogeneous impact of climate change on small mammals of montane California. *Proc. R. Soc. B Biol. Sci.* **282**, 20141857 (2015).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

32. M. J. Santos, J. H. Thorne, C. Moritz, Synchronicity in elevation range shifts among small mammals and vegetation over the last century is stronger for omnivores. *Ecography* **38**, 556–568 (2015).
33. M. L. Pinsky, B. Worm, M. J. Fogarty, J. L. Sarmiento, S. A. Levin, Marine taxa track local climate velocities. *Science* **341**, 1239–1242 (2013).
34. J. Wu, Can changes in the distribution of lizard species over the past 50 years be attributed to climate change? *Theor. Appl. Climatol.* **125**, 785–798 (2016).
35. J. Wu, Detecting and attributing the effect of climate change on the changes in the distribution of Qinghai-Tibet plateau large mammal species over the past 50 years. *Mammal Res.* **60**, 353–364 (2015).
36. J. Wu, Y. Shi, Attribution index for changes in migratory bird distributions: The role of climate change over the past 50 years in China. *Ecol. Inform.* **31**, 147–155 (2016).
37. M. B. Araújo, C. Rahbek, How does climate change affect biodiversity? *Science* **313**, 1396–1397 (2006).
38. F. Valladares, S. Matesanz, F. Guilhaumon, M. B. Araújo, L. Balaguer, M. Benito-Garzón, W. Cornwell, E. Gianoli, M. van Kleunen, D. E. Naya, A. B. Nicotra, H. Poorter, M. A. Zavala, The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecol. Lett.* **17**, 1351–1364 (2014).
39. N. G. King, N. J. McKeown, D. A. Smale, P. J. Moore, The importance of phenotypic plasticity and local adaptation in driving intraspecific variability in thermal niches of marine macrophytes. *Ecography* **41**, 1469–1484 (2018).
40. M. C. Urban, Climate change. Accelerating extinction risk from climate change. *Science* **348**, 571–573 (2015).
41. R. García-Valdés, M. A. Zavala, M. B. Araújo, D. W. Purves, Chasing a moving target: Projecting climate change-induced shifts in non-equilibrial tree species distributions. *J. Ecol.* **101**, 441–453 (2013).
42. J.-C. Svenning, F. Skov, Limited filling of the potential range in European tree species. *Ecol. Lett.* **7**, 565–573 (2004).
43. M. B. Araújo, R. G. Pearson, Equilibrium of species' distributions with climate. *Ecography* **28**, 693–695 (2005).
44. R. J. Wilson, D. Gutiérrez, J. Gutiérrez, D. Martínez, R. Agudo, V. J. Monserrat, Changes to the elevational limits and extent of species ranges associated with climate change. *Ecol. Lett.* **8**, 1138–1146 (2005).
45. B. J. Anderson, H. R. Akçakaya, M. B. Araújo, D. A. Fordham, E. Martinez-Meyer, W. Thuiller, B. W. Brook, Dynamics of range margins for metapopulations under climate change. *Proc. R. Soc. Lond. B Biol. Sci.* **276**, 1415–1420 (2009).
46. R. M. Callaway, R. W. Brooker, P. Choler, Z. Kikvidze, C. J. Lortie, R. Michalet, L. Paolini, F. I. Pugnaire, B. Newingham, E. T. Aschehoug, C. Armas, D. Kikodze, B. J. Cook, Positive interactions among alpine plants increase with stress. *Nature* **417**, 844–848 (2002).
47. L. Hughes, *Saving a Million Species* (Island Press/Center for Resource Economics, 2012), pp. 337–359.
48. S. J. Franks, A. A. Hoffmann, Genetics of climate change adaptation. *Annu. Rev. Genet.* **46**, 185–208 (2012).
49. S. Yalcin, S. J. Leroux, An empirical test of the relative and combined effects of land-cover and climate change on local colonization and extinction. *Glob. Chang. Biol.* **24**, 3849–3861 (2018).
50. J. A. F. Diniz-Filho, L. Mauricio Bini, T. Fernando Rangel, R. D. Loyola, C. Hof, D. Nogués-Bravo, M. B. Araújo, Partitioning and mapping uncertainties in ensembles of forecasts of species turnover under climate change. *Ecography* **32**, 897–906 (2009).
51. S. Dullinger, A. Gattringer, W. Thuiller, D. Moser, N. E. Zimmermann, A. Guisan, W. Willner, C. Plutzar, M. Leitner, T. Mang, M. Caccianiga, T. Dirnböck, S. Ertl, A. Fischer, J. Lenoir, J.-C. Svenning, A. Psomas, D. R. Schmatz, U. Silc, P. Vittoz, K. Hülber, Extinction debt of high-mountain plants under twenty-first-century climate change. *Nat. Clim. Chang.* **2**, 619–622 (2012).
52. R. A. Garcia, N. D. Burgess, M. Cabeza, C. Rahbek, M. B. Araújo, Exploring consensus in 21st century projections of climatically suitable areas for African vertebrates. *Glob. Chang. Biol.* **18**, 1253–1269 (2012).
53. S. Herrando-Pérez, F. Ferri-Yáñez, C. Monasterio, W. Beukema, V. Gomes, J. Belliure, S. L. Chown, D. R. Vieites, M. B. Araújo, Intraspecific variation in lizard heat tolerance alters estimates of climate impact. *J. Anim. Ecol.* **88**, 247–257 (2019).
54. F. Essl, S. Dullinger, W. Rabitsch, P. E. Hulme, P. Pyšek, J. R. Wilson, D. M. Richardson, Delayed biodiversity change: No time to waste. *Trends Ecol. Evol.* **30**, 375–378 (2015).
55. J. R. Bernhardt, H. M. Leslie, Resilience to climate change in coastal marine ecosystems. *Ann. Rev. Mar. Sci.* **5**, 371–392 (2013).
56. R. G. Pearson, W. Thuiller, M. B. Araújo, E. Martinez-Meyer, L. Brotons, C. McClean, L. Miles, P. Segurado, T. P. Dawson, D. C. Lees, Model-based uncertainty in species range prediction. *J. Biogeogr.* **33**, 1704–1711 (2006).
57. J. H. Brown, Why are there so many species in the tropics? *J. Biogeogr.* **41**, 8–22 (2014).
58. B. Collen, M. Ram, T. Zamin, L. Mcrae, The tropical biodiversity data gap: Addressing disparity in global monitoring. *Tropical Conserv. Sci.* **1**, 75–88 (2008).
59. M. J. Trimble, R. J. van Aarde, Geographical and taxonomic biases in research on biodiversity in human-modified landscapes. *Ecosphere* **3**, 1–16 (2012).
60. O. Rydén, A. Zizka, S. C. Jagers, S. I. Lindberg, A. Antonelli, Linking democracy and biodiversity conservation: Empirical evidence and research gaps. *Ambio* **49**, 419–433 (2020).
61. T. Amano, J. D. L. Lamming, W. J. Sutherland, Spatial gaps in global biodiversity information and the role of citizen science. *Bioscience* **66**, 393–400 (2016).
62. N. Morueta-Holme, K. Engemann, P. Sandoval-Acuña, J. D. Jonas, R. Max Segnitz, J.-C. Svenning, Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt. *Proc. Natl. Acad. Sci. U.S.A.* **13**, 12741–12745 (2015).
63. J. Hortal, A. Jiménez-Valverde, J. F. Gómez, J. M. Lobo, A. Baselga, Historical bias in biodiversity inventories affects the observed environmental niche of the species. *Oikos* **117**, 847–858 (2008).
64. C. J. A. Bradshaw, B. W. Brook, S. Delean, D. A. Fordham, S. Herrando-Pérez, P. Cassey, R. Early, C. H. Sekercioglu, M. B. Araújo, Predictors of contraction and expansion of area of occupancy for British birds. *Proc. R. Soc. B Biol. Sci.* **281**, 20140744 (2014).
65. N. J. Gotelli, G. R. Graves, *Null Models in Ecology* (Smithsonian Institution Press, 1996).
66. R. K. Colwell, C. Rahbek, N. J. Gotelli, The mid-domain effect and species richness patterns: What have we learned so far? *Am. Nat.* **163**, E1–E23 (2004).
67. S. P. Hubbell, *The Unified Neutral Theory of Biodiversity and Biogeography* (Princeton Univ. Press, 2001).
68. A. von Humboldt, *Notice De Deux Tentatives d'ascension du Chimborazo* (A. Pihan de la Forest, 1838).
69. G. Rapacciuolo, S. P. Maher, A. C. Schneider, T. T. Hammond, M. D. Jabis, R. E. Walsh, K. J. Iknayan, G. K. Walden, M. F. Oldfather, D. D. Ackerly, S. R. Beissinger, Beyond a warming fingerprint: Individualistic biogeographic responses to heterogeneous climate change in California. *Glob. Chang. Biol.* **20**, 2841–2855 (2014).
70. C. Körner, The use of 'altitude' in ecological research. *Trends Ecol. Evol.* **22**, 569–574 (2007).
71. C. Hof, M. B. Araújo, W. Jetz, C. Rahbek, Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature* **480**, 516–519 (2011).
72. A. Ameztegui, L. Coll, L. Brotons, J. M. Ninot, Land-use legacies rather than climate change are driving the recent upward shift of the mountain tree line in the Pyrenees. *Glob. Ecol. Biogeogr.* **25**, 263–273 (2016).
73. F. Guo, J. Lenoir, T. C. Bonebrake, Land-use change interacts with climate to determine elevational species redistribution. *Nat. Commun.* **9**, 1315 (2018).
74. C. Sirami, P. Caplat, S. Popy, A. Clamens, R. Arlettaz, F. Jiguet, L. Brotons, J.-L. Martin, Impacts of global change on species distributions: Obstacles and solutions to integrate climate and land use. *Glob. Ecol. Biogeogr.* **26**, 385–394 (2017).
75. M. Baker, 1,500 scientists lift the lid on reproducibility. *Nature* **533**, 452–454 (2016).
76. P. H. Harvey, R. K. Colwell, J. W. Silvertown, R. M. May, Null models in ecology. *Annu. Rev. Ecol. Syst.* **14**, 189–211 (1983).
77. M. C. Peel, B. L. Finlayson, T. A. Mcmahon, Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci. Discuss.* **11**, 1633–1644 (2007).
78. P.-E. Betzholtz, L. B. Pettersson, N. Ryrholm, M. Franzén, With that diet, you will go far: Trait-based analysis reveals a link between rapid range expansion and a nitrogen-favoured diet. *Proc. R. Soc. B Biol. Sci.* **280**, 20122305 (2013).
79. S. Bonhommeau, E. Chassot, B. Planque, E. Rivot, A. Knap, O. Le Pape, Impact of climate on eel populations of the Northern Hemisphere. *Mar. Ecol. Prog. Ser.* **373**, 71–80 (2008).
80. G. J. Chirima, N. Owen-Smith, B. F. N. Erasmus, Changing distributions of larger ungulates in the Kruger National Park from ecological aerial survey data. *Koedoe* **54**, 24–35 (2012).
81. L. P. Shoo, S. E. Williams, J.-M. Hero, Detecting climate change induced range shifts: Where and how should we be looking? *Austral Ecol.* **31**, 22–29 (2006).
82. R. J. Rowe, J. A. Finarelli, E. A. Rickart, Range dynamics of small mammals along an elevational gradient over an 80-year interval. *Glob. Chang. Biol.* **16**, 2930–2943 (2010).
83. A. S. Jump, T.-J. Huang, C.-H. Chou, Rapid altitudinal migration of mountain plants in Taiwan and its implications for high altitude biodiversity. *Ecography* **35**, 204–210 (2012).
84. G. Moreno-Rueda, European bird species have expanded northwards during 1950-1993 in response to recent climatic warming, in *Trends in Ornithology Research*, P. K. Ulrich, J. H. Willet, Eds. (Nova Science Publisher, 2010), pp. 137–151.
85. T. H. Oliver, D. B. Roy, T. Brereton, J. A. Thomas, Reduced variability in range-edge butterfly populations over three decades of climate warming. *Glob. Chang. Biol.* **18**, 1531–1539 (2012).
86. E. A. Botts, B. F. N. Erasmus, G. J. Alexander, Observed range dynamics of South African amphibians under conditions of global change. *Austral Ecol.* **40**, 309–317 (2015).
87. A. Atkinson, V. Siegel, E. Pakhomov, P. Rothery, Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature* **432**, 100–103 (2004).
88. J. T. Kerr, A. Pindar, P. Galpern, L. Packer, S. G. Potts, S. M. Roberts, P. Rasmont, O. Schweiger, S. R. Colla, L. L. Richardson, D. L. Wagner, L. F. Gall, D. S. Sikes, A. Pantoja, Climate change impacts on bumblebees converge across continents. *Science* **349**, 177–180 (2015).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

89. P. C. Le Roux, M. A. McGeoch, Rapid range expansion and community reorganization in response to warming. *Glob. Chang. Biol.* **14**, 2950–2962 (2008).
90. K. J. Feeley, M. R. Silman, M. B. Bush, W. Farfan, K. G. Cabrera, Y. Malhi, P. Meir, N. S. Revilla, M. N. R. Quisiyupanqui, S. Saatchi, Upslope migration of Andean trees. *J. Biogeogr.* **38**, 783–791 (2011).
91. J. O. Juvik, B. T. Rodomsky, J. P. Price, E. W. Hansen, C. Kueffer, "The upper limits of vegetation on Mauna Loa, Hawaii": A 50th-anniversary reassessment. *Ecology* **92**, 518–525 (2011).
92. J. K. Hill, C. D. Thomas, R. Fox, M. G. Telfer, S. G. Willis, J. Asher, B. Huntley, Responses of butterflies to twentieth century climate warming: Implications for future ranges. *Proc. R. Soc. Lond. B Biol. Sci.* **269**, 2163–2171 (2002).
93. E. F. Ploquin, J. M. Herrera, J. R. Obeso, Bumblebee community homogenization after uphill shifts in montane areas of northern Spain. *Oecologia* **173**, 1649–1660 (2013).
94. Y. Telwala, B. W. Brook, K. Manish, M. K. Pandit, Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. *PLOS ONE* **8**, e57103 (2013).
95. A. R. D. Stebbing, S. M. T. Turk, A. Wheeler, K. R. Clarke, Immigration of southern fish species to south-west England linked to warming of the North Atlantic (1960–2001). *J. Mar. Biol. Assoc. UK* **82**, 177–180 (2002).
96. J.-C. Quero, Changes in the Euro-Atlantic fish species composition resulting from fishing and ocean warming. *Ital. J. Zool.* **65**, 493–499 (1998).
97. K. Brander, G. Blom, M. F. Borges, K. Erzini, G. Henderson, B. R. MacKenzie, H. Mendes, J. Ribeiro, A. M. P. Santos, R. Toresen, Changes in fish distribution in the eastern North Atlantic: Are we seeing a coherent response to changing temperature. *ICES Mar. Sci. Symp.* **219**, 261–270 (2003).
98. F. A. La Sorte, F. R. Thompson III, Poleward shifts in winter ranges of North American birds. *Ecology* **88**, 1803–1812 (2007).
99. K. Zhu, C. W. Woodall, J. S. Clark, Failure to migrate: Lack of tree range expansion in response to climate change. *Glob. Chang. Biol.* **18**, 1042–1052 (2012).
100. J. Asher, R. Fox, M. S. Warren, British butterfly distributions and the 2010 target. *J. Insect Conserv.* **15**, 291–299 (2011).
101. R. C. Brusca, J. F. Wiens, W. M. Meyer, J. Eble, K. Franklin, J. T. Overpeck, W. Moore, Dramatic response to climate change in the Southwest: Robert Whittaker's 1963 Arizona Mountain plant transect revisited. *Ecol. Evol.* **3**, 3307–3319 (2013).
102. N. K. Dulvy, S. I. Rogers, S. Jennings, V. Stelzenmüller, S. R. Dye, H. R. Skjoldal, Climate change and deepening of the North Sea fish assemblage: A biotic indicator of warming seas. *J. Appl. Ecol.* **45**, 1029–1039 (2008).
103. G. H. Engelhard, J. K. Pinnegar, L. T. Kell, A. D. Rijnsdorp, Nine decades of North Sea sole and plaice distribution. *ICES J. Mar. Sci.* **68**, 1090–1104 (2011).
104. F. Fodrie, K. L. Heck, S. P. Powers, W. M. Graham, K. L. Robinson, Climate-related, decadal-scale assemblage changes of seagrass-associated fishes in the northern Gulf of Mexico. *Glob. Chang. Biol.* **16**, 48–59 (2010).
105. J. Forcada, P. N. Trathan, K. Reid, E. J. Murphy, J. P. Croxall, Contrasting population changes in sympatric penguin species in association with climate warming. *Glob. Chang. Biol.* **12**, 411–423 (2006).
106. R. Fox, Z. Randle, L. Hill, S. Anders, L. Wiffen, M. S. Parsons, Moths count: Recording moths for conservation in the UK. *J. Insect Conserv.* **15**, 55–68 (2011).
107. D. Massimino, A. Johnston, J. W. Pearce-Higgins, The geographical range of British birds expands during 15 years of warming. *Bird Study* **62**, 523–534 (2015).
108. B. G. Freeman, A. M. C. Freeman, Rapid upslope shifts in New Guinean birds illustrate strong distributional responses of tropical montane species to global warming. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 4490–4494 (2014).
109. D. A. Potvin, K. Välimäki, A. Lehikoinen, Differences in shifts of wintering and breeding ranges lead to changing migration distances in European birds. *J. Avian Biol.* **47**, 619–628 (2016).
110. R. Virkkala, A. Lehikoinen, Patterns of climate-induced density shifts of species: Poleward shifts faster in northern boreal birds than in southern birds. *Glob. Chang. Biol.* **20**, 2995–3003 (2014).
111. Y. Grewe, C. Hof, D. M. Dehling, R. Brandl, M. Brändle, Recent range shifts of European dragonflies provide support for an inverse relationship between habitat predictability and dispersal. *Glob. Ecol. Biogeogr.* **22**, 403–409 (2013).
112. E. S. Poloczanska, S. Smith, L. Fauconnet, J. Healy, I. R. Tibbetts, M. T. Burrows, A. J. Richardson, Little change in the distribution of rocky shore faunal communities on the Australian east coast after 50years of rapid warming. *J. Exp. Mar. Biol. Ecol.* **400**, 145–154 (2011).
113. N. R. Pitt, E. S. Poloczanska, A. J. Hobday, Climate-driven range changes in Tasmanian intertidal fauna. *Mar. Freshw. Res.* **61**, 963 (2010).
114. A. L. Sheldon, Possible climate-induced shift of stoneflies in a southern Appalachian catchment. *Freshw. Sci.* **31**, 765–774 (2012).
115. C.-H. Hsieh, H. Kim, W. Watson, E. Di Lorenzo, G. Sugihara, Climate-driven changes in abundance and distribution of larvae of oceanic fishes in the southern California region. *Glob. Chang. Biol.* **15**, 2137–2152 (2009).
116. T. Termaat, V. Kalkman, J. Bouwman, Changes in the range of dragonflies in the Netherlands and the possible role of temperature change. *BioRisk* **5**, 155–173 (2010).
117. S. C. Mason, G. Palmer, R. Fox, S. Gillings, J. K. Hill, C. D. Thomas, T. H. Oliver, Geographical range margins of many taxonomic groups continue to shift polewards. *Biol. J. Linn. Soc.* **115**, 586–597 (2015).
118. J. G. Hiddink, M. T. Burrows, J. García Molinos, Temperature tracking by North Sea benthic invertebrates in response to climate change. *Glob. Chang. Biol.* **21**, 117–129 (2015).
119. F. A. La Sorte, W. Jetz, Tracking of climatic niche boundaries under recent climate change. *J. Anim. Ecol.* **81**, 914–925 (2012).
120. M. O. Hill, C. D. Preston, Disappearance of boreal plants in southern Britain: Habitat loss or climate change? *Biol. J. Linn. Soc.* **115**, 598–610 (2015).
121. R. J. Warren II, L. Chick, Upward ant distribution shift corresponds with minimum, not maximum, temperature tolerance. *Glob. Chang. Biol.* **19**, 2082–2088 (2013).
122. D. S. Wethey, S. A. Woodin, Ecological hindcasting of biogeographic responses to climate change in the European intertidal zone. *Hydrobiologia* **606**, 139–151 (2008).
123. S. A. Keith, R. J. H. Herbert, P. A. Norton, S. J. Hawkins, A. C. Newton, Individualistic species limitations of climate-induced range expansions generated by meso-scale dispersal barriers. *Divers. Distrib.* **17**, 275–286 (2011).
124. C. Péron, M. Authier, C. Barbraud, K. Delord, D. Besson, H. Weimerskirch, Interdecadal changes in at-sea distribution and abundance of subantarctic seabirds along a latitudinal gradient in the Southern Indian Ocean. *Glob. Chang. Biol.* **16**, 1895–1909 (2010).
125. W. F. Precht, R. B. Aronson, Climate flickers and range shifts of reef corals. *Front. Ecol. Environ.* **2**, 307–314 (2004).
126. R. D. Sagarin, J. P. Barry, S. E. Gilman, C. H. Baxter, Climate-related change in an intertidal community over short and long time scales. *Ecol. Monogr.* **69**, 465–490 (1999).
127. S. J. Holbrook, R. J. Schmitt, J. S. Stephens Jr., Changes in an assemblage of temperate reef fishes associated with a climate shift. *Ecol. Appl.* **7**, 1299–1310 (1997).
128. P. Myers, B. L. Lundrigan, S. M. G. Hoffman, A. P. Haraminac, S. H. Seto, Climate-induced changes in the small mammal communities of the Northern Great Lakes Region. *Glob. Chang. Biol.* **15**, 1434–1454 (2009).
129. T.-S. Kwon, C. M. Lee, S.-S. Kim, Northward range shifts in Korean butterflies. *Clim. Change* **126**, 163–174 (2014).
130. R. Virkkala, A. Rajasärkkä, Northward density shift of bird species in boreal protected areas due to climate change. *Boreal Environ. Res.* **16**, 2–13 (2011).
131. R. Virkkala, A. Rajasärkkä, Climate change affects populations of northern birds in boreal protected areas. *Biol. Lett.* **7**, 395–398 (2011).
132. R. Virkkala, A. Rajasärkkä, Preserving species populations in the boreal zone in a changing climate: Contrasting trends of bird species groups in a protected area network. *Nat. Conserv.* **3**, 1–20 (2012).
133. D. Tougou, D. L. Musolin, K. Fujisaki, Some like it hot! Rapid climate change promotes changes in distribution ranges of *Nezara viridula*and *Nezara antennata*in Japan. *Entomol. Exp. Appl.* **130**, 249–258 (2009).
134. N. Ryrholm, Global warming and the change of butterfly distributions: A new opportunity for species diversity or a severe threat (Lepidoptera). *Proc. 13th Int. Colloq. Eur. Invertebr. Surv.* 7–11 (2003).
135. A. Lehikoinen, R. Virkkala, North by north-west: Climate change and directions of density shifts in birds. *Glob. Chang. Biol.* **22**, 1121–1129 (2016).
136. S. Jung, I.-C. Pang, J. Lee, I. Choi, H. K. Cha, Latitudinal shifts in the distribution of exploited fishes in Korean waters during the last 30 years: A consequence of climate change. *Rev. Fish Biol. Fish.* **24**, 443–462 (2014).
137. O. Kalela, Changes in geographic ranges in the avifauna of northern and central Europe in relation to recent changes in climate. *Bird Banding* **20**, 77–103 (1949).
138. R. Virkkala, Long-term decline of southern boreal forest birds: Consequence of habitat alteration or climate change? *Biodivers. Conserv.* **25**, 151–167 (2016).
139. N. Mattila, V. Kaitala, A. Komonen, J. Päivinen, J. S. Kotiaho, Ecological correlates of distribution change and range shift in butterflies. *Insect Conserv. Divers.* **4**, 239–246 (2011).
140. C. Tayleur, P. Caplat, D. Massimino, A. Johnston, N. Jonzén, H. G. Smith, Å. Lindström, Swedish birds are tracking temperature but not rainfall: Evidence from a decade of abundance changes. *Glob. Ecol. Biogeogr.* **24**, 859–872 (2015).
141. J. D. Ash, T. J. Givnish, D. M. Waller, Tracking lags in historical plant species' shifts in relation to regional climate change. *Glob. Chang. Biol.* **23**, 1305–1315 (2016).
142. I. Valiela, J. L. Bowen, Shifts in winter distribution in birds: Effects of global warming and local habitat change. *Ambio* **32**, 476–480 (2003).
143. I. M. D. Maclean, G. E. Austin, M. M. Rehfisch, J. Blew, O. Crowe, S. Delany, K. Devos, B. Deceuninck, K. Günther, K. Laursen, M. Van Roomen, J. Wahl, Climate change causes rapid changes in the distribution and site abundance of birds in winter. *Glob. Chang. Biol.* **14**, 2489–2500 (2008).
144. Å. Lindström, M. Green, G. Paulson, H. G. Smith, V. Devictor, Rapid changes in bird community composition at multiple temporal and spatial scales in response to recent climate change. *Ecography* **36**, 313–322 (2013).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

145. F. Jiguet, V. Devictor, R. Ottvall, C. Van Turnhout, H. Van der Jeugd, A. Lindström, Bird population trends are linearly affected by climate change along species thermal ranges. *Proc. Biol. Sci.* **277**, 3601–3608 (2010).
146. H. I. Dulle, S. W. Ferger, N. J. Cordeiro, K. M. Howell, M. Schleuning, K. Böhning-Gaese, C. Hof, Changes in abundances of forest understorey birds on Africa's highest mountain suggest subtle effects of climate change. *Divers. Distrib.* **22**, 288–299 (2016).
147. K. Princé, B. Zuckerberg, Climate change in our backyards: The reshuffling of North America's winter bird communities. *Glob. Chang. Biol.* **21**, 572–585 (2015).
148. C. Kampichler, C. A. M. van Turnhout, V. Devictor, H. P. van der Jeugd, Large-scale changes in community composition: Determining land use and climate change signals. *PLOS ONE* **7**, e35272 (2012).
149. S. Fraixedas, A. Lehikoinen, A. Lindén, Impacts of climate and land-use change on wintering bird populations in Finland. *J. Avian Biol.* **46**, 63–72 (2015).
150. T. Roth, M. Plattner, V. Amrhein, Plants, birds and butterflies: Short-term responses of species communities to climate warming vary by taxon and with altitude. *PLOS ONE* **9**, e82490 (2014).
151. L. Mair, C. D. Thomas, B. J. Anderson, R. Fox, M. Botham, J. K. Hill, Temporal variation in responses of species to four decades of climate warming. *Glob. Chang. Biol.* **18**, 2439–2447 (2012).
152. R. Bertrand, J. Lenoir, C. Piedallu, G. Riofrío-Dillon, P. de Ruffray, C. Vidal, J.-C. Pierrat, J.-C. Gégout, Changes in plant community composition lag behind climate warming in lowland forests. *Nature* **479**, 517–520 (2011).
153. P. R. Last, W. T. White, D. C. Gledhill, A. J. Hobday, R. Brown, G. J. Edgar, G. Pecl, Long-term shifts in abundance and distribution of a temperate fish fauna: A response to climate change and fishing practices. *Glob. Ecol. Biogeogr.* **20**, 58–72 (2011).
154. F. J. Mueter, M. A. Litzow, Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecol. Appl.* **18**, 309–320 (2008).
155. B. Gregory, L. Christophe, E. Martin, Rapid biogeographical plankton shifts in the North Atlantic Ocean. *Glob. Chang. Biol.* **15**, 1790–1803 (2009).
156. T. Wernberg, B. D. Russell, M. S. Thomsen, C. F. D. Gurgel, C. J. A. Bradshaw, E. S. Poloczanska, S. D. Connell, Seaweed communities in retreat from ocean warming. *Curr. Biol.* **21**, 1828–1832 (2011).
157. A. J. Southward, S. J. Hawkins, M. T. Burrows, Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. *J. Therm. Biol.* **20**, 127–155 (1995).
158. D. F. Doak, W. F. Morris, Demographic compensation and tipping points in climate-induced range shifts. *Nature* **467**, 959–962 (2010).
159. A. Lehikoinen, K. Jaatinen, A. V. Vähätalo, P. Clausen, O. Crowe, B. Deceuninck, R. Hearn, C. A. Holt, M. Hornman, V. Keller, L. Nilsson, T. Langendoen, I. Tománková, J. Wahl, A. D. Fox, Rapid climate driven shifts in wintering distributions of three common waterbird species. *Glob. Chang. Biol.* **19**, 2071–2081 (2013).
160. D. J. Currie, S. Venne, Climate change is not a major driver of shifts in the geographical distributions of North American birds. *Glob. Ecol. Biogeogr.* **26**, 333–346 (2017).
161. L. Comte, G. Grenouillet, Distribution shifts of freshwater fish under a variable climate: Comparing climatic, bioclimatic and biotic velocities. *Divers. Distrib.* **21**, 1014–1026 (2015).
162. J. L. Rich, D. J. Currie, Are North American bird species' geographic ranges mainly determined by climate? *Glob. Ecol. Biogeogr.* **27**, 461–473 (2018).
163. J. Aguirre-Gutiérrez, W. Daniel Kissling, L. G. Carvalheiro, M. F. Wallisdevries, M. Franzén, J. C. Biesmeijer, Functional traits help to explain half-century long shifts in pollinator distributions. *Sci. Rep.* **6**, 24451 (2016).
164. C. W. Woodall, J. A. Westfall, A. W. D'Amato, J. R. Foster, B. F. Walters, Decadal changes in tree range stability across forests of the eastern U.S. *For. Ecol. Manage.* **429**, 503–510 (2018).
165. L. Marion, B. Bergerot, Northern range shift may be due to increased competition induced by protection of species rather than to climate change alone. *Ecol. Evol.* **8**, 8364–8379 (2018).
166. L. Bani, M. Luppi, E. Rocchia, O. Dondina, V. Orioli, Winners and losers: How the elevational range of breeding birds on Alps has varied over the past four decades due to climate and habitat changes. *Ecol. Evol.* **9**, 1289–1305 (2019).
167. S. B. Rumpf, K. Hülber, J. Wessely, W. Willner, D. Moser, A. Gattringer, G. Klonner, N. E. Zimmermann, S. Dullinger, Extinction debts and colonization credits of non-forest plants in the European Alps. *Nat. Commun.* **10**, 4293 (2019).
168. A. Ettinger, J. HilleRisLambers, Competition and facilitation may lead to asymmetric range shift dynamics with climate change. *Glob. Chang. Biol.* **23**, 3921–3933 (2017).
169. T. Termaat, A. J. Van Strien, R. H. A. van Grunsven, G. De Knijf, U. Bjelke, K. Burbach, K.-J. K. Conze, P. Goffart, D. Hepper, V. J. Kalkman, G. Motte, M. D. Prins, F. Prunier, D. Sparrow, G. G. van den Top, C. Vanappelghem, M. Winterholler, M. F. WallisDeVries, Distribution trends of European dragonflies under climate change. *Divers. Distrib.* **25**, 936–950 (2019).
170. W. Cheng, R. C. Kendrick, F. Guo, S. Xing, M. W. Tingley, T. C. Bonebrake, Complex elevational shifts in a tropical lowland moth community following a decade of climate change. *Divers. Distrib.* **25**, 514–523 (2019).
171. L. Boisvert-Marsh, C. Périé, S. de Blois, Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. *Ecosphere* **5**, art83 (2014).
172. G. H. Pyke, J. D. Thomson, D. W. Inouye, T. J. Miller, Effects of climate change on phenologies and distributions of bumble bees and the plants they visit. *Ecosphere* **7**, e01267 (2016).
173. J. Reif, P. Voříšek, K. Šťastný, M. Koschová, V. Bejček, The impact of climate change on long-term population trends of birds in a central European country. *Anim. Conserv.* **11**, 412–421 (2008).
174. X. Zhang, B. Zhang, K. Feeley, G. G. Wang, J. Zhang, L. Zhai, Ecological contingency in species shifts: Downslope shifts of woody species under warming climate and land-use change. *Environ. Res. Lett.* **14**, 114033 (2019).
175. B. G. Freeman, M. N. Scholer, V. Ruiz-Gutierrez, J. W. Fitzpatrick, Climate change causes upslope shifts and mountaintop extirpations in a tropical bird community. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11982–11987 (2018).
176. V. J. Monleon, H. E. Lintz, Evidence of tree species' range shifts in a complex landscape. *PLOS ONE* **10**, e0118069 (2015).
177. P. J. Platts, S. C. Mason, G. Palmer, J. K. Hill, T. H. Oliver, G. D. Powney, R. Fox, C. D. Thomas, Habitat availability explains variation in climate-driven range shifts across multiple taxonomic groups. *Sci. Rep.* **9**, 15039 (2019).
178. U. Enriquez-Urzelai, N. Bernardo, G. Moreno-Rueda, A. Montori, G. Llorente, Are amphibians tracking their climatic niches in response to climate warming? A test with Iberian amphibians. *Clim. Change* **154**, 289–301 (2019).
179. M. J. Glennon, S. F. Langdon, M. A. Rubenstein, M. S. Cross, Relative contribution of climate and non-climate drivers in determining dynamic rates of boreal birds at the edge of their range. *PLOS ONE* **14**, e0224308 (2019).
180. X. He, K. S. Burgess, X.-F. Yang, A. Ahrends, L.-M. Gao, D.-Z. Li, Upward elevation and northwest range shifts for alpine *Meconopsis* species in the Himalaya-Hengduan Mountains region Germplasm Bank of Wild Species. *Ecol. Evol.* **9**, 4055–4064 (2019).
181. S. S. Nooten, S. M. Rehan, Historical changes in bumble bee body size and range shift of declining species. *Biodivers. Conserv.* **29**, 451–467 (2020).
182. T. Gooliaff, K. E. Hodges, Historical distributions of bobcats (Lynxrufus) and Canada lynx (Lynxcanadensis) suggest no range shifts in British Columbia, Canada. *Can. J. Zool.* **96**, 1299–1308 (2018).
183. S. K. Auer, D. I. King, Ecological and life-history traits explain recent boundary shifts in elevation and latitude of western North American songbirds. *Glob. Ecol. Biogeogr.* **23**, 867–875 (2014).
184. C. Cerrato, E. Rocchia, M. Brunetti, R. Bionda, B. Bassano, A. Provenzale, S. Bonelli, R. Viterbi, Butterfly distribution along altitudinal gradients: Temporal changes over a short time period. *Nat. Conserv.* **34**, 91–118 (2019).
185. R. Virkkala, J. Aalto, R. K. Heikkinen, A. Rajasärkkä, S. Kuusela, N. Leikola, M. Luoto, Can topographic variation in climate buffer against climate change-induced population declines in northern forest birds? *Diversity* **12**, 56 (2020).
186. R. Parkash, S. Ramniwas, B. Kajla, Climate warming mediates range shift of two differentially adapted stenothermal Drosophila species in the Western Himalayas. *J. Asia Pac. Entomol.* **16**, 147–153 (2013).
187. M. Dainese, S. Aikio, P. E. Hulme, A. Bertolli, F. Prosser, L. Marini, Human disturbance and upward expansion of plants in a warming climate. *Nat. Clim. Chang.* **7**, 577–580 (2017).
188. F. G. Araújo, T. P. Teixeira, A. P. P. Guedes, M. C. C. de Azevedo, A. L. M. Pessanha, Shifts in the abundance and distribution of shallow water fish fauna on the southeastern Brazilian coast: A response to climate change. *Hydrobiologia* **814**, 205–218 (2018).
189. A. D. Flesch, Patterns and drivers of long-term changes in breeding bird communities in a global biodiversity hotspot in Mexico. *Divers. Distrib.* **25**, 499–513 (2019).
190. S. E. Campana, R. B. Stefánsdóttir, K. Jakobsdóttir, J. Sólmundsson, Shifting fish distributions in warming sub-Arctic oceans. *Sci. Rep.* **10**, 16448 (2020).
191. D. Yemane, S. P. Kirkman, J. Kathena, S. E. N'siangango, B. E. Axelsen, T. Samaai, Assessing changes in the distribution and range size of demersal fish populations in the Benguela Current Large Marine Ecosystem. *Rev. Fish Biol. Fish.* **24**, 463–483 (2014).
192. K. R. Nicastro, G. I. Zardi, S. Teixeira, J. Neiva, E. A. Serrão, G. A. Pearson, Shift happens: Trailing edge contraction associated with recent warming trends threatens a distinct genetic lineage in the marine macroalga Fucus vesiculosus. *BMC Biol.* **11**, 6 (2013).
193. K. Tanaka, S. Taino, H. Haraguchi, G. Prendergast, M. Hiraoka, Warming off southwestern Japan linked to distributional shifts of subtidal canopy-forming seaweeds. *Ecol. Evol.* **2**, 2854–2865 (2012).
194. M. L. Peterson, A. L. Angert, K. M. Kay, Experimental migration upward in elevation is associated with strong selection on life history traits. *Ecol. Evol.* **10**, 612–625 (2020).
195. S. J. Melles, M.-J. Fortin, K. Lindsay, D. Badzinski, Expanding northward: Influence of climate change, forest connectivity, and population processes on a threatened species' range shift. *Glob. Chang. Biol.* **17**, 17–31 (2011).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

196. D. W. Williams, A. Liebhold, Latitudinal shifts in spruce budworm (Lepidoptera: Tortricidae) outbreaks and spruce-fir forest distrbutions with climate change. *Acta Phytophathologica Entomol. Hungarica* **32**, 205–215 (1997).
197. L. Kullman, Tree-limit rise and recent warming: A geoecological case study from the Swedish Scandes. *Nor. Geogr. Tidsskr.* **54**, 49–59 (2000).
198. G. A. Rose, B. DeYoung, D. W. Kulka, S. V. Goddard, G. L. Fletcher, Distribution shifts and overfishing the northern cod (Gadus morhua): A view from the ocean. *Can. J. Fish. Aquat. Sci.* **57**, 644–663 (2000).
199. L. Sirois, Spatiotemporal variation in black spruce cone and seed crops along a boreal forest-tree line transect. *Can. J. For. Res.* **30**, 900–909 (2000).
200. B. J. Roberts, C. P. Catterall, P. Eby, J. Kanowski, Latitudinal range shifts in Australian flying-foxes: A re-evaluation. *Austral Ecol.* **37**, 12–22 (2012).
201. E. A. Beever, C. Ray, J. L. Wilkening, P. F. Brussard, P. W. Mote, Contemporary climate change alters the pace and drivers of extinction. *Glob. Chang. Biol.* **17**, 2054–2070 (2011).
202. E. M. Rubidge, W. B. Monahan, J. L. Parra, S. E. Cameron, J. S. Brashares, The role of climate, habitat, and species co-occurrence as drivers of change in small mammal distributions over the past century. *Glob. Chang. Biol.* **17**, 696–708 (2011).
203. L. P. Erb, C. Ray, R. Guralnick, On the generality of a climate-mediated shift in the distribution of the American pika (Ochotona princeps). *Ecology* **92**, 1730–1735 (2011).
204. B. C. Chessman, Biological traits predict shifts in geographical ranges of freshwater invertebrates during climatic warming and drying. *J. Biogeogr.* **39**, 957–969 (2012).
205. T. G. T. Jaenson, D. G. E. Jaenson, L. Eisen, E. Petersson, E. Lindgren, Changes in the geographical distribution and abundance of the tick *Ixodes ricinus* during the past 30 years in Sweden. *Parasit. Vectors* **5**, 8 (2012).
206. A. Fredston-Hermann, R. Selden, M. Pinsky, S. D. Gaines, B. S. Halpern, Cold range edges of marine fishes track climate change better than warm edges. *Glob. Chang. Biol.* **26**, 2908–2922 (2020).
207. M. I. Pardi, R. C. Terry, E. A. Rickart, R. J. Rowe, Testing climate tracking of montane rodent distributions over the past century within the Great Basin ecoregion. *Glob. Ecol. Conserv.* **24**, e01238 (2020).
208. C. W. Barrows, L. C. Sweet, J. Rangitsch, K. Lalumiere, T. Green, S. Heacox, M. Davis, M. Vamstad, J. Heintz, J. E. Rodgers, Responding to increased aridity: Evidence for range shifts in lizards across a 50-year time span in Joshua Tree National Park. *Biol. Conserv.* **248**, 108667 (2020).
209. K. J. Iknayan, S. R. Beissinger, In transition: Avian biogeographic responses to a century of climate change across desert biomes. *Glob. Chang. Biol.* **26**, 3268–3284 (2020).
210. L. Marshall, F. Perdijk, N. Dendoncker, W. Kunin, S. Roberts, J. C. Biesmeijer, Bumblebees moving up: Shifts in elevation ranges in the Pyrenees over 115 years. *Proc. R. Soc. B* **287**, 20202201 (2020).
211. D. R. Warren, J. B. Dunham, D. Hockman-Wert, Geographic variability in elevation and topographic constraints on the distribution of native and nonnative trout in the Great Basin. *Trans. Am. Fish. Soc.* **143**, 205–218 (2014).
212. K. M. Hughes, L. Dransfeld, M. P. Johnson, Changes in the spatial distribution of spawning activity by north-east Atlantic mackerel in warming seas: 1977–2010. *Mar. Biol.* **161**, 2563–2576 (2014).
213. J. J. Kirchman, K. J. Schneider, Range expansion and the breakdown of Bergmann's Rule in Red-Bellied Woodpeckers (*Melanerpes carolinus*). *Wilson J. Ornithol.* **126**, 236–248 (2014).
214. E. Delava, R. Allemand, L. Léger, F. Fleury, P. Gibert, The rapid northward shift of the range margin of a Mediterranean parasitoid insect (Hymenoptera) associated with regional climate warming. *J. Biogeogr.* **41**, 1379–1389 (2014).
215. R. K. Gallon, M. Robuchon, B. Leroy, L. Le Gall, M. Valero, E. Feunteun, Twenty years of observed and predicted changes in subtidal red seaweed assemblages along a biogeographical transition zone: Inferring potential causes from environmental data. *J. Biogeogr.* **41**, 2293–2306 (2014).
216. A. Battisti, M. Stastny, S. Netherer, C. Robinet, A. Schopf, A. Roques, S. Larsson, Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. *Ecol. Appl.* **15**, 2084–2096 (2005).
217. B. D. Uher-Koch, R. M. Buchheit, C. R. Eldermire, H. M. Wilson, J. A. Schmutz, Shifts in the wintering distribution and abundance of Emperor Geese in Alaska. *Glob. Ecol. Conserv.* **25**, e01397 (2020).
218. C. J. Raxworthy, R. G. Pearson, N. Rabibisoa, A. M. Rakotondrazafy, J.-B. B. Ramanamanjato, A. P. Raselimanana, S. Wu, R. A. Nussbaum, D. A. Stone, Extinction vulnerability of tropical montane endemism from warming and upslope displacement: A preliminary appraisal for the highest massif in Madagascar. *Glob. Chang. Biol.* **14**, 1703–1720 (2008).
219. I.-C. Chen, H.-J. Shiu, S. Benedick, J. D. Holloway, V. K. Chey, H. S. Barlow, J. K. Hill, C. D. Thomas, Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proc. Natl. Acad. Sci.* **106**, 1479–1483 (2009).
220. K. S.-H. Peh, Potential effects of climate change on elevational distributions of tropical birds in Southeast Asia. *Condor* **109**, 437–441 (2007).
221. T. A. Seimon, A. Seimon, P. Daszaka, S. R. P. Halloy, L. M. Schloegel, C. A. Aguilar, P. Sowell, A. D. Hyatt, B. Konecky, J. Simmons, Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation. *Glob. Chang. Biol.* **13**, 288–299 (2007).
222. G. Grabherr, M. Gottfried, H. Paull, Climate effects on mountain plants. *Nature* **369**, 448 (1994).
223. J. Nye, J. Link, J. Hare, W. Overholtz, Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Mar. Ecol. Prog. Ser.* **393**, 111–129 (2009).
224. M. Konvicka, M. Maradova, J. Benes, Z. Fric, P. Kepka, Uphill shifts in distribution of butterflies in the Czech Republic: Effects of changing climate detected on a regional scale. *Glob. Ecol. Biogeogr.* **12**, 403–410 (2003).
225. L. Kullman, Rapid recent range-margin rise of tree and shrub species in the Swedish Scandes. *J. Ecol.* **90**, 68–77 (2002).
226. S. D. Wilson, C. Nilsson, Arctic alpine vegetation change over 20 years. *Glob. Chang. Biol.* **15**, 1676–1684 (2009).
227. N. Paprocki, J. A. Heath, S. J. Novak, Regional distribution shifts help explain local changes in wintering raptor abundance: Implications for interpreting population trends. *PLOS ONE* **9**, e86814 (2014).
228. J.-A. Grytnes, J. Kapfer, G. Jurasinski, H. H. Birks, H. Henriksen, K. Klanderud, A. Odland, M. Ohlson, S. Wipf, H. John, B. Birks, Identifying the driving factors behind observed elevational range shifts on European mountains. *Glob. Ecol. Biogeogr.* **23**, 876–884 (2014).
229. A. M. A. Franco, J. K. Hill, C. Kitschke, Y. C. Collingham, D. B. Roy, R. Fox, B. Huntley, C. D. Thomas, Impacts of climate warming and habitat loss on extinctions at species' low-latitude range boundaries. *Glob. Chang. Biol.* **12**, 1545–1553 (2006).
230. C. Moritz, J. L. Patton, C. J. Conroy, J. L. Parra, G. C. White, S. R. Beissinger, Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. *Science* **322**, 261–264 (2008).
231. J. Lenoir, J. C. Gégout, P. A. Marquet, P. De Ruffray, H. Brisse, J. C. Gegout, P. A. Marquet, P. De Ruffray, H. Brisse, J. C. Gégout, P. A. Marquet, P. De Ruffray, H. Brisse, A significant upward shift in plant species optimum elevation during the 20th century. *Science* **320**, 1768–1771 (2008).
232. H. Pauli, M. Gottfried, K. Reiter, C. Klettner, G. Grabherr, Signals of range expansions and contractions of vascular plants in the high Alps: Observations (1994–2004) at the GLORIA* master site Schrankogel, Tyrol, Austria. *Glob. Chang. Biol.* **13**, 147–156 (2007).
233. G. Parolo, G. Rossi, Upward migration of vascular plants following a climate warming trend in the Alps. *Basic Appl. Ecol.* **9**, 100–107 (2008).
234. P. Vittoz, J. Bodin, S. Ungricht, C. A. Burga, G.-R. Walther, One century of vegetation change on Isla Persa, a nunatak in the Bernina massif in the Swiss Alps. *J. Veg. Sci.* **19**, 671–680 (2008).
235. J. D. M. Speed, G. Austrheim, A. J. Hester, A. Mysterud, Elevational advance of alpine plant communities is buffered by herbivory. *J. Veg. Sci.* **23**, 617–625 (2012).
236. P. Dieker, C. Drees, T. Assmann, Two high-mountain burnet moth species (Lepidoptera, Zygaenidae) react differently to the global change drivers climate and land-use. *Biol. Conserv.* **144**, 2810–2818 (2011).
237. L. Comte, G. Grenouillet, Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography* **36**, 1236–1246 (2013).
238. V. A. Felde, J. Kapfer, J. Grytnes, Upward shift in elevational plant species ranges in Sikkilsdalen, central Norway. *Ecography* **35**, 922–932 (2012).
239. J. Reif, J. Flousek, The role of species' ecological traits in climatically driven altitudinal range shifts of central European birds. *Oikos* **121**, 1053–1060 (2012).
240. J. U. Jepsen, S. B. Hagen, R. A. Ims, N. G. Yoccoz, Climate change and outbreaks of the geometrids Operophtera brumata and Epirrita autumnata in subarctic birch forest: Evidence of a recent outbreak range expansion. *J. Anim. Ecol.* **77**, 257–264 (2008).
241. S. Popy, L. Bordignon, R. Prodon, A weak upward elevational shift in the distributions of breeding birds in the Italian Alps. *J. Biogeogr.* **37**, 57–67 (2010).
242. R. Maggini, A. Lehmann, M. Kéry, H. Schmid, M. Beniston, L. Jenni, N. Zbinden, Are Swiss birds tracking climate change?: Detecting elevational shifts using response curve shapes. *Ecol. Model.* **222**, 21–32 (2011).
243. A. Corten, Northern distribution of North Sea herring as a response to high water temperatures and/or low food abundance. *Fish. Res.* **50**, 189–204 (2001).
244. R. J. Wilson, D. Gutierrez, J. Gutierrez, V. J. Monserrat, An elevational shift in butterfly species richness and composition accompanying recent climate change. *Glob. Chang. Biol.* **13**, 1873–1887 (2007).
245. P. Wardle, M. C. Coleman, Evidence for rising upper limits of four native New Zealand forest trees. *N. Z. J. Bot.* **30**, 303–314 (1992).
246. B. C. Beckmann, B. V. Purse, D. B. Roy, H. E. Roy, P. G. Sutton, C. D. Thomas, Two species with an unusual combination of traits dominate responses of british grasshoppers and crickets to environmental change. *PLOS ONE* **10**, e0130488 (2015).
247. P. Lesica, B. McCune, E. Ezcurra, Decline of arctic-alpine plants at the southern margin of their range following a decade of climatic warming. *J. Veg. Sci.* **15**, 679–690 (2004).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

248. P. Vittoz, C. Randin, A. Dutoit, F. Bonnet, O. Hegg, Low impact of climate change on subalpine grasslands in the Swiss Northern Alps. *Glob. Chang. Biol.* **15**, 209–220 (2009).
249. A. J. Richardson, D. S. Schoeman, Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* **305**, 1609–1612 (2004).
250. D. J. Beare, F. Burns, A. Greig, E. G. Jones, K. Peach, M. Kienzle, E. McKenzie, D. G. Reid, Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. *Mar. Ecol. Prog. Ser.* **284**, 269–278 (2004).
251. D. Beare, F. Burns, E. Jones, K. Peach, E. Portilla, T. Greig, E. McKenzie, D. Reid, An increase in the abundance of anchovies and sardines in the north-western North Sea since 1995. *Glob. Chang. Biol.* **10**, 1209–1213 (2004).
252. J. Penuelas, M. Boada, A global change-induced biome shift in the Montseny mountains (NE Spain). *Glob. Chang. Biol.* **9**, 131–140 (2003).
253. B. Zuckerberg, A. M. Woods, W. F. Porter, Poleward shifts in breeding bird distributions in New York State. *Glob. Chang. Biol.* **15**, 1866–1883 (2009).
254. H. Yamano, K. Sugihara, K. Nomura, Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophys. Res. Lett.* **38**, L04601 (2011).
255. B. Worm, D. P. Tittensor, Range contraction in large pelagic predators. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 11942–11947 (2011).
256. R. Menéndez, A. González-Megías, P. Jay-Robert, R. Marquéz-Ferrando, Climate change and elevational range shifts: Evidence from dung beetles in two European mountain ranges. *Glob. Ecol. Biogeogr.* **23**, 646–657 (2014).
257. J. E. Brommer, The range margins of northern birds shift polewards. *Ann. Zool. Fennici* **41**, 391–397 (2004).
258. M. L. Forister, A. C. McCall, N. J. Sanders, J. A. Fordyce, J. H. Thorne, J. O'Brien, D. P. Waetjen, A. M. Shapiro, Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 2088–2092 (2010).
259. E. Frei, J. Bodin, G.-R. Walther, Plant species' range shifts in mountainous areas—All uphill from here? *Bot. Helv.* **120**, 117–128 (2010).
260. J. Reif, K. Šťastný, V. Bejček, Contrasting Effects of climatic and habitat changes on birds with Northern range limits in Central Europe as revealed by an analysis of breeding bird distribution in the Czech Republic. *Acta Ornithol.* **45**, 83–90 (2010).
261. R. Hickling, D. B. Roy, J. K. Hill, C. D. Thomas, A northward shift of range margins in British Odonata. *Glob. Chang. Biol.* **11**, 502–506 (2005).
262. J. P. Barry, C. H. Baxter, R. D. Sagarin, S. E. Gilman, Climate-related, long-term faunal changes in a California rocky intertidal community. *Science* **267**, 672–675 (1995).
263. C. Parmesan, Climate and species' range. *Nature* **382**, 765–766 (1996).
264. A. T. Hitch, P. L. Leberg, Breeding distributions of North American bird species moving north as a result of climate change. *Conserv. Biol.* **21**, 534–539 (2007).
265. K. W. McDonald, C. J. W. McClure, B. W. Rolek, G. E. Hill, Diversity of birds in eastern North America shifts north with global warming. *Ecol. Evol.* **2**, 3052–3060 (2012).
266. A. L. Perry, P. J. Low, J. R. Ellis, J. D. Reynolds, Climate change and distribution shifts in marine fishes. *Science* **308**, 1912–1915 (2005).
267. A. E. Kelly, M. L. Goulden, Rapid shifts in plant distribution with recent climate change. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 11823–11826 (2008).
268. R. Hickling, D. B. Roy, J. K. Hill, R. Fox, C. D. Thomas, The distributions of a wide range of taxonomic groups are expanding polewards. *Glob. Chang. Biol.* **12**, 450–455 (2006).
269. J. Pöyry, M. Luoto, R. K. Heikkinen, M. Kuussaari, K. Saarinen, Species traits explain recent range shifts of Finnish butterflies. *Glob. Chang. Biol.* **15**, 732–743 (2009).
270. L. Godet, M. Jaffré, V. Devictor, Waders in winter: Long-term changes of migratory bird assemblages facing climate change. *Biol. Lett.* **7**, 714–717 (2011).
271. A. T. Peterson, Subtle recent distributional shifts in Great Plains bird species. *Southwest. Nat.* **48**, 289–292 (2003).
272. P. F. Lima, A. P. Ribeiro, N. Queiroz, J. S. Hawkins, M. A. Santos, Do distributional shifts of northern and southern species of algae match the warming pattern? *Glob. Chang. Biol.* **13**, 2592–2604 (2007).
273. M. M. Rivadeneira, M. Fernández, Shifts in southern endpoints of distribution in rocky intertidal species along the south-eastern Pacific coast. *J. Biogeogr.* **32**, 203–209 (2005).
274. G. Moreno-Rueda, J. M. Pleguezuelos, M. Pizarro, A. Montori, Northward shifts of the distributions of spanish reptiles in association with climate change. *Conserv. Biol.* **26**, 278–283 (2012).
275. C. L. Angelo, C. C. Daehler, Upward expansion of fire-adapted grasses along a warming tropical elevation gradient. *Ecography* **36**, 551–559 (2013).
276. V. Devictor, C. van Swaay, T. Brereton, D. Chamberlain, J. Heliölä, S. Herrando, R. Julliard, M. Kuussaari, Å. Lindström, D. B. Roy, O. Schweiger, J. Settele, C. Stefanescu, A. Van Strien, C. Van Turnhout, Z. Vermouzek, M. W. DeVries, I. Wynhoff, F. Jiguet, Differences in the climatic debts of birds and butterflies at a continental scale. *Nat. Clim. Change* **2**, 121–124 (2012).
277. J. Bodin, V. Badeau, E. Bruno, C. Cluzeau, J.-M. Moisselin, G.-R. Walther, J.-C. Dupouey, Shifts of forest species along an elevational gradient in Southeast France: Climate change or stand maturation? *J. Veg. Sci.* **24**, 269–283 (2013).
278. B. Beckage, B. Osborne, D. G. Gavin, C. Pucko, T. Siccama, T. Perkins, A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 4197–4202 (2008).
279. I.-C. Chen, J. K. Hill, H.-J. Shiu, J. D. Holloway, S. Benedick, V. K. Chey, H. S. Barlow, C. D. Thomas, Asymmetric boundary shifts of tropical montane Lepidoptera over four decades of climate warming. *Glob. Ecol. Biogeogr.* **20**, 34–45 (2011).
280. J. Alheit, T. Pohlmann, M. Casini, W. Greve, R. Hinrichs, M. Mathis, K. O'Driscoll, R. Vorberg, C. Wagner, Climate variability drives anchovies and sardines into the North and Baltic Seas. *Prog. Oceanogr.* **96**, 128–139 (2012).
281. K. M. Alofs, D. A. Jackson, N. P. Lester, Ontario freshwater fishes demonstrate differing range-boundary shifts in a warming climate. *Divers. Distrib.* **20**, 123–136 (2014).
282. G. A. Breed, S. Stichter, E. E. Crone, Climate-driven changes in northeastern US butterfly communities. *Nat. Clim. Change* **3**, 142–145 (2013).
283. J. E. Brommer, A. Lehikoinen, J. Valkama, The breeding ranges of central european and arctic bird species move poleward. *PLOS ONE* **7**, e43648 (2012).
284. P. Kočárek, J. HoluSa, R. Vlk, P. Marhoul, T. Zuna-Kratky, Recent expansions of the bush-crickets Phaneroptera falcata and Phaneroptera nana (Orthoptera: Tettigoniidae) in the Czech Republic. *Articulata* **23**, 67–75 (2008).
285. A. Bergamini, S. Ungricht, H. Hofmann, An elevational shift of cryophilous bryophytes in the last century – an effect of climate warming? *Divers. Distrib.* **15**, 871–879 (2009).
286. G.-R. Walther, S. Beissner, C. A. Burga, Trends in the upward shift of alpine plants. *J. Veg. Sci.* **16**, 541–548 (2005).

Acknowledgments: We thank C. Parmesan for early discussions and two anonymous referees for useful suggestions. **Funding:** S.T. and M.B.A. were funded by the Ministry of Economy and Competitiveness through research projects CGL2015-68438-P and PGC2018–099363-B-I00. M.B.A. is also funded through EC INFRAIA-01-2016-2017 project number 731065. **Author contributions:** S.T., C.R., and M.B.A. conceptualized and planned the research. S.T. and B.N. wrote the scripts for the analysis. S.T. conducted the review of the literature and the subsequent analysis. S.T. and M.B.A. wrote the manuscript with contributions from all authors. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 5 August 2020
Accepted 11 February 2021
Published 7 April 2021
10.1126/sciadv.abe1110

Citation: S. Taheri, B. Naimi, C. Rahbek, M. B. Araújo, Improvements in reports of species redistribution under climate change are required. *Sci. Adv.* **7**, eabe1110 (2021).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021

Science Advances

Improvements in reports of species redistribution under climate change are required

Shirin Taheri, Babak Naimi, Carsten Rahbek and Miguel B. Araújo

Sci Adv **7** (15), eabe1110.
DOI: 10.1126/sciadv.abe1110

ARTICLE TOOLS	http://advances.sciencemag.org/content/7/15/eabe1110
SUPPLEMENTARY MATERIALS	http://advances.sciencemag.org/content/suppl/2021/04/05/7.15.eabe1110.DC1
REFERENCES	This article cites 280 articles, 21 of which you can access for free http://advances.sciencemag.org/content/7/15/eabe1110#BIBL
PERMISSIONS	http://www.sciencemag.org/help/reprints-and-permissions

Use of this article is subject to the Terms of Service

Science Advances (ISSN 2375-2548) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science Advances* is a registered trademark of AAAS.

Copyright © 2021 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).

Downloaded from http://advances.sciencemag.org/ on May 26, 2021