

BIODIVERSITY CHANGE

Landscape-scale forest loss as a catalyst of population and biodiversity change

Gergana N. Daskalova^{1*}, Isla H. Myers-Smith¹, Anne D. Bjorkman^{2,3}, Shane A. Blowers^{4,5}, Sarah R. Supp⁶, Anne E. Magurran⁷, Maria Dornelas⁷

Global biodiversity assessments have highlighted land-use change as a key driver of biodiversity change. However, there is little empirical evidence of how habitat transformations such as forest loss and gain are reshaping biodiversity over time. We quantified how change in forest cover has influenced temporal shifts in populations and ecological assemblages from 6090 globally distributed time series across six taxonomic groups. We found that local-scale increases and decreases in abundance, species richness, and temporal species replacement (turnover) were intensified by as much as 48% after forest loss. Temporal lags in population- and assemblage-level shifts after forest loss extended up to 50 years and increased with species' generation time. Our findings that forest loss catalyzes population and biodiversity change emphasize the complex biotic consequences of land-use change.

Accelerating human impacts are reshaping Earth's ecosystems (1). The abundance of species' populations (2, 3) and the richness (4–6) and composition (6) of ecological assemblages at sites around the world are being altered over time in complex ways (7–9). However, there is currently only a limited quantitative understanding of how global change drivers, such as land-use change, influence the observed heterogeneous local-scale patterns in population abundance and biodiversity (8, 10, 11). In terrestrial ecosystems, much current knowledge stems from space-for-time approaches (12, 13) and model projections (14, 15) that attribute population and richness declines to different types of land-use change, including reductions in forest cover. Yet space-for-time methods may not accurately represent the effects of global change drivers, because they do not account for ecological lags (8, 16, 17) and community self-regulation (18). Furthermore, ongoing controversy about the diverse impacts of habitat fragmentation on biodiversity (19–21) could be in part attributable to a lack of observational data from sites encompassing the full spectrum of forest fragmentation. Recent global-scale datasets of past land cover reconstructions (22) and contemporary high-resolution remote-sensing observations (23, 24) provide an opportunity to quantify landscape-scale decreases and increases in forested areas around the world (hereafter, forest loss and gain). By in-

tegrating forest loss estimates with population and biodiversity observations (25, 26) (Figs. 1 and 2A), our analysis provides insight into the influence of land-use change on local-scale population and biodiversity change around the planet.

In our study, we set out to conduct a global-extent attribution analysis of the influence of forest cover change on population and biodiversity change (Fig. 1). We quantitatively tested specific predictions of how the timing and magnitude of landscape-scale forest loss influence species' populations and ecological assemblages across terrestrial ecosystems around the planet (Figs. 1 and 2 and table S1) (27). Land-use change, and particularly forest cover loss, alters habitat and resource availability (12, 28, 29) and is a global threat for the persistence of terrestrial species (30) (Fig. 2 and fig. S12). We thus predicted the greatest impacts on populations and biodiversity when time-series monitoring encompassed the 10-year period that included the largest reduction in forested areas at each site (calculated between the years 850 and 2015, hereafter "all-time peak forest loss"). We also expected greater population and species richness declines and higher turnover after, relative to before, contemporary peak forest loss (i.e., the year of the largest reduction in forested area within the duration of each time series). Finally, species with longer generation times typically respond more slowly to environmental change (31). We thus predicted that lags in ecological responses to forest loss would increase with longer generation times across taxa.

We measured landscape-scale historic and contemporary forest loss by integrating information from the Land Use Harmonization (22) and Global Forest Change (23) databases. We also used the ESA Landcover (32) and KK09 (33) databases to examine whether our results were consistent across land-use change data sources. We compared historic and con-

temporary forest loss with temporal population change (trends in the numerical abundance of species) and biodiversity change (trends in species richness and turnover in assemblage composition) (Figs. 1 and 2). We analyzed 2729 populations of 730 species and biodiversity change in 3361 ecological assemblages (Figs. 2A and 3). We measured population change using the Living Planet Database, which includes 133,092 records of the number of individuals of a species in a given area over time (25). We measured biodiversity change using the BioTIME database, which comprises 4,970,128 records of the number and abundance of species in ecological assemblages over time (26). Together, these time series represent a range of taxa including amphibians (388), birds (5090), mammals (266), reptiles (76), invertebrates (80), and plants (187) and 2157 sites that cover almost the entire spectrum of forest loss and gain around the world (Fig. 2B). We used a standardized cell size of approximately 96 km² to match response variables (population change, richness change, and turnover) to landscape-scale forest change. Our analyses were robust to the spatial scale over which we calculated forest change (figs. S13 and S14) (27).

We carried out the following workflow for our global assessment of the consequences of forest cover change for population and biodiversity trends over time. To relate population and biodiversity change to historic forest loss, we quantified the baseline all-time peak forest loss at each site. To relate population and biodiversity change to contemporary forest loss, we compared population and biodiversity change before and after contemporary peak forest loss. To investigate temporal lags, we quantified the time period between contemporary peak forest loss and maximum change in populations and assemblages detected after peak forest loss had occurred at each site (Fig. 1B). We calculated population change (μ) using state-space models that account for observation error and random fluctuations (34), and calculated richness change (slopes of rate of change over time) using mixed-effects models. We quantified temporal change in species composition as the turnover component of Jaccard's dissimilarity measure (change due to species replacement) (35). Turnover is often independent of changes in species richness (9) and is the dominant component of compositional change across time series of ecological assemblages (36). We used a hierarchical Bayesian modeling framework, with individual time series nested within biomes (37), to account for the spatial structure of the data (27).

Historical baselines

In line with our first prediction ("historical baselines"), we found that local-scale population declines were more pronounced when the monitoring occurred during the period

¹School of GeoSciences, University of Edinburgh, Edinburgh EH9 3FF, Scotland. ²Biological and Environmental Sciences, University of Gothenburg, 405 30 Gothenburg, Sweden.

³Gothenburg Global Biodiversity Centre, 405 30 Gothenburg, Sweden. ⁴German Centre for Integrative Biodiversity Research (iDiv), 04103 Leipzig, Germany. ⁵Department of Computer Science, Martin Luther University Halle-Wittenberg, 06108 Halle (Salle), Germany. ⁶Data Analytics Program, Denison University, Granville, OH 43023, USA. ⁷Centre for Biological Diversity, University of St Andrews, St Andrews KY16 9TF, Scotland.

*Corresponding author. Email: gndaskalova@gmail.com

of all-time peak forest loss (Fig. 1B and Fig. 3, B and C). For many of the sites represented by the time series we studied, major changes in forest cover occurred during the past two centuries. In regions such as Europe and North America, all-time peak forest loss was typically during the early 1800s, before population, biodiversity, and satellite monitoring had begun (Figs. 2C and 3B). The Living Planet Database and BioTIME time series captured more than half of the spectrum of contemporary forest cover change around the world, in contrast to previous criticisms of some of these data underrepresenting areas with anthropogenic impact (38) (Fig. 2, B and C, and Fig. 3B). Yet in only ~5% of monitored time series did forest loss lead to a conversion in the dominant habitat type (e.g., from primary forest to urban areas). Habitat conversions corresponded with both gains and losses in populations and biodiversity, with the highest rates of turnover when primary forests were converted to agricultural and urban areas or to secondary forests (fig. S17). The links among historical baselines, the timing of all-time peak forest loss, and resulting ecological change

emphasize the need for a long-term perspective to quantify the complexity of biodiversity change in the Anthropocene (11, 17).

Contemporary forest loss

Contrary to our second prediction (“contemporary forest loss”), we found that forest loss acted as a catalyst amplifying both increases and decreases in local-scale populations and assemblages over time (Figs. 3 and 4 and figs. S4 to S6, S9, and S10). Across time series, more than half of all populations and assemblages (61%) experienced higher rates of change after the largest forest loss event within each time series. Contemporary peak forest loss intensified population declines, population increases, and richness losses—but not richness gains—relative to the period before peak forest loss (Fig. 4). In nearly one-third of time series (32%), more than 10% of the species in the assemblage at the time of contemporary peak forest loss were replaced by new species by the end of the time series (Fig. 4, G and H). The assemblages that experienced the most richness change also experienced the most turnover [Pearson correlation = 0.37; 95% con-

fidence interval (CI) = 0.31 to 0.43]. The influence of contemporary peak forest loss on population and biodiversity change was not strongly correlated to the magnitude of the specific forest loss event (figs. S4 to S6). Our findings indicate a wide spectrum of population and biodiversity responses to forest loss that might be overlooked without accounting for temporal dynamics and lagged responses (12, 13, 15, 39).

Temporal lags

In line with our third prediction (“temporal lags”), we found evidence for up to half-century ecological lags in local-scale changes in population abundance, species richness, and turnover after contemporary peak forest loss (Fig. 5). On average, we documented maximum change in populations and ecological assemblages 6 to 13 years after forest loss across taxa. Yet nearly half of population and biodiversity change (40%) happened within 3 years of peak forest loss, demonstrating that rapid shifts in populations and assemblages occur frequently after habitat change (Fig. 5 and fig. S7). Consistent with our prediction, the

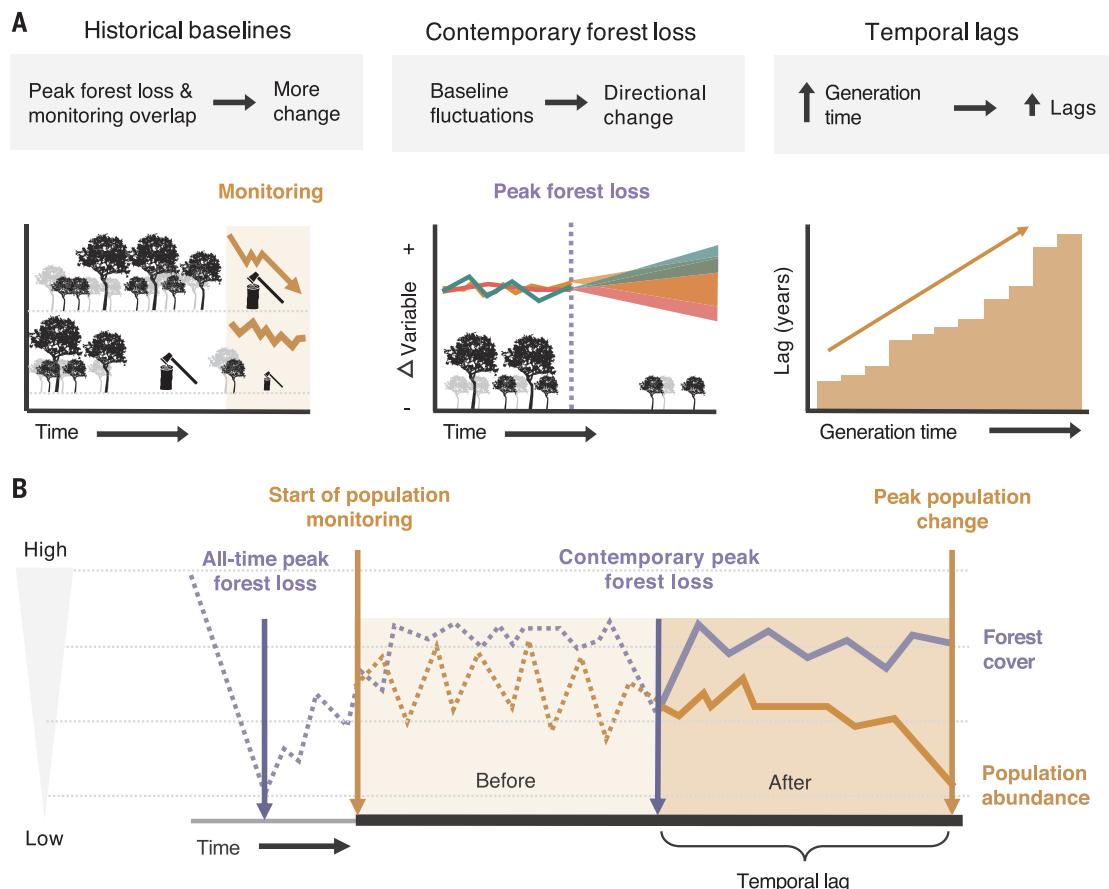


Fig. 1. Influence of forest loss on population and biodiversity change. We tested three pathways through which forest loss can influence the population abundance of species and the richness and turnover (temporal species replacement) of ecological assemblages: historical baselines of forest loss, timing of contemporary

forest loss, and temporal lags in population and biodiversity responses. (A) Conceptual diagram of our predictions outlined with respect to population change, richness change, and turnover. (B) Analytical workflow for determining all-time and contemporary peak forest loss and temporal lags [further details in (27)].

period between peak forest loss and peak change in populations and biodiversity was longer for taxa with longer generation times (e.g., large mammals and birds; Fig. 5B and table S2). Population declines and increases

occurred on similar time scales (Fig. 5C). Losses in species richness lagged behind gains by approximately half a year (slope = 0.5, CI = 0.1 to 1.05), indicating that extinction debts and immigration credits accumulated at roughly

the same speed across taxa. The similar pace and temporal delay of population declines and increases, and of richness gains and losses, could help to explain previous findings of community self-regulation (18) and no net population

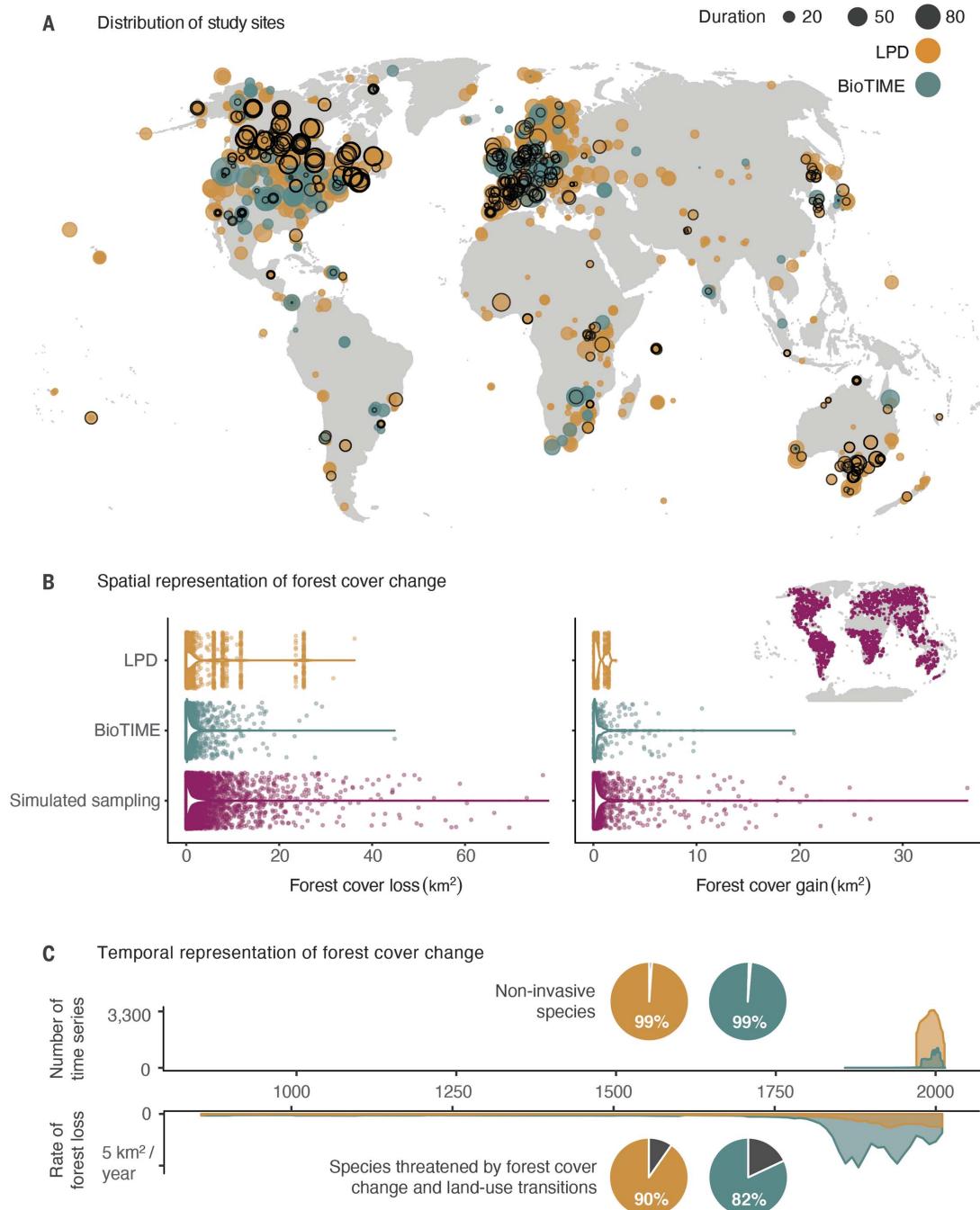
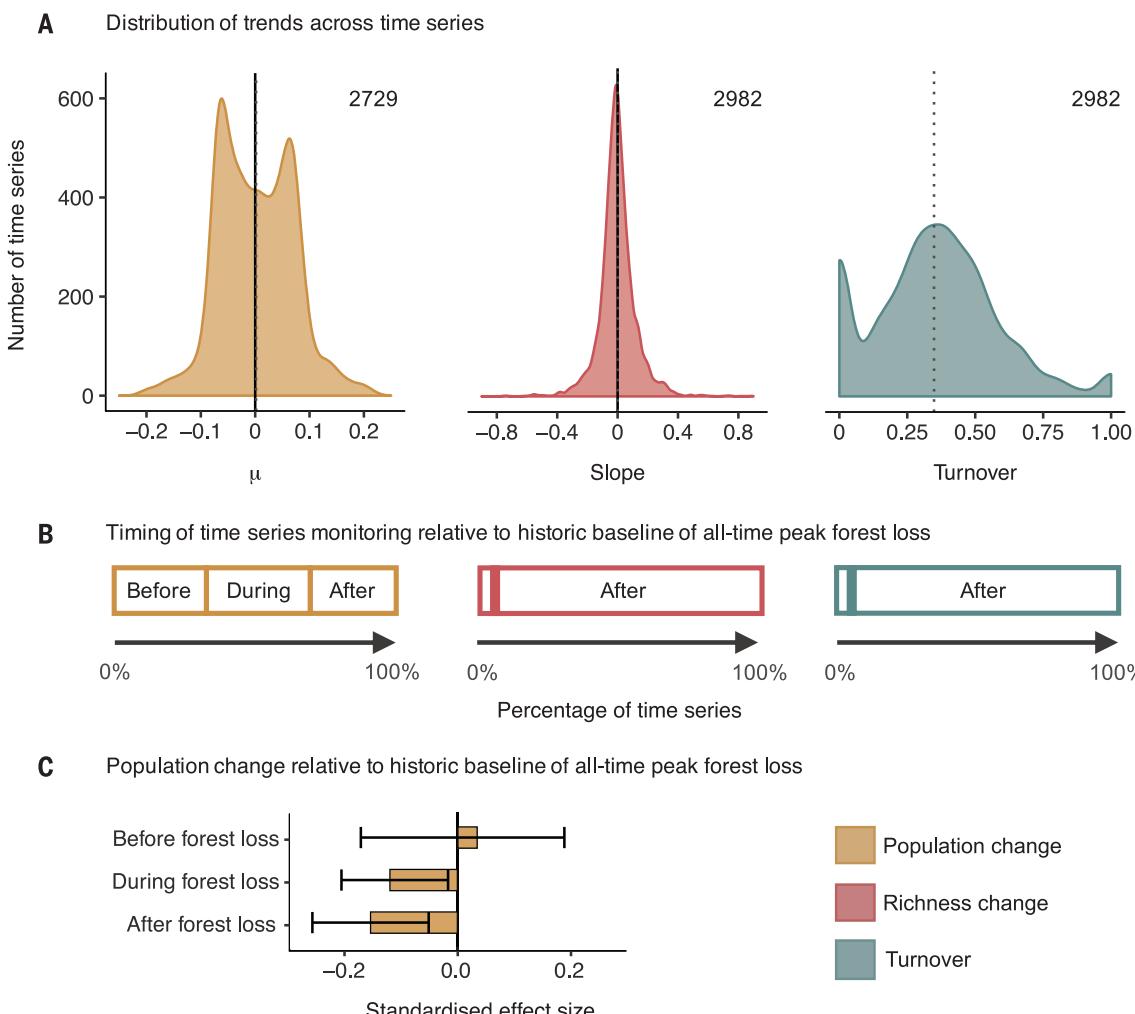


Fig. 2. Population and biodiversity monitoring over time broadly spans the global variation in forest cover change. (A) Locations and duration of 542 Living Planet Database (LPD) and 199 BioTIME studies, containing 6090 time series from 2157 sites [black outline denotes sites that were forested at the start of the monitoring (1247 sites); see table S1 for sample size in each woody biome]. (B) Among all time series, 44% experienced historic or contemporary forest loss of comparable magnitude to forest cover change across a simulated random sample of geographical locations (shown on map inset) from the global

distribution of forest cover loss and gain. We did not detect directional effects of the magnitude of forest gain across monitored sites (figs. S4 to S6). (C) The number of time series increased over time (top), but the rates of forest loss were often higher before the start of monitoring (bottom; see figs. S2 and S3 for variation in monitoring periods among time series). Insets show the proportion of study species that are not classified as invasive (top) and that are threatened by land-use change, based on species' IUCN threat assessments (bottom; see fig. S12 for details).

Fig. 3. Heterogeneity in population and biodiversity trends and land-use histories from sites around the world. (A) All three metrics of ecological change (population change, richness change, and turnover) show heterogeneous distributions across sites. (B) Population monitoring occurred at different time periods relative to all-time peak forest loss (for 33% of sites before, for 37% during, and for 30% after), whereas biodiversity monitoring predominantly started after all-time peak forest loss had occurred (94% of sites). (C) Population declines were more acute when all-time peak forest loss occurred during the population monitoring period (slope = -0.007 , CI = -0.012 to -0.001 ; see table S2 for model outputs). Low sample size for the “before” (101) and “during” (38) categories precluded a similar analysis for richness change and turnover. Lines in (A) denote zero (solid) and mean values (dotted). Numbers in (A) show sample size (i.e., number of time series).



change (2, 3, 10) or richness change (5, 6) at local scales. Temporal lags in biodiversity change have also been observed in post-agricultural forests (4, 40) and fragmented grasslands (31), where agricultural activity ceased decades to centuries ago, yet richness and assemblage composition change continue to the modern day. Overall, our results indicate that increasing rates of land-use change in the Anthropocene (41, 42) will alter ecosystems on both short- and long-term time scales that need to be captured in ongoing and future biodiversity monitoring.

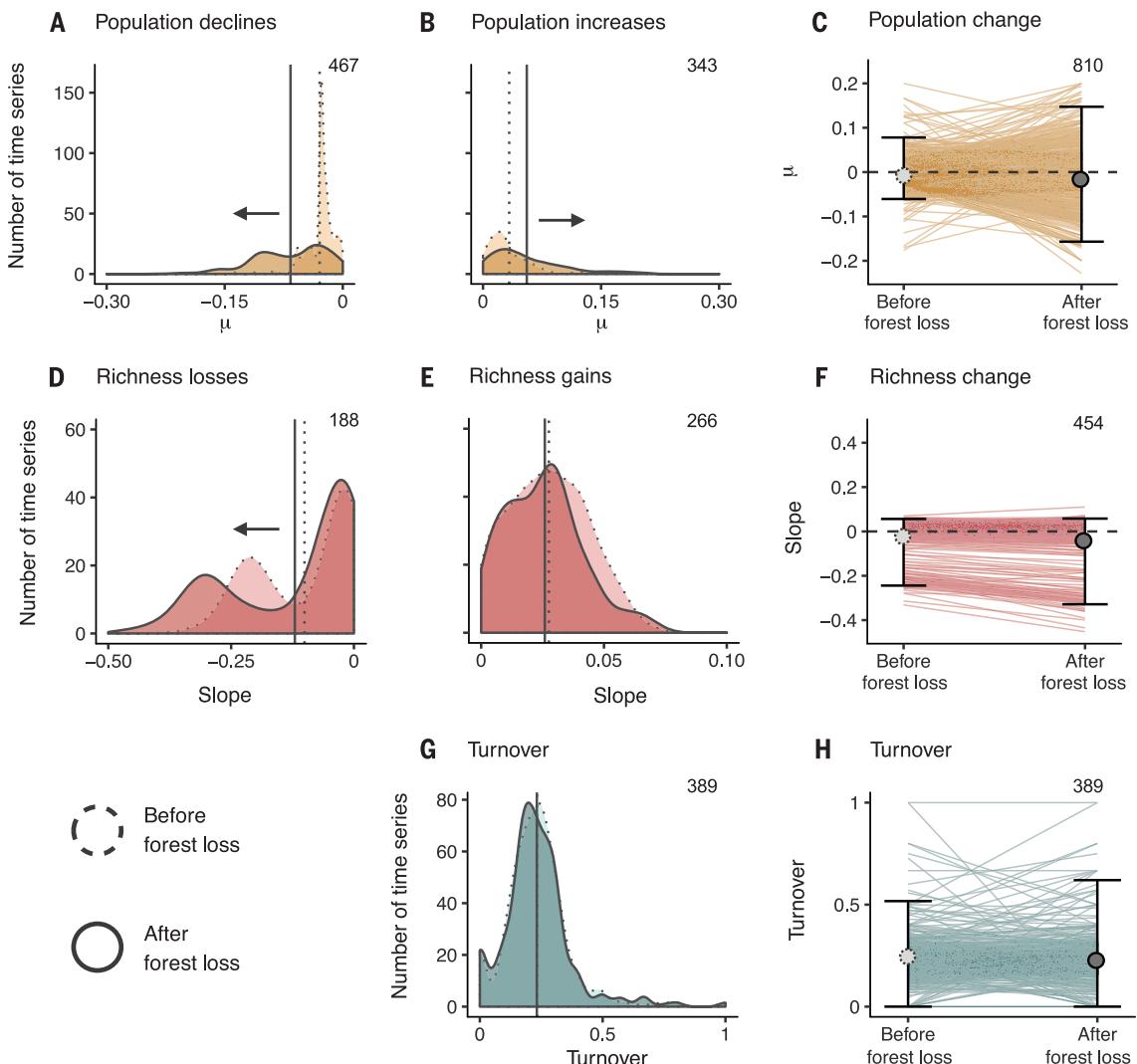
Heterogeneity in responses to forest cover loss could be due to a number of factors, including (i) temporal lags in population or assemblage responses, as observed in our study and elsewhere (17, 31); (ii) context-specific responses to forest loss, such as the same amount of habitat change corresponding to biodiversity declines at one site but increases at another (13, 43, 44); and (iii) interactions with other drivers occurring simultaneously with forest loss (11, 45, 46). Our finding that forest loss was concurrent with both declines and in-

creases in populations and assemblages is consistent with the varied and often positive effects of habitat fragmentation on biodiversity metrics such as species richness (19). However, forest loss occurring outside of the period of population or biodiversity monitoring, as well as the type of woody vegetation being gained and lost, might influence our ability to detect a causal link between forest loss and biodiversity change (17, 47). Increases in woody vegetation caused by agroforestry or plantations might not reflect ecosystem recovery, such as with natural succession after forest cover loss (48–50). Our finding that forest cover gain did not directly correspond with gains in population abundance and species richness highlights the need for high-resolution temporal data of the specific vegetation types constituting forest cover changes around the world. The complexity and heterogeneity of forest cover change effects on biodiversity (13, 43, 51, 52) demonstrate that caution is warranted with respect to recent calls for global afforestation as a climate change mitigation tool (53).

Variation in species' vulnerability to forest cover loss (43, 51) may be contributing to the wide spectrum of population and biodiversity responses to shifts in forest cover. Species that have experienced frequent habitat disturbance during their evolutionary history might be more resilient to land-use change, whereas novel habitat alterations could have a greater influence on species' persistence and abundance (13, 43) (Fig. 3). In a post hoc test, we found that in forest-dominated sites, where past disturbances were likely less frequent, declines in species' abundance were more frequent than increases when contemporary forest loss occurred, whereas richness change and turnover did not show directional trends (fig. S16). Additionally, in our study, rare and common species, as defined by their range size, mean population size, and habitat specificity (54), responded in similar ways to forest loss (figs. S11 and S12). In contrast to this result, space-for-time comparisons that do not account for temporal dynamics and lagged responses have found that land-use change has a more negative impact on rare species

Fig. 4. At the site level, population and biodiversity change increase after contemporary peak forest loss.

In total, population and richness change increased across 61% and decreased across 39% of the 1653 time series for which baseline comparisons were possible (i.e., the time series were long enough to include at least 5 years before and after forest loss). Only turnover included instances of no difference in the amount of change before and after peak forest loss (6% of time series). (A, B, D, E, and G) Distributions compare population declines (μ) (A), population increases (μ) (B), richness losses (slopes) (D), richness gains (slopes) (E), and turnover (Jaccard's dissimilarity) (G) in the periods before and after contemporary peak forest loss, the largest forest loss event during the monitoring of each site. Vertical lines over distributions show the mean for each category (dotted, before; solid, after). (C, F, and H) Temporal trends before and after peak forest loss are indicated with lines for individual time series. Light and dark gray points and error bars show mean values and 2.5% and 97.5% quantiles. Duration varied among time series but was consistent for each individual time series (i.e., n years before forest loss = n years after forest loss, $n \geq 5$ years; see fig. S8 for relationship between duration and number of survey points). Numbers on plots indicate sample size. See table S2 for model outputs.



Downloaded from <http://science.sciencemag.org/> on June 18, 2020

than on common species (55). Accounting for both inter- and intraspecific heterogeneity in species' vulnerability to forest cover change is key when scaling from localized impacts of human activities to global-scale biodiversity patterns and attribution of change (1, 19–21, 39, 43, 51).

Taxonomic, spatial, and temporal imbalances in sampling can make large-scale attribution analyses of biodiversity trends and global change drivers challenging and can influence the inferences that we draw from such studies (figs. S2, S3, S8, S9, and S11 to S14). For this reason, we explored in greater detail three specific challenges of our terrestrial biodiversity attribution analyses. First, tropical species and locations are underrepresented in current open-source temporal biodiversity databases (Fig. 2A) (38). In a post hoc test, we found that in the tropics, where there is intense, often

unprecedented forest loss, the effects of forest loss were stronger and more negative across sites with available data, relative to the rest of the globe (figs. S9 and S10 and tables S1 and S2). Second, the spatial scales at which biodiversity is monitored (from 1 m^2 to $25 \times 10^8\text{ km}^2$) and the resolution of forest cover datasets (from 30 m to $\sim 20\text{ km}$; figs. S13 and S14) could introduce spatial mismatches between the driver and response. Nonetheless, we found that the heterogeneous relationships among richness change, turnover, and forest loss were consistent across forest loss calculated on scales from 10 to 500 km^2 (fig. S14). Third, temporal mismatches and lags (Figs. 1C and 5) can obscure the ways in which forest loss may be related to population and biodiversity change. We found that attribution signals were strongest when a peak in forest loss occurred during the time-series monitor-

ing (Figs. 3 and 4). Our results indicate that biodiversity assessments and global change attribution analyses will be improved by better spatial and temporal matching of biodiversity and environmental impact data.

Our analysis reveals an intensification of both increases and decreases of populations and biodiversity by up to 48% after forest loss at sites around the planet. This finding demonstrates heterogeneity in the influence of forest cover change on populations and ecological assemblages and challenges the assumption that land-use change predominantly leads to population declines and species richness loss (12, 14, 39). A current assumption underlying existing projections of biodiversity responses to land-use change (12, 14) is that space-for-time approaches accurately reflect longer-term population and biodiversity dynamics (41). In contrast, we found temporal

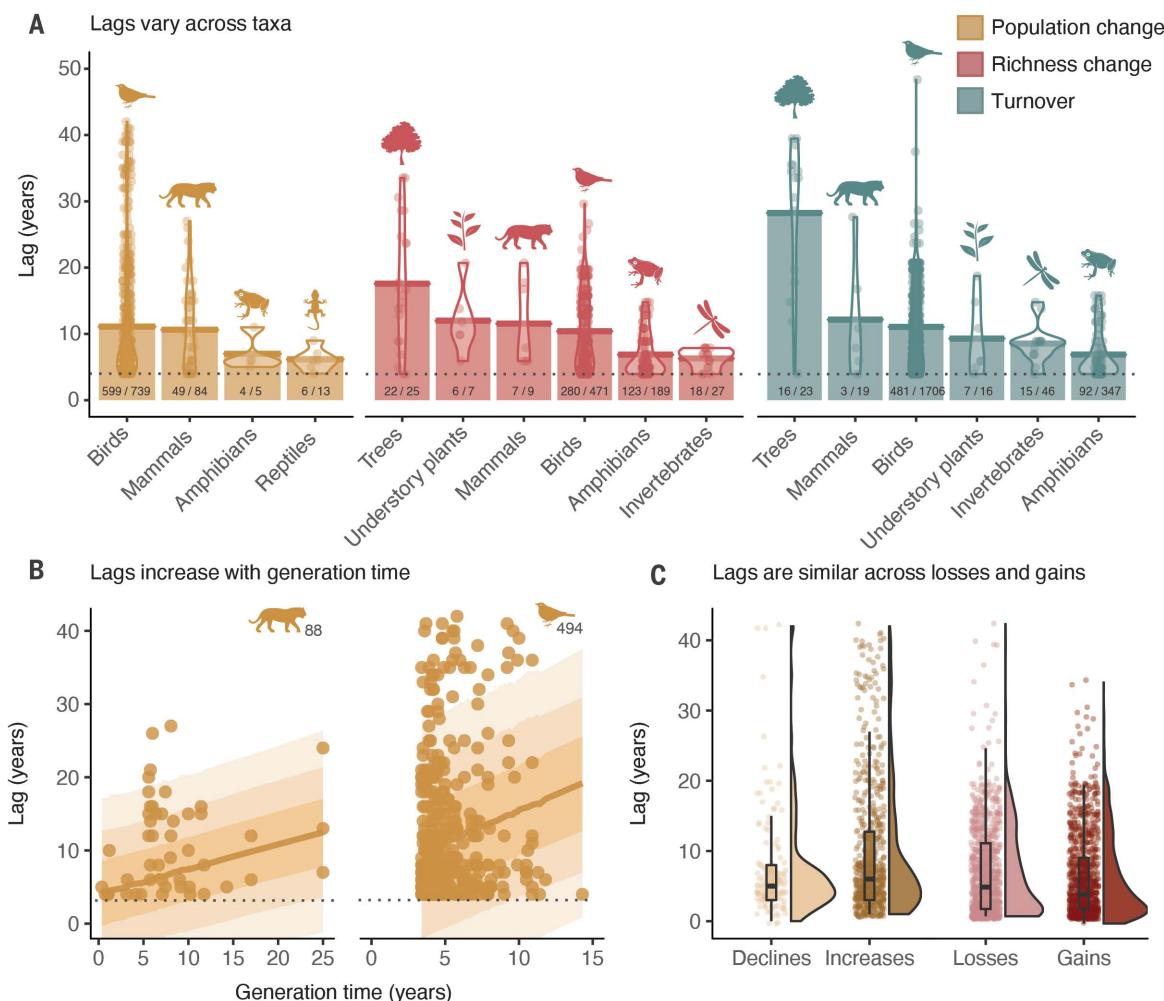


Fig. 5. Temporal lags in population and biodiversity change after contemporary peak forest loss. Population and assemblage change after contemporary peak forest loss may be delayed by up to half a century, with taxa and species with long generation times showing the longest temporal lags. (A) We compared lags of 3 (dashed horizontal line) or more years between peak forest loss during the monitoring for each time series and peak change in population or biodiversity across six taxa (sample size was 841 time series for population change, 728 for richness

change, and 2157 for turnover). Bars show mean lag for each taxon, violins show the distribution of lag values, and the points are lag values for each time series. Numbers on bars indicate how many time series experienced lags out of the total sample size for each taxon. (B) We found that temporal lags in mammal and bird population change increased with longer species generation times. (C) Temporal lags were similar across population declines and increases and across species richness losses and gains. See table S2 for model outputs.

lags of up to 50 years in population and biodiversity change after forest loss that differed across taxa and among species' generation times. Our analyses highlight that the local-scale responses of populations and assemblages to forest cover loss and gain are complex and variable over time. Incorporating the full spectrum of population and biodiversity responses to land-use change will improve projections of the future impacts of global change on biodiversity and thus contribute to the conservation of the world's biota during the Anthropocene.

REFERENCES AND NOTES

- IPBES, Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019).
- G. N. Daskalova, I. H. Myers-Smith, J. L. Godlee, bioRxiv 272898 [preprint]. 16 April 2018.
- M. Dornelas et al., *Ecol. Lett.* **22**, 847–854 (2019).
- L. Baeten, M. Hermy, S. Van Daele, K. Verheyen, *J. Ecol.* **98**, 1447–1453 (2010).
- M. Vellend et al., *Proc. Natl. Acad. Sci. U.S.A.* **110**, 19456–19459 (2013).
- M. Dornelas et al., *Science* **344**, 296–299 (2014).
- A. E. Magurran et al., *Proc. Natl. Acad. Sci. U.S.A.* **115**, 1843–1847 (2018).
- N. G. Yoccoz, K. E. Ellingsen, T. Tveraa, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 1681–1683 (2018).
- H. Hillebrand et al., *J. Appl. Ecol.* **55**, 169–184 (2018).
- B. Leung, D. A. Greenberg, D. M. Green, *Divers. Distrib.* **23**, 1372–1380 (2017).
- D. E. Bowler et al., *People Nat.* **2**, 380–394 (2020).
- T. Newbold et al., *Nature* **520**, 45–50 (2015).
- M. G. Betts et al., *Nature* **547**, 441–444 (2017).
- T. Newbold, *Proc. R. Soc. B* **285**, 20180792 (2018).
- T. Newbold, D. P. Tittensor, M. B. J. Harfoot, J. P. W. Scharlemann, D. W. Purves, bioRxiv 439059 [preprint]. 10 October 2018.
- S. C. Elmendorf et al., *Proc. Natl. Acad. Sci. U.S.A.* **112**, 448–452 (2015).
- J.-B. Mihoub et al., *Sci. Rep.* **7**, 41591 (2017).
- N. J. Gotelli et al., *Sci. Adv.* **3**, e1700315 (2017).
- L. Fahrig, *Annu. Rev. Ecol. Evol. Syst.* **48**, 1–23 (2017).
- N. M. Haddad et al., *Ecography* **40**, 48–55 (2017).
- E. I. Damschen et al., *Science* **365**, 1478–1480 (2019).
- G. C. Hurtt et al., *Clim. Change* **109**, 117–161 (2011).
- M. C. Hansen et al., *Science* **342**, 850–853 (2013).
- S. Channan, K. Collins, W. R. Emanuel, *Global Mosaics of the Standard MODIS Land Cover Type Data* (University of Maryland and Pacific Northwest National Laboratory, 2014); <https://modis.gsfc.nasa.gov/data/dataprod/mod12.php>.
- Living Planet Index database (2016); www.livingplanetindex.org.
- M. Dornelas et al., *Glob. Ecol. Biogeogr.* **27**, 760–786 (2018).
- See supplementary materials.
- R. Elahi et al., *Curr. Biol.* **25**, 1938–1943 (2015).
- D. F. Sax, S. D. Gaines, *Trends Ecol. Evol.* **18**, 561–566 (2003).
- IUCN Red List of Threatened Species, Version 2017-3 (2017); www.iucnredlist.org.
- J. Krauss et al., *Ecol. Lett.* **13**, 597–605 (2010).
- ESA Climate Change Initiative, ESA Land Cover Product (1992–2015). ESA Climate Change Initiative—Land Cover led by UCLouvain (2017); www.esa-landcover-cci.org/?q=node/175.
- J. O. Kaplan, K. M. Krumhardt, N. Zimmermann, *Quat. Sci. Rev.* **28**, 3016–3034 (2009).

34. J.-Y. Humbert, L. S. Mills, J. S. Horne, B. Dennis, *Oikos* **118**, 1940–1946 (2009).
35. A. Baselga, *Glob. Ecol. Biogeogr.* **19**, 134–143 (2010).
36. S. A. Blowers et al., *Science* **366**, 339–345 (2019).
37. D. M. Olson, E. Dinerstein, *Ann. Mo. Bot. Gard.* **89**, 199 (2002).
38. A. Gonzalez et al., *Ecology* **97**, 1949–1960 (2016).
39. G. Ceballos, P. R. Ehrlich, R. Dirzo, *Proc. Natl. Acad. Sci. U.S.A.* **114**, E6089–E6096 (2017).
40. M. Vellend et al., *Ecology* **87**, 542–548 (2006).
41. A. De Palma et al., *Adv. Ecol. Res.* **58**, 163–199 (2018).
42. L. Egli, C. Meyer, C. Scherber, H. Kreft, T. Tscharntke, *Glob. Change Biol.* **24**, 2212–2228 (2018).
43. M. G. Betts et al., *Science* **366**, 1236–1239 (2019).
44. M. G. Betts, B. Phalan, S. J. K. Frey, J. S. Rousseau, Z. Yang, *Divers. Distrib.* **24**, 439–447 (2018).
45. F. E. B. Spooner, R. G. Pearson, R. Freeman, *Glob. Change Biol.* **24**, 4521–4531 (2018).
46. J. D. Fridley, J. P. Wright, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 4702–4706 (2018).
47. F. Isbell, D. Tilman, P. B. Reich, A. T. Clark, *Nat. Ecol. Evol.* **3**, 1533–1538 (2019).
48. J. W. Veldman et al., *Science* **366**, eaay7976 (2019).
49. P. Potapov et al., *Ecol. Soc.* **13**, art51 (2008).
50. P. G. Curtis, C. M. Slay, N. L. Harris, A. Tyukavina, M. C. Hansen, *Science* **361**, 1108–1111 (2018).
51. C. D. L. Orme et al., *Nat. Ecol. Evol.* **3**, 886–891 (2019).
52. C. Banks-Leite et al., *Science* **345**, 1041–1045 (2014).
53. J.-F. Bastin et al., *Science* **365**, 76–79 (2019).
54. D. Rabinowitz, in *The Biological Aspects of Rare Plants Conservation*, H. Syngle, Ed. (Wiley, 1981), pp. 205–217.
55. L. Sykes, L. Santini, A. Etard, T. Newbold, *Conserv. Biol.* **34**, 688–696 (2019).

ACKNOWLEDGMENTS

We thank WWF International and the Zoological Society of London for compiling the Living Planet Database; R. Freeman and L. McRae for useful discussions; the BioTIME team for compiling the BioTIME database; F. Moyes for managing the BioTIME database; the creators of the Land Use Harmonization Database; the Hansen lab for producing the Forest Cover Change Database; NASA for producing the MODIS Landcover Database; the Forest & Nature Lab at Ghent University for a stimulating discussion on historic and contemporary land-use change and choosing appropriate baselines for comparison of biodiversity change through time; A. Phillipmore and K. Dexter for providing advice during the conceptualization of the study; L. Antão and M. Vellend for providing feedback on the draft manuscript; and the anonymous reviewers whose comments greatly enhanced our work. **Funding:** The BioTIME database was supported by ERC AdG BioTIME 250189 and ERC PoC BioCHANGE 727440. We thank the ERC projects BioTIME and BioCHANGE for supporting the initial data synthesis work that led to this study, and the Leverhulme Centre for Anthropocene Biodiversity for continued funding of the database. Also supported by a Carnegie-Caledonian PhD Scholarship and NERC doctoral training partnership grant NE/L002558/1 (G.N.D.), a Leverhulme Fellowship and the Leverhulme Centre for Anthropocene Biodiversity (M.D.), Leverhulme Project Grant RPG-2019-402 (A.E.M. and M.D.), and the German Centre of Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (funded by the German Research Foundation; FZT 118, S.A.B.). **Author contributions:** G.N.D., M.D., and I.H.M.-S. conceptualized the study; G.N.D. integrated databases and conducted statistical analyses with input from S.A.B., I.H.M.-S., A.D.B., and M.D.; G.N.D. created

the figures with input from co-authors; S.A.B., M.D., and S.R.S. wrote the code for the rarefaction of the BioTIME studies; G.N.D. wrote the first draft; and all authors contributed to revisions. I.H.M.-S. was the primary supervisor, M.D. the co-supervisor, and A.D.B. is on the supervisory committee for G.N.D. A.E.M. and M.D. fund the compilation of the BioTIME database. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Code for the rarefaction of the BioTIME Database is available at <https://doi.org/10.5281/zenodo.1475218>. Code for statistical analyses is available at <http://doi.org/10.5281/zenodo.1490144>. Population and biodiversity data are freely available in the Living Planet and BioTIME databases (25, 26). The Living Planet Database can be accessed on www.livingplanetindex.org/data_portal. The BioTIME Database can be accessed on Zenodo at <https://doi.org/10.5281/zenodo.1211105> or through the BioTIME website at <http://biotime.st-andrews.ac.uk>. The public studies that were included in the version of BioTIME we analyzed can be downloaded from http://biotime.st-andrews.ac.uk/BioTIME_download.php. Land-use change data are publicly available in the Land Use Harmonization Database (22), the Forest Cover Change Database (23), and the MODIS Landcover Database (24).

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/368/6497/1341/suppl/DC1
Materials and Methods
Figs. S1 to S17
Tables S1 to S4
References (56–271)

6 November 2019; accepted 7 April 2020
10.1126/science.aba1289

Landscape-scale forest loss as a catalyst of population and biodiversity change

Gergana N. Daskalova, Isla H. Myers-Smith, Anne D. Bjorkman, Shane A. Blowers, Sarah R. Supp, Anne E. Magurran and Maria Dornelas

Science 368 (6497), 1341-1347.
DOI: 10.1126/science.aba1289

Land-use change and forest biodiversity

Land-use change by humans, particularly forest loss, is influencing Earth's biodiversity through time. To assess the influence of forest loss on population and biodiversity change, Daskalova *et al.* integrated data from more than 6000 time series of species' abundance, richness, and composition in ecological assemblages around the world. Forest loss leads to both positive and negative responses of populations and biodiversity, and the temporal lags in population and biodiversity change after forest loss can extend up to half a century. Land-use change precipitates divergent population and biodiversity change. This analysis has consequences for projections of human impact, ongoing conservation, and assessments of biodiversity change.

Science, this issue p. 1341

ARTICLE TOOLS

<http://science.scienmag.org/content/368/6497/1341>

SUPPLEMENTARY MATERIALS

<http://science.scienmag.org/content/suppl/2020/06/17/368.6497.1341.DC1>

REFERENCES

This article cites 193 articles, 18 of which you can access for free
<http://science.scienmag.org/content/368/6497/1341#BIBL>

PERMISSIONS

<http://www.scienmag.org/help/reprints-and-permissions>

Use of this article is subject to the [Terms of Service](#)

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.

Copyright © 2020 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works