Local changes dominate variation in biotic homogenization and differentiation

Authors: Shane A. Blowes[1,2*], Brian McGill[3], Viviana Brambilla[4,5], Cher F. Y. Chow[4], Thore Engel[6,1,7,2], Ada Fontrodona-Eslava[4], Inês S. Martins[4,8], Daniel McGlinn[9], Faye Moyes[4], Alban Sagouis[1,2], Hideyasu Shimadzu[10,11], Roel van Klink[1,2], Wu-Bing Xu[1,2], Nicholas J. Gotelli[12], Anne Magurran[4], Maria Dornelas[4,5,8], Jonathan M. Chase[1,2]

[1]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig; Leipzig, Germany.

[2]Department of Computer Science, Martin Luther University Halle-Wittenberg; Halle (Saale), Germany.

[3]School of Biology and Ecology and Mitchell Center for Sustainability Solutions, University of Maine; Orono, ME, USA.

[4]Centre for Biological Diversity, School of Biology, University of St Andrews; St Andrews, Scotland.

[5]Guia Marine Lab, MARE, Faculty of Sciences, University of Lisbon; Lisbon, Portugal.

[6]Institute of Biodiversity, Friedrich Schiller University Jena, Dornburger Straße 159, 07743 Jena, Germany

[7]Helmholtz Centre for Environmental Research - UFZ, Department of Ecosystem Services, Permoserstr. 15, 04318 Leipzig, Germany

[8]Leverhulme Centre for Anthropocene Biodiversity, Berrick Saul Second Floor, University of York; York, UK.

[9]Department of Biology, College of Charleston; Charleston, SC, USA.

[10]Department of Mathematical Sciences, Loughborough University; Leicestershire, UK.

[11]Department of Data Science, Kitasato University, Kanagawa, Japan.

[12]Department of Biology, University of Vermont; Burlington, VT, USA.

[*]Corresponding author: shane.blowes@idiv.de

Abstract: It is commonly thought that the biodiversity crisis includes widespread decreases in the uniqueness of different sites in a landscape (biotic homogenization). Using a typology relating homogenization and differentiation to local and regional diversity changes, we synthesize patterns across 283 metacommunities surveyed for 10-91 years, and 54 species checklists (13-500+ years). On average, there is a 0.2% increase in species shared among communities/year (i.e., weak homogenization), but across data sets, differentiation frequently occurs, with no statistically significant change being most common. Local (not regional) diversity frequently underlies composition change, and homogenization is strongly associated with checklist data that have longer durations and large spatial scales. Conservation and management can benefit from the multiscale perspective used here as it disentangles the implications of both the differentiation and homogenization currently unfolding.

One-Sentence Summary: Biotic homogenization is most prevalent at large temporal and spatial scales.

Humans are fundamentally altering the Earth's land cover, climate, water and nutrient cycles (*1*). With this ever growing human footprint, Earth's biodiversity is inevitably changing (*2*). There is substantial evidence that humans are accelerating the global extinction rate (*3*). However, at local scales, no overall directional trend, or slight increases in diversity are typically detected amidst substantial variability (*4-7*), though not without controversy (*8*). One common explanation for the perceived discrepancy between declining diversity globally and unchanged diversity at local sites on average, is biotic homogenization (*9-11*).

Biotic homogenization is a frequently observed pattern by which spatially distinct locations become more similar to one another in species composition through time (*12-14*). Two opposing forces can lead to homogenization: increased numbers of widespread (high occupancy) species (e.g., often non-native species), or extirpation of rare (low occupancy) species from regions. One driver for homogenization is when anthropogenic use creates environments with high habitat similarity (e.g., agricultural practices or harvesting). However, human activities can also create more heterogeneous environments (*15*), for example, by habitat fragmentation and other processes, which can lead to biotic differentiation. Moreover, non-native species that are introduced but do not become widespread, or when formerly widespread species are locally extirpated can also lead to differentiation (*16-17*). While both biotic homogenization and differentiation are frequently observed and theoretically expected under different scenarios, an empirical assessment of their prevalence in surveys of biodiversity change through time is lacking. Moreover, despite the intrinsic connection between homogenization and differentiation of community composition and rates of change in diversity across spatial scales (*16-17*), the empirical relationships among these have not been well quantified and synthesized.

Visualizing Whittaker's scale-explicit diversity partition

We can illustrate the relationship between homogenization and differentiation and rates of change across spatial scales using Whittaker's (*18*) diversity partition, where the diversity of a single site (i.e., a local site) is α-diversity, and the combined diversity of several local sites (i.e., a region) is γ-diversity. Variation in species composition among local sites, referred to as β-diversity, is given by: $\beta = \gamma/\overline{\alpha}$ (where $\overline{\alpha}$ is the average local diversity across sites in a region). Therefore, if rates of change in α- and γ-diversity through time are not equal, β-diversity changes through time. Moreover, these changes in β-diversity can be mathematically linked to changes in the number of sites species occupy (i.e., occupancy). Average occupancy, or the proportion of sites within a region occupied by species *i* (o_i), is related to Whittaker's formula by $\beta = \gamma/\overline{\alpha} = \gamma/(\Sigma o_i) = \gamma/(\gamma\overline{o}) = 1/\overline{o}$ (*19*). Thus, whether β-diversity decreases through time (homogenization) or increases through time (differentiation) is directly linked to change in diversity at two different scales, and to changes in the average proportion of sites that species occupy (Fig. 1).

A more ecologically informed understanding of scale-dependent biodiversity change can be gained by explicitly considering change in α-, β - and γ-diversity simultaneously. We illustrate this more detailed picture of scale-dependent change in Figure 1, showing six qualitatively distinct scenarios that emerge in the intersecting space of temporal changes in α- and γ-diversity. The 1:1 line (i.e., $\Delta\gamma = \Delta\alpha$, $\Delta\beta = 0$) represents equal log-proportional changes at both scales (i.e., log γ/year = log α/year), and delineates the boundary between homogenization and differentiation (Fig.1). When $\Delta\alpha > \Delta\gamma$ (i.e., below the 1:1 line), homogenization occurs due to

increased average occupancy; three of the six scenarios are possible. (1) Increased numbers of high occupancy species, due for example, to environmental changes that favor widespread, generalist and/or non-native species, could drive increases in α-diversity proportionately more than γ-diversity, leading to homogenization (with $\Delta\alpha>\Delta\gamma>0$, Fig. 1i). (2) If widespread species replace low occupancy species, average occupancy increases, and homogenization is associated with diversity gains at the α-scale and losses at the γ-scale ($\Delta\alpha>0$, $\Delta\gamma<0$, Fig. 1ii). (3) If low occupancy species (e.g., endemic species restricted to few sites), are regionally extirpated, and homogenization is associated with diversity loss at both the α- and γ-scale ($\Delta\gamma<\Delta\alpha<0$, Fig. 1iii). These distinct scenarios all describe cases of biotic homogenization, but variation in the nature of scale-dependent change could have different implications for policy and conservation. Three further parallel and distinct scenarios of differentiation (and decreasing average occupancy) through time are also possible. (4) Fewer widespread or high occupancy species could, for example, result from increased habitat heterogeneity, and greater losses at α- relative to γ-scales combine to increase β-diversity ($\Delta\alpha<\Delta\gamma<0$, Fig. 1iv). Increased habitat heterogeneity could also lead to increases in γ-diversity, accompanied by either: (5) α-diversity declines if low occupancy species replace high occupancy species ($\Delta\alpha<\Delta\gamma$, $\Delta\alpha<0$, $\Delta\gamma>0$, Fig. 1v); or, (6) increased α-diversity due to increased numbers of low occupancy species ($\Delta\gamma>\Delta\alpha>0$, Fig. 1vi; see Fig. S1 for further illustration of scale-dependent variation).

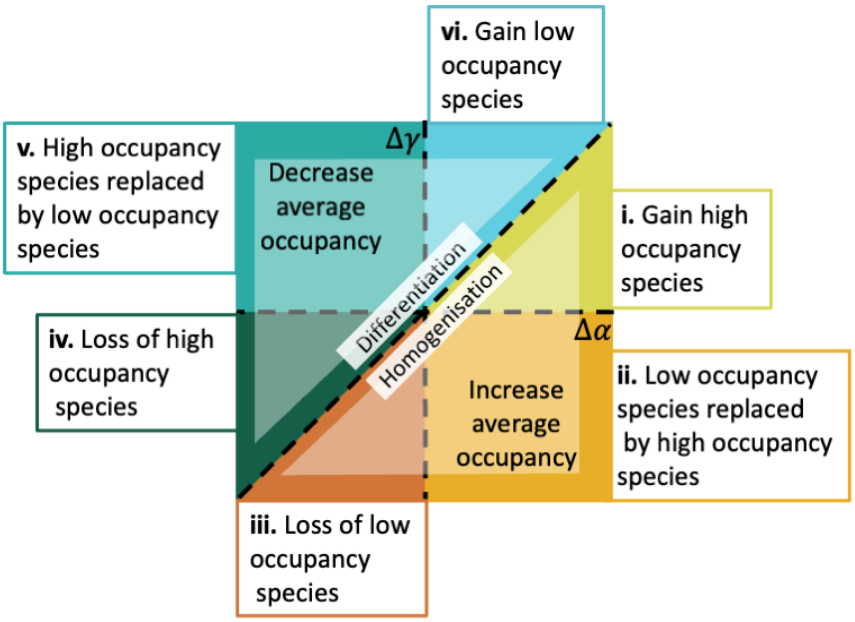

Figure 1: Mechanisms that underpin changes in spatial variation of species composition can be understood by examining the relationship between changes in regional- and local-scale species richness through time. *When richness changes at regional ($\Delta\gamma$) and local ($\Delta\alpha$) scales are calculated as proportional changes, assemblages below the dashed 1:1 line, i.e., $\Delta\gamma<\Delta\alpha$, are being homogenized, β-diversity is decreasing, and average occupancy is increasing. Conversely, assemblages above the diagonal dashed 1:1 line, i.e., $\Delta\gamma>\Delta\alpha$, are differentiating, β-diversity is increasing, and average occupancy is decreasing. In regions where (i) $\Delta\gamma<\Delta\alpha$, and $\Delta\gamma>0$, $\Delta\alpha>0$, the number of species with high occupancy (i.e., that occupy the majority of sites in the region) is increasing; (ii) $\Delta\gamma<\Delta\alpha$, $\Delta\gamma<0$ and $\Delta\alpha>0$, average occupancy is increasing, e.g., due to species with low occupancy being replaced by those with high occupancy; (iii) $\Delta\gamma<\Delta\alpha$ and $\Delta\gamma$, $\Delta\alpha<0$, the number of species with low occupancy is decreasing; (iv) $\Delta\gamma>\Delta\alpha$ and $\Delta\gamma$, $\Delta\alpha<0$, the number of species with high occupancy is*

decreasing; (v) $\Delta\gamma > \Delta\alpha$, $\Delta\gamma > 0$ and $\Delta\alpha < 0$, species with low occupancy (i.e., occupy few sites in the region) are replacing those with high occupancy; (vi) $\Delta\gamma > \Delta\alpha$ and $\Delta\gamma$, $\Delta\alpha > 0$, the number of species with low occupancy (i.e., occupy relatively few sites in the region) is increasing.

To assess overarching trends in scale-dependent biodiversity change, we use a compilation of 337 datasets documenting taxonomic diversity through time across spatial scales (Fig. S2) and the typology of Figure 1 to estimate changes in α-, β-, and γ-diversity. Among these biodiversity datasets, there were 283 studies where we could calculate sample effort-controlled species richness from local sites (α-diversity) and from the broader region (γ-diversity), for which we set a minimum of at least four sites per region and at least ten years between the first and last samples; 173 studies came from already compiled databases (*20-22*), and 110 datasets had a similar structure, but were specifically compiled for this and related studies (see Material and Methods). The remaining 54 datasets were compiled from presence-absence species 'checklists' collected from multiple sites (at least four) and time periods separated by a minimum of 10 years; these data typically encompass much longer timespans, documenting historical species composition prior to major human disruption and a more contemporary time period, but only have two time points. We include species checklist data despite their coarse nature as they have made key contributions to our understanding of long-term trends in introductions and extinctions (*23, 24*), as well biotic homogenization (*25, 26*).

We first asked whether there were any general tendencies among all 337 datasets with respect to the six qualitatively distinct scale-dependent biodiversity change scenarios overviewed in Figure 1 (plus the case where there is no change at either scale). We calculated temporal changes in diversity at the smaller, α-scale, at which one sample was taken, and a larger γ-scale, where diversity was taken as the sum of species in all of the local samples combined. The grain of the α-scale and extent of γ-scales varied among datasets, ranging, for example, from quadrat samples of plant communities collected over small spatial extents ($<< 1km^2$) to species checklists of birds on islands distributed across several oceans. To these data, we fit multilevel models separately to rates of change for each scale calculated as a log-ratio using two time points (start and end of the time series) standardized by the duration between samples (i.e., $\log[(S_{t2}/S_{t1})/(t2 - t1 + 1)]$, where S is species richness, and t1 and t2 denote the year of first and last sample, respectively); both models adjusted for residual heterogeneity associated with duration and the different data sources (i.e., resurveys and checklists; see Material and Methods).

Scale-dependent diversity changes and biotic homogenization and differentiation

All possible outcomes were observed across the different data sets (Fig. 2a). In combination, α- and γ-scale changes result in many data sets having no trend in β-diversity, many with trends towards homogenization (lower β-diversity through time), and many with trends towards differentiation (higher β-diversity through time), though few individual data sets had values of $\Delta\beta$ that statistically differed from zero (Fig. 2e). Overall, we found a weak mean trend towards homogenization ($\Delta\beta$ = -0.002; Fig. 2b). This trend equates approximately to 2 out of 1000 entirely distinct (i.e., no shared species) communities (*27*) being removed per year (rate of change calculated as the distance from the 1:1 line; 90% credible interval: -0.003, -0.0008). Stated differently, this represents an average increase by 0.2%/year of the number of shared species among localities within a region. This mean result was driven by approximately half of

the datasets that had only two time points (i.e., checklists [n = 54], and resurvey data [n = 118] where contemporary samples were collected to document changes compared to a historical sample; Fig. S3); in contrast, data with a time series (i.e., multiple years) actually showed a slight tendency to differentiation (mean $\Delta\beta$=0.0002, Fig. S3) rather than homogenization. Homogenization in the data with only two time points was strongly associated with checklist data (Fig. 2a), and residual variation was a decreasing function of sampling duration, especially for checklist samples at the α-scale (Fig. S4). Importantly, we found that homogenization is more likely at intermediate to large spatial and temporal scales, and associated with small effect-sizes for the long duration checklists (Fig. S5). These patterns suggest both differentiation and homogenization are frequent at smaller to intermediate scales as environmental heterogeneity can increase or decrease through time, but as spatial scale increases, homogenization appears to become more likely (*9, 17*).

Contrary to expectations, the weak trend towards homogenization is associated with gains in α-diversity, more often than losses in γ-diversity. Our conceptual typology (Fig. 1) allows us to parse underlying scale-dependent changes across the different data sets. Most noticeably, variation in β-diversity is primarily driven by changes in α-diversity (Fig. 2c-e). When α-diversity increases, β-diversity goes down since changes in γ-diversity are comparatively small, and vice versa. Thus, the weak overall trend to homogenization ($\Delta\beta < 0$) is associated with a small net average increase in α-diversity ($\Delta\alpha$ = 0.003; 90% credible interval: 0.002- 0.005). This runs contrary to the narrative that no change (or increases) in species richness at smaller spatial scales are due to biotic homogenization and decreased biodiversity at larger spatial scales (*9-11*). Instead, we see smaller positive changes (relative to the smaller α-scale changes) in γ-scale richness (i.e., $\Delta\gamma < \Delta\alpha$, $\Delta\gamma$ = 0.0004, 90% credible interval: 0.0002 - 0.0006) and biotic homogenization associated with increased average occupancy. Across all datasets, we find that increased numbers of widespread, high occupancy species are a key driver of biotic homogenization (see Fig. 1i, Fig. S5, S7).

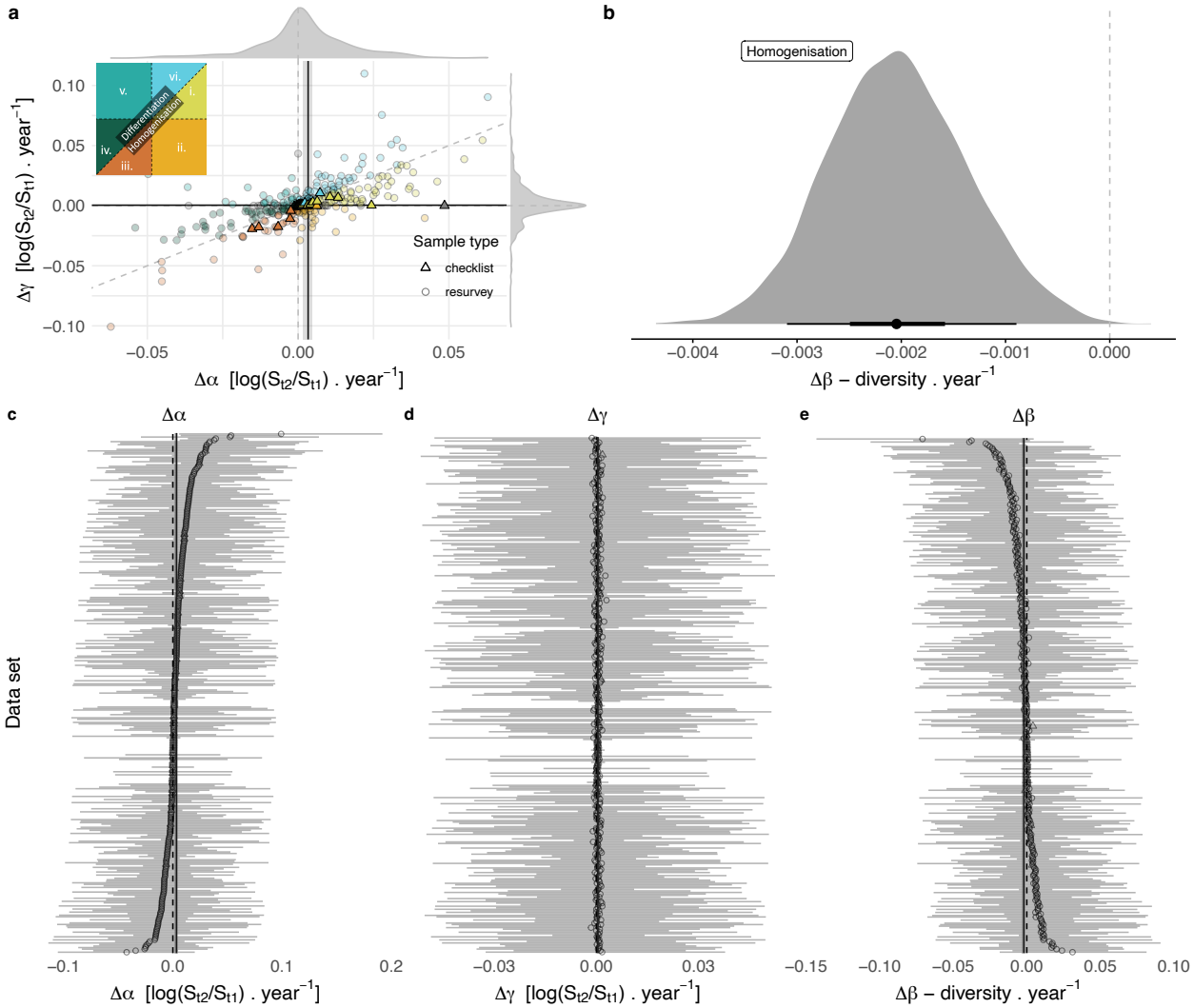

Figure 2: Patterns of homogenization and differentiation across 283 metacommunites and 54 checklists. *(a) Empirical estimates of γ-scale changes as a function of α-scale changes, both axes show log-ratios standardized by the number of years between the estimates, and external kernels show density of empirical data; black lines show median γ- and α-scale changes, and shading (not visible for γ-scale) shows the 90% credible interval from multi-level models fit separately to these data at each scale. Dashed grey lines show x = 0, y = 0, and x = y. (b) Kernel density plot of change in β-diversity per year calculated as the distance from 1:1 line (left = homogenization, right = differentiation) of 1000 draws of the posterior distributions of α- and γ-scale intercepts; black point shows median, bar represents 50% (thick) and 90% (thin) credible intervals. Model estimates of change for each region at the (c) α-, (d) γ-, and (e) β-scales; each point represents a single region, with the bar showing the 90% credible interval; regions are in the same order on panels c-e, arranged by the magnitude of the α-scale estimate. Two regions with Δα > 0.1 (0.1 and 0.2) were removed for clarity from panel a; point color represents categories of change from Fig. 1, points falling on boundaries between categories are gray.*

The subset of data for which time series of species' relative abundances were available (n = 165; duration range = 10-90 years, median = 16) also show that variation in homogenization and differentiation is frequently dominated by α-scale changes (Fig. 3a, b). These time series data do

not include checklists and many of the resurvey studies that had long durations and large spatial scales, and the increased power to detect temporal changes (especially at the γ-scale) revealed more cases where α- and γ-scale changes were approximately equal, and some cases where $\Delta\gamma > \Delta\alpha$ (Fig. 3a, b). This results in overall average α- and γ-scale changes being more closely balanced (Fig. 3c), and average $\Delta\beta$ slightly increasing (differentiating), but broadly overlapping zero (Fig. 3d).

We found qualitatively similar results using a diversity metric related to Simpson's concentration (which we refer to as diversity; *28*) and the time series of species' relative abundances, though there were more cases where $\Delta\gamma > \Delta\alpha$ (Fig. 3b; Fig. S6). Species richness is more strongly influenced by rare species than our diversity measure (*28*), suggesting that our overall results are not primarily driven by rare species. Indeed, variation in the diversity measure used here shows that altered numbers of relatively abundant species, either at the α-scale of local sites or the larger γ-scale, can also drive changes in spatial β-diversity (Fig. 3b, Fig. S6). Numerically abundant species are often expected to contribute disproportionately to the provision of ecosystem function or services (*29-32*). Our results showing the importance of relatively abundant (or common) species for homogenization and differentiation, combined with their effects on ecosystem services, suggest that there is an urgent need to study the biodiversity dynamics of common species, not just the rare species that are often the focus of conservation biology.

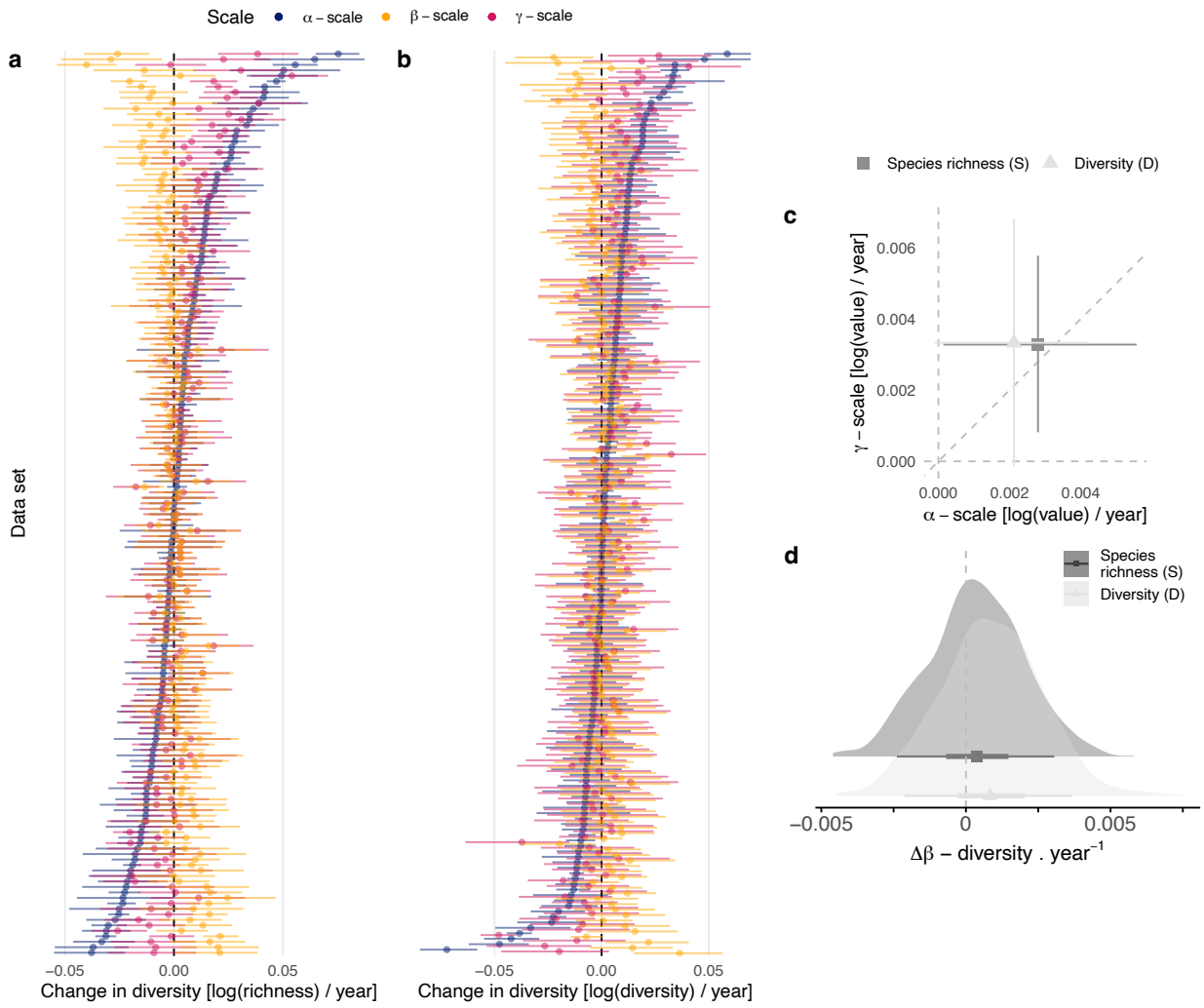

Figure 3: Scale-dependent diversity changes across a subset of 165 metacommunities estimated using models fit to time series of relative abundances. *Regional variation in α-, β- and γ-diversity change estimated using (a) species richness (S), (b) a diversity metric (D), equal to the inverse of Simpson's concentration (28), and more influenced by numerically abundant species; (c) overall average rates of α- and γ-scale diversity change, and (d) overall estimates of Δβ-diversity. Data sets (regions) in a and b are arranged in order of the magnitude of α-diversity changes for each diversity order (i.e., ordered differently on panel a and b). Δβ-diversity was estimated as the distance from the 1:1 line and calculated using 1000 draws from posterior distributions, where each x,y coordinate was a single draw from the population-level (fixed effect) slope parameter of α- and γ-scale models. Points and whiskers show median and 90% credible intervals on a-c, and median, 50% and 90% credible intervals on d.*

Although we find some overall tendencies across all of our compiled data (i.e., local gains in species richness slightly outpace regional gains, leading to homogenization, especially for long duration checklist studies), our results suggest that changes in *α*-, *β*-, and *γ*-diversity through time are highly variable across locations, taxa, and time. This matches general findings on local diversity (*4-6, 33*), and population trends (*34, 35*), where variation in the direction of change means that the strength of overall net trends are weak and often statistically indistinguishable

from zero. We argue that perhaps these results should not be surprising. Certainly humans are having many impacts that could lead to biotic homogenization, including transporting species beyond their historical biogeographic boundaries, and recreating urban or high intensity agricultural landscapes repeatedly (*12-14*). However, at the same time, many other impacts could lead to differentiation, including: substantial fragmentation of the landscape, the creation of strong spatial gradients of human impact intensity, applying spatially varying resource management practices and land use regulations, and climate change, which induces species to shift at different rates, all leading to spatial heterogeneity (*15, 16, 36*). In this context, we stress that the lack of strong overall scale-dependent biodiversity change and prevalence of homogenization should not in any way be taken to indicate that humans are not having a large impact on biodiversity. Both reductions in β-diversity, as in homogenization, or increases, as in differentiation, are likely a result of humans modifying nature. Furthermore, our focus on scale-explicit diversity, and temporal changes of spatial variation in species composition (i.e., the number of distinct assemblages within a region), is not able to track species identities. On top of the α-, β - and γ-diversity change shown here, for many of these assemblages the identity of species within them is also likely changing (*4, 6*). A loss of a shared species matched by a gain of a different shared species between communities has no net effect on β diversity but clearly involves change, possibly driven by humans. Simple descriptions for biodiversity change may often be hard to find.

Our results support moving beyond a belief in the predominance of ubiquitous biodiversity loss and homogenization, and instead working to understand the multiscale nature of biodiversity change and embracing its variability. Our conceptual classification emphasizes that different metacommunities are experiencing fundamentally different types of temporal change across scales, resulting in variable trends, and often no trend, in spatial β-diversity through time. Respectively, biotic homogenization and differentiation were often characterized by gains or losses in the number of regionally widespread, and/or relatively abundant species. This suggests that there is still time to protect many rare and narrow-ranged species before they ultimately contribute to homogenization. It also means that efforts to slow the spread of widespread (possibly non-native) species are vital for preventing biotic homogenization. Conversely, greater attention to variation and changes in the number of common species (*29, 37*), whether they be those with high occupancy within a region or having high relative abundance at either local or regional scales, will increase our understanding of both biotic homogenization and differentiation. Many species require protection across multiple sites or at landscape (or larger) spatial scales for effective conservation (*38, 39*). The simple conceptual typology introduced here simultaneously considers change in α-, β- and γ-diversity through time, showing how contemporary biodiversity monitoring for management and conservation can embrace a multiscale approach.

References and Notes

1. H. Haberl, K. H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzar, S. Gingrich, W. Lucht, M. Fischer-Kowalski, Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences*. **104**, 12942–12947 (2007).

2. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. Butchart, K. M. Chan, Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*. **366** (2019).

3. D. Barnosky, N. Matzke, S. Tomiya, G. O. Wogan, B. Swartz, T. B. Quental, C. Marshall, J. L. McGuire, E. L. Lindsey, K. C. Maguire, Has the Earth's sixth mass extinction already arrived? *Nature*. **471**, 51–57 (2011).

4. M. Dornelas, N. J. Gotelli, B. McGill, H. Shimadzu, F. Moyes, C. Sievers, A. E. Magurran, Assemblage time series reveal biodiversity change but not systematic loss. *Science*. **344**, 296–299 (2014).

5. S. A. Blowes, S. R. Supp, L. H. Antão, A. Bates, H. Bruelheide, J. M. Chase, F. Moyes, A. Magurran, B. McGill, I. H. Myers-Smith, M. Winter, A. D. Bjorkman, D. E. Bowler, J. E. Byrnes, A. Gonzalez, J. Hines, F. Isbell, H. P. Jones, L. M. Navarro, P. L. Thompson, M. Vellend, C. Waldock, M. Dornelas, The geography of biodiversity change in marine and terrestrial assemblages. *Science*. **366**, 339–345 (2019).

6. M. Vellend, L. Baeten, I. H. Myers-Smith, S. C. Elmendorf, R. Beauséjour, C. D. Brown, P. De Frenne, K. Verheyen, S. Wipf, Global meta-analysis reveals no net change in local-scale plant biodiversity over time. *Proceedings of the National Academy of Sciences*. **110**, 19456–19459 (2013).

7. R. Elahi, M. I. O'Connor, J. E. Byrnes, J. Dunic, B. K. Eriksson, M. J. Hensel, P. J. Kearns, Recent trends in local-scale marine biodiversity reflect community structure and human impacts. *Current Biology*. **25**, 1938–1943 (2015).

8. R. B. Primack, A. J. Miller-Rushing, R. T. Corlett, V. Devictor, D. Johns, R. Loyola, B. Hass, R. J. Pakeman, L. Pejchar, Biodiversity gains? The debate on changes in local-vs global-scale species richness. *Biol Conserv*. **219**, A1 (2018).

9. M. Vellend, L. Baeten, A. Becker-Scarpitta, V. Boucher-Lalonde, J. L. McCune, J. Messier, I. H. Myers-Smith, D. F. Sax, Plant biodiversity change across scales during the Anthropocene. *Annual Review of Plant Biology*. **68**, 563–586 (2017).

10. J. Cardinale, A. Gonzalez, G. R. Allington, M. Loreau, Is local biodiversity declining or not? A summary of the debate over analysis of species richness time trends. *Biological Conservation*. **219**, 175–183 (2018).

11. K. Eriksson, H. Hillebrand, Rapid reorganization of global biodiversity. *Science*. **366**, 308–309 (2019).

12. M. L. McKinney, J. L. Lockwood, Biotic homogenization: a few winners replacing many losers in the next mass extinction. *Trends in ecology & evolution*. **14**, 450–453 (1999).

13. J. L. Lockwood, M. L. McKinney, *Biotic homogenization* (Springer, 2001).

14. J. D. Olden, T. P. Rooney, On defining and quantifying biotic homogenization. *Glob Ecol Biogeogr*. **15**, 113–120 (2006).

15. S. Martins, M. Dornelas, M. Vellend, C. D. Thomas, A millennium of increasing diversity of ecosystems until the mid-20th century. *Global Change Biology*. **28**, 5945–5955 (2022).

16. J. B. Socolar, J. J. Gilroy, W. E. Kunin, D. P. Edwards, How should beta-diversity inform biodiversity conservation? *Trends Ecol Evol*. **31**, 67–80 (2016).

17. J. M. Chase, B. J. McGill, P. L. Thompson, L. H. Antão, A. E. Bates, S. A. Blowes, M. Dornelas, A. Gonzalez, A. E. Magurran, S. R. Supp, M. Winter, A. D. Bjorkman, H. Bruelheide, J. E. Byrnes, J. Sarmento Cabral, R. Elahi, C. Gomez, H. M. Guzman, F. Isbell, I. H. Myers-Smith, H. P. Jones, J. Hines, M. Vellend, C. Waldock, M. O'Connor, Species richness change across spatial scales. *Oikos*, 1–13 (2019).

18. R. H. Whittaker, Vegetation of the Siskiyou mountains, Oregon and California. *Ecol Monogr*. **30**, 279–338 (1960).

19. H. T. Arita, J. A. Christen, P. Rodríguez, J. Soberón, Species diversity and distribution in presence-absence matrices: mathematical relationships and biological implications. *The American Naturalist*. **172**, 519–532 (2008).

20. M. Dornelas, L. H. Antao, F. Moyes, A. E. Bates, A. E. Magurran, D. Adam, A. A. Akhmetzhanova, W. Appeltans, J. M. Arcos, H. Arnold, BioTIME: A database of biodiversity time series for the Anthropocene. *Glob Ecol Biogeogr*. **27**, 760–786 (2018).

21. L. Comte, J. Carvajal-Quintero, P. A. Tedesco, X. Giam, U. Brose, T. Erős, A. F. Filipe, M.-J. Fortin, K. Irving, C. Jacquet, S. Larsen, S. Sharma, A. Ruhi, F. G. Becker, L. Casatti, G. Castaldelli, R. B. Dala-Corte, S. R. Davenport, N. R. Franssen, E. García-Berthou, A. Gavioli, K. B. Gido, L. Jimenez-Segura, R. P. Leitão, B. McLarney, J. Meador, M. Milardi, D. B. Moffatt, T. V. T. Occhi, P. S. Pompeu, D. L. Propst, M. Pyron, G. N. Salvador, J. A. Stefferud, T. Sutela, C. Taylor, A. Terui, H. Urabe, T. Vehanen, J. R. S. Vitule, J. O. Zeni, J. D. Olden, RivFishTIME: A global database of fish time-series to study global change ecology in riverine systems. *Global Ecology and Biogeography*. **30**, 38–50 (2021).

22. R. van Klink, D. E. Bowler, O. Comay, M. M. Driessen, S. K. M. Ernest, A. Gentile, F. Gilbert, K. B. Gongalsky, J. Owen, G. Pe'er, I. Pe'er, V. H. Resh, I. Rochlin, S. Schuch,

A. B. Swengel, S. R. Swengel, T. J. Valone, R. Vermeulen, T. Wepprich, J. L. Wiedmann, J. M. Chase, InsectChange: a global database of temporal changes in insect and arachnid assemblages. *Ecology*. **102**, e03354 (2021).

23. F. Sax, S. D. Gaines, J. H. Brown, Species invasions exceed extinctions on islands worldwide: a comparative study of plants and birds. *The American Naturalist*. **160**, 766–783 (2002).

24. Essl, D. Moser, T. Dirnböck, S. Dullinger, N. Milasowszky, M. Winter, W. Rabitsch, Native, alien, endemic, threatened, and extinct species diversity in European countries. *Biological Conservation*. **164**, 90–97 (2013).

25. B. Baiser, J. D. Olden, S. Record, J. L. Lockwood, M. L. McKinney, Pattern and process of biotic homogenization in the New Pangaea. *Proceedings of the Royal Society B: Biological Sciences*. **279**, 4772–4777 (2012).

26. B. Baiser, D. Valle, Z. Zelazny, J. G. Burleigh, Non-random patterns of invasion and extinction reduce phylogenetic diversity in island bird assemblages. *Ecography*. **41**, 361–374 (2018).

27. L. Jost, Partitioning diversity into independent alpha and beta components. *Ecology*. **88**, 2427–2439 (2007).

28. L. Jost, Entropy and diversity. *Oikos*. **113**, 363–375 (2006).

29. K. J. Gaston, Valuing common species. *Science*. **327**, 154–155 (2010).

30. H. Hillebrand, D. M. Bennett, M. W. Cadotte, Consequences of dominance: a review of evenness effects on local and regional ecosystem processes. *Ecology*. **89**, 1510–1520 (2008).

31. R. Winfree, J. W. Fox, N. M. Williams, J. R. Reilly, D. P. Cariveau, Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. *Ecol Lett*. **18**, 626–635 (2015).

32. M. L. Avolio, E. J. Forrestel, C. C. Chang, K. J. La Pierre, K. T. Burghardt, M. D. Smith, Demystifying dominant species. *New Phytologist*. **223**, 1106–1126 (2019).

33. Pilotto, I. Kühn, R. Adrian, R. Alber, A. Alignier, C. Andrews, J. Bäck, L. Barbaro, D. Beaumont, N. Beenaerts, Meta-analysis of multidecadal biodiversity trends in Europe. *Nature communications*. **11**, 3486 (2020).

34. M. Dornelas, N. J. Gotelli, H. Shimadzu, F. Moyes, A. E. Magurran, B. J. McGill, A balance of winners and losers in the Anthropocene. *Ecol Lett*. **22**, 847–854 (2019).

35. N. Daskalova, I. H. Myers-Smith, J. L. Godlee, Rare and common vertebrates span a wide spectrum of population trends. *Nature Communications*, 4394 (2020).

36. E. S. Poloczanska, C. J. Brown, W. J. Sydeman, W. Kiessling, D. S. Schoeman, P. J. Moore, K. Brander, J. F. Bruno, L. B. Buckley, M. T. Burrows, Global imprint of climate change on marine life. *Nature Climate Change*. **3**, 919–925 (2013).

37. K. J. Gaston, Common ecology. *Bioscience*. **61**, 354–362 (2011).

38. C. Boyd, T. M. Brooks, S. H. Butchart, G. J. Edgar, G. A. Da Fonseca, F. Hawkins, M. Hoffmann, W. Sechrest, S. N. Stuart, P. P. Van Dijk, Spatial scale and the conservation of threatened species. *Conservation Letters*. **1**, 37–43 (2008).

39. J. R. Allan, H. P. Possingham, S. C. Atkinson, A. Waldron, M. Di Marco, S. H. Butchart, V. M. Adams, W. D. Kissling, T. Worsdell, C. Sandbrook, The minimum land area requiring conservation attention to safeguard biodiversity. *Science*. **376**, 1094–1101 (2022).

40. W. Addinck, M. de Kluijver, North Sea observations of Crustacea, Polychaeta, Echinodermata, Mollusca and some other groups between 1986 and 2003. Expert Centre for Taxonomic Identification (ETI), the Netherlands (2003), (available at https://ipt.vliz.be/eurobis/resource?r=zma_noordzee https://www.eurobis.org/imis?module=dataset&dasid=1037).

41. J. Anderson, L. Vermeire, P. B. Adler, Fourteen years of mapped, permanent quadrats in a northern mixed prairie, USA. *Ecology*. **92**, 1703 (2011).

42. Andrews Forest LTER Site, J. F. Franklin, Long-term growth, mortality and regeneration of trees in permanent vegetation plots in the Pacific Northwest, 1910 to present (2012), , doi:10.6073/pasta/2315afa15ad0a2317b49565da6258c47.

43. Animal Demography Unit, Coordinated Waterbird Counts (CWAC) (2012), (available at https://obis.org/dataset/a60f84ee-0e25-428e-b171-16686b554702).

44. Australian Antarctic Data Centre, Seabirds of the Southern and South Indian Ocean. *Occurrence dataset* (2022), , doi:10.15468/tu0dcw.

45. T. E. Barreto, thesis, University of Campinas, PhD thesis.

46. B. Bestelmeyer, D. Lightfoot, R. L. Schooley, Rodent data from trapping webs in the long-term Small Mammal Exclusion Study (SMES) at Jornada Basin LTER, 1995-2007 (2019), , doi:10.6073/pasta/0c38baecb2e10b4fe70d187ba6f08dda.

47. Birds Canada, Marsh Monitoring Program, (available at http://www.naturecounts.ca/).

48. Birds Canada, Marsh Monitoring Program, (available at http://www.naturecounts.ca/).

49. Birds Canada, British Columbia Coastal Waterbirds Survey (2008), (available at https://www.naturecounts.ca/).

50. T. C. Bonebrake, E. J. Pickett, T. P. N. Tsang, C. Y. Tak, M. Q. Vu, L. Van Vu, Warming threat compounds habitat degradation impacts on a tropical butterfly community in Vietnam. *Global Ecology and Conservation*. **8**, 203–211 (2016).

51. M. G. Bradford, H. T. Murphy, A. J. Ford, D. L. Hogan, D. J. Metcalfe, Long?term stem inventory data from tropical rain forest plots in Australia. *Ecology*. **95** (2014), , doi:10.1890/14-0458R.1.

52. S. K. R. Brown, K. Zwanenburg, R. Branton, ECNASAP East Coast of North America Groundfish data. *East Coast North America Strategic Assessment Project*, (available at http://ipt.iobis.org/obiscanada/resource?r=ecnasap https://obis.org/dataset/11bc2cb2-a837-4cd1-9450-52e3bb427cf6).

53. P. Budy, C. Luecke, J. O'brien, Zooplankton density for lake samples collected near Toolik Lake Arctic LTER in the summer from 1983 to 1992 (1985), , doi:10.6073/pasta/e711d62032f0b78b9a91070a38f2b43f.

54. P. Budy, C. Luecke, J. O'Brien, Zooplankton density for lake samples collected near Toolik Lake Arctic LTER in the summers between 1993-2002 (1995), , doi:10.6073/pasta/ed17faaca17d524a06c50a6027411cf3.

55. D. Clark, B. Branton, DFO Maritimes Research Vessel Trawl Surveys (2007), (available at https://www.gbif.org/dataset/86711916-f762-11e1-a439-00145eb45e9a).

56. D. Clark, B. Branton, DFO Maritimes Research Vessel Trawl Surveys, OBIS Canada Digital Collections (2007).

57. Coral Reef Ecosystem Division (CRED), Pacific Island Fisheries Sciences Center, NOAA National Marine Fisheries Service, CRED Towed-Diver Fish Biomass Surveys in the Pacific Ocean 2000-2010 (2011), (available at https://obis.org/dataset/1d3d2e69-3256-44c4-af75-ca6491f795c6).

58. J. G. Douglass, K. E. France, J. P. Richardson, J. E. Duffy, Seasonal and interannual change in a Chesapeake Bay eelgrass community: Insights into biotic and abiotic control of community structure. *Limnology and Oceanography*. **55**, 1499–1520 (2010).

59. C. Dyrness, C. B. Halpern, Plant succession and biomass dynamics following logging and burning in the Andrews Experimental Forest Watersheds 1 and 3, 1962-Present (2010), , doi:https://doi.org/10.6073/pasta/08dd6cb668df706061bf260b183561a0.

60. S. C. Elmendorf, Global Tundra Vegetation Change - 30 years of plant abundance data from unmanipulated and experimentally-warmed plots. *CCIN reference number 10786* (2012), (available at http://www.polardata.ca).

61. S. C. Elmendorf, G. H. R. Henry, R. D. Hollister, R. G. Björk, A. D. Bjorkman, T. V. Callaghan, L. S. Collier, E. J. Cooper, J. H. C. Cornelissen, T. A. Day, Global assessment

of experimental climate warming on tundra vegetation: heterogeneity over space and time. *Ecology letters*. **15**, 164–175 (2012).

62. S. C. Elmendorf, G. H. R. Henry, R. D. Hollister, R. G. Björk, N. Boulanger-Lapointe, E. J. Cooper, J. H. C. Cornelissen, T. A. Day, E. Dorrepaal, T. G. Elumeeva, Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*. **2**, 453–457 (2012).

63. S. C. Elmendorf, G. H. R. Henry, R. D. Hollister, A. M. Fosaa, W. A. Gould, L. Hermanutz, A. Hofgaard, I. S. Jónsdóttir, J. C. Jorgenson, E. Lévesque, Experiment, monitoring, and gradient methods used to infer climate change effects on plant communities yield consistent patterns. *Proceedings of the National Academy of Sciences*. **112**, 448–452 (2015).

64. F. T. Farah, R. R. Rodrigues, F. A. M. Santos, J. Y. Tamashiro, G. J. Shepherd, T. Siqueira, J. L. F. Batista, B. J. F. Manly, Forest destructuring as revealed by the temporal dynamics of fundamental species–case study of Santa Genebra Forest in Brazil. *Ecological Indicators*. **37**, 40–44 (2014).

65. M. Friggens, M. Friggens, SEV008 - Sevilleta LTER Small Mammal Population Data (2008), (available at https://sevlter.unm.edu/data/sev-008/4786).

66. C. Gjerdrum, D. Fifield, CWS-EC Eastern Canada Seabirds at Sea (ECSAS) (2019), (available at https://obis.org/dataset/51391fb1-ae4d-44d8-9178-a06f95545604).

67. C. Halpern, DEMO: Vegetation Data - Post-Harvest. Demonstration of Ecosystem Management Options (2015), (available at http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=TP104).

68. C. B. Halpern, C. Dyrness, Plant succession and biomass dynamics following logging and burning in the Andrews Experimental Forest Watersheds 1 and 3, 1962-Present (2010), (available at http://andrewsforest.oregonstate.edu/data/abstract.cfm?dbcode=TP073).

69. C. B. Halpern, C. Dyrness, Plant succession and biomass dynamics following logging and burning in the Andrews Experimental Forest Watersheds 1 and 3, 1962-Present (2010), (available at http://andrewsforest.oregonstate.edu/data/abstract.cfm?dbcode=TP073).

70. C. B. Halpern, J. A. Lutz, Canopy closure exerts weak controls on understory dynamics: a 30-year study of overstory-understory interactions (2013), , doi:10.5061/dryad.1q88j.

71. C. B. Halpern, J. A. Lutz, Canopy closure exerts weak controls on understory dynamics: a 30-year study of overstory-understory interactions (2013), , doi:10.5061/dryad.1q88j.

72. C. B. Halpern, J. Halaj, S. A. Evans, M. Dovčiak, Level and pattern of overstory retention interact to shape long?term responses of understories to timber harvest. *Ecological Applications*. **22**, 2049–2064 (2012).

73. C. B. Halpern, J. A. Lutz, Canopy closure exerts weak controls on understory dynamics: a 30-year study of overstory–understory interactions. *Ecological Monographs*. **83**, 221–237 (2013).

74. C. B. Halpern, J. A. Lutz, Canopy closure exerts weak controls on understory dynamics: a 30-year study of overstory–understory interactions. *Ecological Monographs*. **83**, 221–237 (2013).

75. C. B. Halpern, J. A. Lutz, Canopy closure exerts weak controls on understory dynamics: a 30-year study of overstory–understory interactions. *Ecological Monographs*. **83**, 221–237 (2013).

76. C. B. Halpern, D. McKenzie, S. A. Evans, D. A. Maguire, Initial responses of forest understories to varying levels and patterns of green-tree retention. *Ecological Applications*. **15**, 175–195 (2005).

77. C. B. Halpern, D. McKenzie, S. A. Evans, D. A. Maguire, Initial responses of forest understories to varying levels and patterns of green-tree retention. *Ecological Applications*. **15**, 175–195 (2005).

78. D. C. Hartnett, S. L. Collins, PVC02 Plant Species Composition on Selected Watersheds at Konza Prairie ver 9 (2016), , doi:10.6073/pasta/7b6df00de4d0fcecfd344c02de9f9c62.

79. HMANA, Hawk Migration Association of North America (HMANA), (available at https://www.hmana.org/).

80. R. D. Hollister, J. L. May, K. S. Kremers, C. E. Tweedie, S. F. Oberbauer, J. A. Liebig, T. F. Botting, R. T. Barrett, J. L. Gregory, Warming experiments elucidate the drivers of observed directional changes in tundra vegetation. *Ecology and Evolution*. **5**, 1881–1895 (2015).

81. R. Hundt, Ökologisch-geobotanische Untersuchungen an den mitteldeutschen Wiesengesellschaften unter besonderer Berücksichtigung ihres Wasserhaushaltes und ihrer Veränderung durch die Intensivbewirtschaftung im Rahmen der Großflächenproduktion. Biosphärenreservat Rh. *Monografie*. **3**, 366 (2001).

82. Institute of Agricultural and Fisheries research (ILVO), Macrobenthos monitoring at long-term monitoring stations in the Belgian part of the North Sea between 1979 and 1999 (2016), doi:https://doi.org/10.14284/201.

83. International Council for the Exploration of the Sea, ICES DATRAS: Beam Trawl Survey (2010), (available at https://datras.ices.dk/Data{_}products/Download/Download{_}Data{_}public.aspx).

84. International Council for the Exploration of the Sea, ICES DATRAS: North Sea International Bottom Trawl Survey (2010), (available at https://datras.ices.dk/Data{_}products/Download/Download{_}Data{_}public.aspx).

85. International Council for the Exploration of the Sea, ICES DATRAS: Baltic International Trawl Survey (2013), (available at https://datras.ices.dk/Data{_}products/Download/Download{_}Data{_}public.aspx).

86. International Council for the Exploration of the Sea, ICES DATRAS: Scottish West Coast Survey For Commercial Fish Species 1985-2013 (2013), (available at https://datras.ices.dk).

87. U. Jandt, H. Bruelheide, German vegetation reference database (GVRD). *Biodiversity & Ecology*. **4** (2012), p. 355.

88. J. Jones, J. Miller, Spatial and temporal distribution and abundance of moths in the Andrews Experimental Forest, 1994 to 2008, (available at http://andrewsforest.oregonstate.edu/data/abstract.cfm?dbcode=SA015).

89. D. A. Kelt, P. L. Meserve, J. R. Gutiérrez, W. B. Milstead, M. A. Previtali, Long-term monitoring of mammals in the face of biotic and abiotic influences at a semiarid site in north-central Chile. *Ecology*. **94**, 977 (2013).

90. S. C. Kendeigh, *Bird populations in east central Illinois: Fluctuations, variations, and development over a half-century* (University of Illinois Press, 1982).

91. S. C. Kendeigh, *Bird populations in east central Illinois: Fluctuations, variations, and development over a half-century* (University of Illinois Press, 1982).

92. S. C. Kendeigh, *Bird populations in east central Illinois: Fluctuations, variations, and development over a half-century* (University of Illinois Press, 1982).

93. M. K. Kennedy, J. A. Spry, BioChem: Atlantic Zone Monitoring Program (AZMP) Maritimes Region zooplankton collection (2011), (available at https://obis.org/dataset/f9a6159e-d03b-45f2-a44a-eafb791e5987 http://ipt.obis.org/nonode/resource?r=biochem{_}azmp{_}maritimes).

94. J. Knops, D. Tilman, Core Old Field Grasshopper Sampling:Successional Dynamics on a Resampled Chronosequence (experiment 014) (2006), , doi:10.6073/pasta/239b3023d75d83e795a15b36fac702e2.

95. D. J. Kushner, A. Rassweiler, J. P. McLaughlin, K. D. Lafferty, A multi-decade time series of kelp forest community structure at the California Channel Islands. *Ecology*. **94**, 2655–2655 (2013).

96. D. Landis, S. Gage, Insect Populations via Sticky Traps at KBS-LTER (2014), , doi:10.6073/pasta/6b6cc0ad7897d9008e8cf918bbf552d2.

97. R. Lathrop, Madison Wisconsin Lakes Zooplankton 1976 - 1994 (2013), , doi:10.6073/pasta/ec3d0186753985147d4f283252388e05.

98. J. S. Lefcheck, thesis, The College of William & Mary, PhD thesis (2015).

99. D. Lightfoot, Small Mammal Exclosure Study (SMES) Vegetation Data from the Chihuahuan Desert Grassland and Shrubland at the Sevilleta National Wildlife Refuge, New Mexico (2006-2009) (2011), , doi:https://doi.org/10.6073/pasta/d80d5e2196cd11ef79df23ebe5a77c19.

100. D. Lightfoot, Lizard pitfall trap data (LTER-II, LTER-III) (2013), (available at https://lter.jornada.nmsu.edu/data-catalog/).

101. D. Lightfoot, Small Mammal Exclosure Study (SMES) Leaf Litter Study in the Chihuahuan Desert Grassland and Shrubland at the Sevilleta National Wildlife Refuge, New Mexico ver 128607 (2016), , doi:10.6073/pasta/2f99420037c88c1c751b38ea8f3a91b1.

102. M. C. Mack, E. A. G. Schuur, M. S. Bret-Harte, G. R. Shaver, F. S. Chapin, Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. *Nature*. **431**, 440–443 (2004).

103. W. O. McLarney, J. Meador, J. F. Chamblee, Upper Little Tennessee River Biomonitoring Program Database (2010), (available at https://biotime.st-andrews.ac.uk/getDatasetsQ.php?study=229).

104. J. Merritt, Long Term Mammal Data from Powdermill Biological Station 1979-1999 ver 17 (2013), , doi:10.6073/pasta/83c888854e239a79597999895bb61cfe.

105. N. A. Milchakova, V. G. Ryabogina, E. B. Chernyshova, Macroalgae of the Crimean coastal zone (the Black Sea, 1967-2007) (2011), (available at https://ipt.vliz.be/eurobis/resource?r=milchakova_macroalgae_blacksea).

106. Monitoring Site 1000 Project, Biodiversity Center, Ministry of Environment of Japan, Monitoring site 1000 Shorebird Survey. *ShorebirdsDatapackage2012.zip* (2013), (available at https://www.biodic.go.jp/moni1000/findings/data/index.html).

107. Monitoring Site 1000 Project, Biodiversity Center, Ministry of Environment of Japan, Monitoring site 1000 Forest and grassland research - Surface wandering beetles survey data. *GBDataPackage2014ver1.zip* (2014), (available at http://www.biodic.go.jp/moni1000/findings/data/index.html).

108. J. J. Moore, C. M. Howson, "Survey of the rocky shores in the region of Sullom Voe, Shetland, July 2013" (A report to SOTEAG from Aquatic Survey & Monitoring

Ltd., Cosheston, Pembrokeshire, 2014), p. 30 pp + iv, (available at https://www.soteag.org.uk/environmental-monitoring/monitoring-reports/).

109. Moorea Coral Reef LTER, R. Carpenter, Coral Reef: Long-term Population and Community Dynamics: Other Benthic Invertebrates, ongoing since 2005 ver 29. (2015), , doi:https://doi.org/10.6073/pasta/61cc126fc5a5a0a99b62b3aaac56f3e8.

110. S. K. Morgan Ernest, G. M. Yenni, G. Allington, E. M. Christensen, K. Geluso, J. R. Goheen, M. R. Schutzenhofer, S. R. Supp, K. M. Thibault, J. H. Brown, T. J. Valone, Long-term monitoring and experimental manipulation of a Chihuahuan desert ecosystem near Portal, Arizona (1977-2013). *Ecology*. **97**, 1082–1082 (2016).

111. E. Muldavin, S. Collins, 2003 Prescribed Burn Effect on Chihuahuan Desert Grasses and Shrubs at the Sevilleta National Wildlife Refuge, New Mexico: Species Composition Study (2004-present) ver 122109 (2016), , doi:10.6073/pasta/7d62bbb0e65c4b8f3728a8888d40421a.

112. National Biodiversity Network, Joint Nature Conservation Committee - Marine Nature Conservation Review (MNCR) and associated benthic marine data held and managed by JNCC. *Occurrence dataset*, , doi:10.15468/ocjqwv.

113. F. Neat, N. Campbell, Demersal fish diversity of the isolated Rockall plateau compared with the adjacent west coast shelf of Scotland. *Biological Journal of the Linnean Society*. **104**, 138–147 (2011).

114. S. Nishida, CMarZ (Census of Marine Zooplankton)-Asia Database. *National Museum of Nature and Science, Japan* (2013), (available at https://doi.org/10.15468/jpjdyu https://www.godac.jamstec.go.jp/bismal/e/dataset/cmarz_asia).

115. NOAA's National Marine Fisheries Service (NMFS) Northeast Fisheries Science Center, Northeast Fisheries Science Center Bottom Trawl Survey Data (2005), (available at https://www1.usgs.gov/obis-usa/ipt/resource?r=nefsc_bottom_trawl_surveys_coml).

116. Northeast Fisheries Science Center, NOAA National Marine Fisheries Service, U.S. Department of Commerce, NEFSC Benthic Database (2010), (available at http://www.usgs.gov/obis-usa/).

117. Northeast Fisheries Science Center, NOAA National Marine Fisheries Service, U.S. Department of Commerce, NEFSC Benthic Database (2010), (available at http://www.usgs.gov/obis-usa/).

118. NTL Long-Term Ecological Research Network, North Temperate Lakes LTER: Zooplankton - Trout Lake Area 1982 - current (2010), (available at https://lter.limnology.wisc.edu/node/55119 https://doi.org/10.6073/pasta/e8938a65e47b4bc2a9a8bef0712ff5c6).

119. Ocean Biodiversity Information System, South Western Pacific Regional OBIS Data Asteroid Subset (South Western Pacific OBIS). *Occurrence dataset*, , doi:10.15468/notzfl.

120. Ocean Biodiversity Information System, South Western Pacific Regional OBIS Data provider for the NIWA Marine Biodata Information System. *Occurrence dataset*, , doi:10.15468/zuuiyu.

121. E. M. Olsen, S. M. Carlson, J. Gjøsæter, N. C. Stenseth, Nine decades of decreasing phenotypic variability in Atlantic cod. *Ecology Letters*. **12**, 622–631 (2009).

122. K. L. Pardieck, D. J. Ziolkowski Jr., M.-A. R. Hudson, North American Breeding Bird Survey Dataset 1966 - 2014, version 2014.0 (2015), (available at www.pwrc.usgs.gov/BBS/RawData/).

123. R. Pélissier, J.-P. Pascal, N. Ayyappan, B. R. Ramesh, S. Aravajy, S. R. Ramalingam, Tree demography in an undisturbed Dipterocarp permanent sample plot at Uppangala, Western Ghats of India. *Ecology*. **92**, 1376 (2011).

124. E. Pollard, M. L. Hall, T. J. Bibby, "Monitoring the Abundance of Butterflies 1976-1985" in *Research and Survey in Nature Conservation, Nº2* (Nature Conservancy Council, 1986).

125. L. Pombo, M. Elliott, J. E. Rebelo, Environmental influences on fish assemblage distribution of an estuarine coastal lagoon, Ria de Aveiro (Portugal). *Scientia Marina*. **69**, 143–159 (2005).

126. L. Pombo, J. E. Rebelo, Spatial and temporal organization of a coastal lagoon fish community-Ria de Aveiro, Portugal. *Cybium*. **26**, 185–196 (2002).

127. L. Pombo, J. E. Rebelo, M. Elliott, The structure, diversity and somatic production of the fish community in an estuarine coastal lagoon, Ria de Aveiro (Portugal). *Hydrobiologia*. **587**, 253–268 (2007).

128. S. D. J. Privett, R. M. Cowling, H. C. Taylor, Thirty years of change in the fynbos vegetation of the Cape of Good Hope Nature Reserve, South Africa. *Bothalia*. **31**, 99–115 (2001).

129. J. Read, P. N. Halpin, L. B. Crowder, B. D. Best, E. Fujioka, OBIS-SEAMAP: mapping marine mammals, birds and turtles. *World Wide Web electronic publication* (2010), (available at http://seamap.env.duke.edu).

130. J. E. Rebelo, The ichthyofauna and abiotic hydrological environment of the Ria de Aveiro, Portugal. *Estuaries*. **15**, 403–413 (1992).

131. M. Reichert, MARMAP Blackfish Trap Survey 1990-2009 (2009), (available at http://www.usgs.gov/obis-usa/).

132. M. Reichert, MARMAP Chevron Trap Survey 1990-2009 (2009), (available at http://www.usgs.gov/obis-usa/).

133. R. Rinnan, S. Stark, A. Tolvanen, Responses of vegetation and soil microbial communities to warming and simulated herbivory in a subarctic heath. *Journal of Ecology*. **97**, 788–800 (2009).

134. R. Rocha, thesis, University of Lisbon, Lisbon,Portugal (2017).

135. R. Rocha, A. López-Baucells, F. Z. Farneda, M. Groenenberg, P. E. D. Bobrowiec, M. Cabeza, J. M. Palmeirim, C. F. J. Meyer, Consequences of a large-scale fragmentation experiment for Neotropical bats: disentangling the relative importance of local and landscape-scale effects. *Landscape Ecology*. **32**, 31–45 (2017).

136. R. Rocha, O. Ovaskainen, A. López-Baucells, F. Z. Farneda, E. M. Sampaio, P. E. D. Bobrowiec, M. Cabeza, J. M. Palmeirim, C. F. J. Meyer, Secondary forest regeneration benefits old-growth specialist bats in a fragmented tropical landscape. *Scientific Reports*. **8**, 3819 (2018).

137. L. G. Rudstam, Zooplankton survey of Oneida Lake, New York, 1964 - 2012, (available at https://knb.ecoinformatics.org/view/kgordon.17.56).

138. E. M. Sampaio, E. K. V. Kalko, E. Bernard, B. Rodríguez-Herrera, C. O. Handley, A Biodiversity Assessment of Bats (Chiroptera) in a Tropical Lowland Rainforest of Central Amazonia, Including Methodological and Conservation Considerations. *Studies on Neotropical Fauna and Environment*. **38**, 17–31 (2003).

139. R. Sanquetta, Monitoring experiences at the Atlantic rainforest biome using permanent plots. (Experiencias de monitoramento no bioma mata atlantica com uso de parcelas permanentes) (2008).

140. Santa Barbara Coastal LTER, D. C. Reed, SBC LTER: Reef: Kelp Forest Community Dynamics: Fish abundance. *ver 28* (2014), doi:10.6073/pasta/e37ed29111b2fddffc08355252b8b8c7.

141. Santa Barbara Coastal LTER, D. C. Reed, SBC LTER: Reef: Kelp Forest Community Dynamics: Fish abundance. *ver 28* (2014), doi:10.6073/pasta/e37ed29111b2fddffc08355252b8b8c7.

142. Santa Barbara Coastal LTER, D. C. Reed, SBC LTER: Reef: Kelp forest community dynamics: Abundance and size of giant kelp (Macrocystis pyrifera), ongoing since 2000. *ver 18* (2014), doi:10.6073/pasta/d90872297e30026b263a119d4f5bca9f.

143. Santa Barbara Coastal LTER, D. C. Reed, SBC LTER: Reef: Kelp forest community dynamics: Cover of sessile organisms, Uniform Point Contact. *ver 23* (2014), doi:10.6073/pasta/f906c91e98c2a5fe752dfa0ccdc8895f.

144. Santa Barbara Coastal LTER, D. C. Reed, SBC LTER: Reef: Kelp forest community dynamics: Invertebrate and algal density. *ver 21* (2014), , doi:10.6073/pasta/cd4cf864efecd69891dfe1d73b9ac9c3.

145. S. K. Sarker, J. Matthiopoulos, S. N. Mitchell, Z. U. Ahmed, M. B. A. Mamun, R. Reeve, 1980s–2010s: The world's largest mangrove ecosystem is becoming homogeneous. *Biological Conservation*. **236**, 79–91 (2019).

146. G. Shaver, Above ground plant biomass a moist acidic tussock tundra experimental site, 1984, Acric LTER, Toolik Lake, Alaska (2015), , doi:doi.org/10.6073/pasta/08a91cb2697f7cdc82d654e82b53c5c5.

147. G. R. Shaver, F. S. Chapin III, Production: biomass relationships and element cycling in contrasting arctic vegetation types. *Ecological Monographs*. **61**, 1–31 (1991).

148. P. Stapp, SGS-LTER Long-Term Monitoring Project: Small Mammals on Trapping Webs on the Central Plains Experimental Range, Nunn, Colorado, USA 1994 - 2006, ARS Study Number 118 (2013), , doi:10.6073/pasta/2e311b4e40fea38e573890f473807ba9.

149. R. Stoffels, New Zealand Freshwater Fish Database (extended). *Sampling event dataset* (2022), doi:10.15468/jbpw92.

150. R. Stoffels, New Zealand Freshwater Fish Database (extended). *Sampling event dataset* (2022), doi:10.15468/jbpw92.

151. S. Svensson, Species composition and population fluctuations of alpine bird communities during 38 years in the Scandinavian mountain range. *Ornis Svecica*. **16**, 183–210 (2006).

152. H. P. A. Sweatman, A. J. Cheal, G. J. Coleman, S. Delean, B. M. Fitzpatrick, I. R. Miller, R. Ninio, K. Osborne, C. M. Page, A. A. Thompson, "Long-Term Monitoring of the Great Barrier Reef. Status Report Number 5. LTM No.5" (data set, Australian Institute of Marine Science, 2001), p. 106.

153. H. C. Taylor, A vegetation survey of the Cape of Good Hope Nature Reserve. I. The use of association-analysis and Braun-Blanquet methods. *Bothalia*. **15**, 245–258 (1984).

154. W. Thuiller, J. A. Slingsby, S. D. J. Privett, R. M. Cowling, Stochastic Species Turnover and Stable Coexistence in a Species-Rich, Fire-Prone Plant Community. *PLOS ONE*. **2**, e938 (2007).

155. L. Tomialojć, T. Wesolowski, Die Stabilität der Vogelgemeinschaft in einem Urwald der gemässigten Zone: Ergebnisse einer 15jährigen Studie aus dem Nationalpark von Bialowieza (Polen). *Der Ornithologische Beobachter*. **91**, 73–110 (1994).

156. L. Tomiałojć, T. Wesolowski, Structure of a primaeval forest bird community during 1970s and 1990s (Bialowieza National Park, Poland). *Acta Ornithologica*. **31**, 133–154 (1996).

157. L. Tomiałojć, T. Wesolowski, W. Walankiewicz, Breeding bird community of a primaeval temperate forest (Bialowieza National Park, Poland). *Acta Ornithologica*. **20**, 241–310 (1984).

158. U.S. Environmental Protection Agency, Environmental Monitoring and Assessment Program (EMAP) Database (2012), (available at https://obis.org/dataset/41a50544-957c-4193-8bbf-25a25f749e85 https://archive.epa.gov/emap/archive-emap/web/html/index-21.html).

159. United States Geological Survey, NOAA AFSC North Pacific Groundfish Observer, , doi:10.15468/bg83kc.

160. USFS, Landbird Monitoring Program (UMT-LBMP), (available at http://www.avianknowledge.net/).

161. M. Valeix, H. Fritz, S. Chamaillé?Jammes, M. Bourgarel, F. Murindagomo, Fluctuations in abundance of large herbivore populations: insights into the influence of dry season rainfall and elephant numbers from long?term data. *Animal Conservation*. **11**, 391–400 (2008).

162. L. A. Viereck, K. Van Cleve, F. S. Chapin, R. W. Ruess, T. N. Hollingsworth, Bonanza Creek LTER, Vegetation Plots of the Bonanza Creek LTER Control Plots: Species Count (1975 - 2004). *ver 20* (2016), , doi:10.6073/pasta/8dd0e1ac48e2f82b51adabfbd3c62ae2.

163. L. V. Vu, Diversity and similarity of butterfly communities in five different habitat types at Tam Dao National Park, Vietnam. *Journal of Zoology*. **277**, 15–22 (2009).

164. R. Waide, Bird abundance - point counts ver 4630180 (2015), , doi:10.6073/pasta/0d96957379936a038ebbbcc6135b2fab.

165. S. L. Webb, S. E. Scanga, Windstorm disturbance without patch dynamics: twelve years of change in a Minnesota forest. *Ecology*. **82**, 893–897 (2001).

166. T. Wesolowski, D. Czeszczewik, G. Hebda, M. Maziarz, C. Mitrus, P. Rowiński, 40 years of breeding bird community dynamics in a primeval temperate forest (Bialowieza National Park, Poland). *Acta Ornithologica*. **50**, 95–120 (2015).

167. T. Wesolowski, C. Mitrus, D. Czeszczewik, P. Rowiński, Breeding bird dynamics in a primeval temperate forest over thirty-five years: variation and stability in the changing world. *Acta Ornithologica*. **45**, 209–232 (2010).

168. T. Wesolowski, P. Rowiński, C. Mitrus, D. Czeszczewik, Breeding bird community of a primeval temperate forest (Bialowieza National Park, Poland) at the beginning of the 21st century. *Acta Ornithologica*. **41**, 55–70 (2006).

169. T. Wesolowski, L. Tomialojć, C. Mitrus, P. Rowinski, D. Czeszczewik, The breeding bird community of a primaeval temperate forest (Bialowieza National Park, Poland) at the end of the 20th century. *Acta Ornithologica*. **37**, 27–45 (2002).

170. M. R. Willig, C. P. Bloch, El Verde long-term invertebrate data - Luquillo Forest Dynamics Plot (LFDP) (2016), , doi:10.6073/pasta/ec88f3dd4ed8e172802b52ff3bb82aa8.

171. K. D. Woods, Multidecade, spatially explicit population studies of canopy dynamics in Michigan oldgrowth forests. *Ecology*. **90**, 3587 (2009).

172. K. D. Woods, Multi-decade biomass dynamics in an old-growth hemlock-northern hardwood forest, Michigan, USA. *PeerJ*. **2**, e598 (2014).

173. H. Ylänne, S. Stark, A. Tolvanen, Vegetation shift from deciduous to evergreen dwarf shrubs in response to selective herbivory offsets carbon losses: evidence from 19 years of warming and simulated herbivory in the subarctic tundra. *Global Change Biology*. **21**, 3696–3711 (2015).

174. L. Zachmann, C. Moffet, P. Adler, Mapped quadrats in sagebrush steppe: long-term data for analyzing demographic rates and plant–plant interactions. *Ecology*. **91**, 3427–3427 (2010).

175. M. L. Zettler, Macrozoobenthos baltic sea (1980-2005) as part of the IOW-Monitoring (2005), (available at https://ipt.vliz.be/eurobis/resource?r=macroben_zettler_evco).

176. The Main Cropping System Experiment (MCSE), (available at http://lter.kbs.msu.edu/research/long-term-experiments/main-cropping-system-experiment/).

177. Whale Catches in Southern Ocean, (available at http://www.iobis.org).

178. L. A. Bêche, P. G. Connors, V. H. Resh, A. M. Merenlender, Resilience of fishes and invertebrates to prolonged drought in two California streams. *Ecography*. **32**, 778–788 (2009).

179. S. E. Bunn, E. G. Abal, M. J. Smith, S. C. Choy, C. S. Fellows, B. D. Harch, M. J. Kennard, F. Sheldon, Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation. *Freshwater Biology*. **55**, 223–240 (2010).

180. de Sostoa, N. Caiola, F. Casals, E. García-Berthou, C. Alcaraz, L. Benejam, A. Maceda, C. Solà, A. Munné, Ajust de l'Índex d'Integritat Biòtica (IBICAT) basat en l'ús dels peixos com a indicadors de la qualitat ambiental als rius de Catalunya. 187 p. *Agència Catalana de l'Aigua, Departament de Medi Ambient i Habitatge, Generalitat de Catalunya* (2010).

181. T. Erős, P. Sály, P. Takács, C. L. Higgins, P. Bíró, D. Schmera, Quantifying temporal variability in the metacommunity structure of stream fishes: the influence of non-native species and environmental drivers. *Hydrobiologia*. **722**, 31–43 (2014).

182. K. B. Gido, D. L. Propst, J. D. Olden, K. R. Bestgen, Multidecadal responses of native and introduced fishes to natural and altered flow regimes in the American Southwest. *Canadian Journal of Fisheries and Aquatic Sciences*. **70**, 554–564 (2013).

183. K. B. Gido, D. L. Propst, J. E. Whitney, S. C. Hedden, T. F. Turner, T. J. Pilger, Pockets of resistance: Response of arid-land fish communities to climate, hydrology, and wildfire. *Freshwater Biology*. **64**, 761–777 (2019).

184. Lévèque, J. M. Hougard, V. Resh, B. Statzner, L. Yaméogo, Freshwater ecology and biodiversity in the tropics: what did we learn from 30 years of onchocerciasis control and the associated. *Hydrobiologia*. **500**, 23–49 (2003).

185. W. O. McLarney, J. Meador, J. Chamblee, Upper Little Tennessee River Biomonitoring Program Database. *Coweeta Long Term Ecological Research Program. Available at: https://coweeta. uga. edu/dbpublic/dataset_details. asp* (2013).

186. M. Milardi, A. Gavioli, E. Soana, M. Lanzoni, E. A. Fano, G. Castaldelli, The role of species introduction in modifying the functional diversity of native communities. *Science of the Total Environment*. **699**, 134364 (2020).

187. M. Pyron, C. C. Vaughn, M. R. Winston, J. Pigg, Fish assemblage structure from 20 years of collections in the Kiamichi River, Oklahoma. *The Southwestern Naturalist*, 336–343 (1998).

188. de Sostoa, F. Casals, N. M. Caiola, D. Vinyoles, S. Sánchez, C. Franch, Desenvolupament d'un índex d'integritat biòtica (IBICAT) basat en l'ús dels peixos com a indicadors de la qualitat ambiental dels rius a Cataluña. *Documents tècnics de l'Agència Catalana de l'Aigua. Generalitat de Catalunya. Departament de Medi Ambient* (2003).

189. Terui, N. Ishiyama, H. Urabe, S. Ono, J. C. Finlay, F. Nakamura, Metapopulation stability in branching river networks. *Proceedings of the National Academy of Sciences*. **115**, E5963–E5969 (2018).

190. J. E. Whitney, K. B. Gido, E. C. Martin, K. J. Hase, The first to arrive and the last to leave: colonisation and extinction dynamics of common and rare fishes in intermittent prairie streams. *Freshwater Biology*. **61**, 1321–1334 (2016).

191. M. R. Winston, C. M. Taylor, J. Pigg, Upstream extirpation of four minnow species due to damming of a prairie stream. *Transactions of the American Fisheries Society*. **120**, 98–105 (1991).

192. J. M. Alston, C. G. Reed, L. M. Khasoha, B. R. P. Brown, G. Busienei, N. Carlson, T. C. Coverdale, M. Dudenhoeffer, M. A. Dyck, J. Ekeno, A. A. Hassan, R. Hohbein, R. P. Jakopak, B. Kimiti, S. Kurukura, P. Lokeny, A. M. Louthan, S. Musila, P. M. Musili, T. Tindall, S. Weiner, T. R. Kartzinel, T. M. Palmer, R. M. Pringle, J. R. Goheen, Ecological consequences of large herbivore exclusion in an African savanna: 12 years of data from the UHURU experiment. *Ecology*. **103** (2022), doi:10.1002/ecy.3649.

193. J. Alston, C. Reed, L. Khasoha, B. Brown, G. Busienei, N. Carlson, T. Coverdale, M. Dudenhoeffer, M. Dyck, J. Ekeno, A. Hassan, R. Hohbein, R. Jakopak, B. Kimiti, S. Kurukura, P. Lokeny, A. Louthan, S. Musila, P. Musili, T. Tindall, S. Weiner, T. Kartzinel, T. Palmer, R. Pringle, J. Goheen, Ecological consequences of large herbivore exclusion in an African savanna: 12 years of data from the UHURU experiment (2021), doi:10.5061/DRYAD.1G1JWSTXW.

194. Alves, A. Valdivia, R. B. Aronson, N. Bood, K. D. Castillo, C. Cox, C. Fieseler, Z. Locklear, M. McField, L. Mudge, J. Umbanhowar, J. F. Bruno, Twenty years of change in benthic communities across the Belizean Barrier Reef. *PLOS ONE*. **17**, e0249155 (2022).

195. Baiser, D. Valle, Z. Zelazny, J. G. Burleigh, Data from: Non-random patterns of invasion and extinction reduce phylogenetic diversity in island bird assemblages (2017), doi:10.5061/DRYAD.RS714.

196. R. Beldade, S. C. Mills, J. Claudet, I. M. Côté, More coral, more fish? Contrasting snapshots from a remote Pacific atoll. *PeerJ*. **3**, e745 (2015).

197. M. F. G. Brito, V. S. Daga, J. R. S. Vitule, Fisheries and biotic homogenization of freshwater fish in the Brazilian semiarid region. *Hydrobiologia*. **847**, 3877–3895 (2020).

198. H. Bruelheide, T. Sperle, Table S5: Occupancy change observations in bog species in the Black Forest (Germany) across all sites from 1972-2019 (2020), doi:10.5061/DRYAD.MW6M905VJ.

199. L. E. Burlakova, A. Y. Karatayev, A. R. Hrycik, S. E. Daniel, K. Mehler, L. G. Rudstam, J. M. Watkins, R. Dermott, J. Scharold, A. K. Elgin, T. F. Nalepa, E. K. Hinchey, S. J. Lozano, Density data for Lake Ontario benthic invertebrate assemblages from 1964 to 2018. *Ecology*. **102** (2021), doi:10.1002/ecy.3528.

200. M. CARLSON, R. A. DANIELS, Status of Fishes in New York: Increases, Declines and Homogenization of Watersheds. *The American Midland Naturalist*. **152**, 104–139 (2004).

201. S. A. Castro, P. Rojas, I. Vila, E. Habit, J. Pizarro-Konczak, S. Abades, F. M. Jaksic, Partitioning \upbeta-diversity reveals that invasions and extinctions promote the biotic homogenization of Chilean freshwater fish fauna. *PLOS ONE*. **15**, e0238767 (2020).

202. K. Cervantes-Yoshida, R. A. Leidy, S. M. Carlson, Contemporary Land Change Alters Fish Communities in a San Francisco Bay Watershed, California, U.S.A. *PLOS ONE*. **10**, e0141707 (2015).

203. K. Cervantes-Yoshida, R. A. Leidy, S. M. Carlson, Data from: Contemporary land change alters fish communities in a San Francisco Bay drainage, California, U.S.A. (2016), , doi:10.5061/DRYAD.54HR0.

204. 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. *Global Ecology and Biogeography*. **20**, 34–45 (2010).

205. Chiarucci, S. Fattorini, B. Foggi, S. Landi, L. Lazzaro, J. Podani, D. Simberloff, Plant recording across two centuries reveals dramatic changes in species diversity of a Mediterranean archipelago. *Scientific Reports*. **7** (2017), doi:10.1038/s41598-017-05114-5.

206. S. Chiba, K. Roy, Selectivity of terrestrial gastropod extinctions on an oceanic archipelago and insights into the anthropogenic extinction process. *Proceedings of the National Academy of Sciences*. **108**, 9496–9501 (2011).

207. Christensen, D. James, C. J. Maxwell, A. Slaughter, P. B. Adler, K. Havstad, B. Bestelmeyer, Quadrat-based monitoring of desert grassland vegetation at the Jornada Experimental Range, New Mexico, 1915–2016. *Ecology*. **102** (2021), doi:10.1002/ecy.3530.

208. Closset-Kopp, T. Hattab, G. Decocq, Do drivers of forestry vehicles also drive herb layer changes (1970–2015) in a temperate forest with contrasting habitat and management conditions? *Journal of Ecology*. **107**, 1439–1456 (2019).

209. Corke, The status and conservation needs of the terrestrial herpetofauna of the windward islands (West Indies). *Biological Conservation*. **62**, 47–58 (1992).

210. M. Dunbar, J. Murphy, R. Clarke, C. Davies, P. Scarlett, Headwater stream invertebrate data 2007 [Countryside Survey] (2016), , doi:10.5285/18849325-358B-4AF1-B20D-D750B1C723A3.

211. M. Dunbar, J. Murphy, R. Clarke, C. Davies, P. Scarlett, Headwater stream macrophyte data 2007 [Countryside Survey] (2016), , doi:10.5285/249A90EC-238B-4038-A706-6633C3690D20.

212. P. Economo, M. Janda, B. Guénard, E. Sarnat, Assembling a species–area curve through colonization, speciation and human-mediated introduction. *Journal of Biogeography*. **44**, 1088–1097 (2016).

213. P. Economo, M. Janda, B. Guénard, E. Sarnat, Data from: Assembling a species–area curve through colonization, speciation and human-mediated introduction (2017), , doi:10.5061/DRYAD.2F7B2.

214. K. E. Ellingsen, N. G. Yoccoz, T. Tveraa, J. E. Hewitt, S. F. Thrush, Long-term environmental monitoring for assessment of change: measurement inconsistencies over time and potential solutions. *Environmental Monitoring and Assessment*. **189** (2017), doi:10.1007/s10661-017-6317-4.

215. K. E. Ellingsen, N. G. Yoccoz, T. Tveraa, J. E. Hewitt, S. F. Thrush, Data from: Long-term environmental monitoring for assessment of change: measurement inconsistencies over time and potential solutions (2018), , doi:10.5061/DRYAD.2V7M4.

216. G. Fitzgerald, E. Kott, R. P. Lanno, D. G. Dixon, *Journal of Aquatic Ecosystem Stress and Recovery*. **6**, 111–127 (1997).

217. M. T. Furse, J. Bass, J. H. Blackburn, R. J. M. Gunn, M. Inglebrot, A. Matthews, K. Symes, J. M. Winder, R. T. Clarke, Headwater stream invertebrate data 1990 [Countryside Survey] (2016), , doi:10.5285/B4C17F35-1B50-4ED7-87D2-B63004A96CA2.

218. M. T. Furse, J. Davy-Bowker, F. H. Dawson, R. J. M. Gunn, J. H. Blackburn, I. M. Gunn, J. M. Winder, P. M. Scarlett, M. Gravelle, N. Kneebone, I. Nesbitt, M. Amarillo, C. Brereton, C. Cannan, G. Collett, D. Collier, G. Cooper, M. Dent, C. M. Fairfax, D. Hardie, P. Henville, C. Hilton, B. James, C. Moorhouse, Z. Randle, C. Shirley, S. R. Small, K. E. Vowles, R. T. Clarke, J. W. Watkins, Headwater stream invertebrate data 1998 [Countryside Survey] (2016), , doi:10.5285/FD0CE233-3B4D-4A5E-ABCB-C0A26DD71C95.

219. M. T. Furse, J. Davy-Bowker, F. H. Dawson, R. J. M. Gunn, J. H. Blackburn, I. M. Gunn, J. M. Winder, P. M. Scarlett, M. Gravelle, N. Kneebone, I. Nesbitt, M. Amarillo, C. Brereton, C. Cannan, G. Collett, D. Collier, G. Cooper, M. Dent, C. M. Fairfax, D. Hardie, P. Henville, C. Hilton, B. James, C. Moorhouse, Z. Randle, C. Shirley, S. R. Small, K. E. Vowles, R. T. Clarke, J. W. Watkins, Headwater stream macrophyte data 1998 [Countryside Survey] (2016), doi:10.5285/E0B638D5-8271-4442-97EF-CF46EA220F5D.

220. Gaget, V. Devictor, B. Frochot, R. Desbrosses, M.-C. Eybert, B. Faivre, Disentangling the latitudinal and altitudinal shifts in community composition induced by climate change: the case of riparian birds (2020), doi:10.5061/DRYAD.1RN8PK0RX.

221. Gaget, V. Devictor, B. Frochot, R. Desbrosses, M.-C. Eybert, B. Faivre, Disentangling the latitudinal and altitudinal shifts in community composition induced by climate change: The case of riparian birds. *Journal of Biogeography*. **48**, 526–536 (2020).

222. Gibb, B. Grossman, C. Dickman, O. Decker, G. Wardle, Data from: Long-term responses of desert ant assemblages to climate (2019), doi:10.5061/DRYAD.VC80R13.

223. Gibb, B. F. Grossman, C. R. Dickman, O. Decker, G. M. Wardle, Long-term responses of desert ant assemblages to climate. *Journal of Animal Ecology*. **88**, 1549–1563 (2019).

224. M. Green, R. L. Dunbrack, A. E. Bates, Signals of resilience and change in tidepool fish communities on the Pacific coast of Vancouver Island, Canada. *Diversity and Distributions*. **27**, 2170–2179 (2021).

225. Gruman, A. Harrington, S. Kratchner, L. Meth, T. Okey, J. Silberg, B. Starzomski, Replication data for: Long term monitoring of the rocky intertidal on Wizard Island in Barkley Sound (2019), , doi:10.5683/SP2/VBPBFN.

226. Guohuan Su, S. Villeger, Brosse Sebastien, Shengli Tao, J. Xu, M. Logez, Scripts and files for "Human Impacts on Global Freshwater Fish Biodiversity" (2021), doi:10.6084/M9.FIGSHARE.13383170.V1.

227. W. Hoagstrom, S. S. Wall, J. G. Kral, B. G. Blackwell, C. R. Berry, ZOOGEOGRAPHIC PATTERNS AND FAUNAL CHANGE OF SOUTH DAKOTA FISHES. *Western North American Naturalist*. **67**, 161–184 (2007).

228. Keith, C. Simpson, K. Wilkins, M. Tozer, D. Williams, T. Mason, Upland Health Swamps Plot Network: Royal National Park, Sydney Basin data packages 1965 - 2018 (2018), doi:10.25911/5C130CA59C5A8.

229. M. Kleunen, P. Pyšek, W. Dawson, F. Essl, H. Kreft, J. Pergl, P. Weigelt, A. Stein, S. Dullinger, C. König, B. Lenzner, N. Maurel, D. Moser, H. Seebens, J. Kartesz, M. Nishino, A. Aleksanyan, M. Ansong, L. A. Antonova, J. F. Barcelona, S. W. Breckle, G. Brundu, F. J. Cabezas, D. Cárdenas, J. Cárdenas-Toro, N. Castaño, E. Chacón, C. Chatelain, B. Conn, M. S. Dechoum, J.-M. Dufour-Dror, A. L. Ebel, E. Figueiredo, O. Fragman-Sapir, N. Fuentes, Q. J. Groom, L. Henderson, Inderjit, N. Jogan, P. Krestov, A. Kupriyanov, S. Masciadri, J. Meerman, O. Morozova, D. Nickrent, A. Nowak, A. Patzelt, P. B. Pelser, W. Shu, J. Thomas, A. Uludag, M. Velayos, A. Verkhosina, J. L. Villaseñor, E. Weber, J. J. Wieringa, A. Yazlık, A. Zeddam, E. Zykova, M. Winter, The Global Naturalized Alien Flora database. *Ecology*. **100** (2018), doi:10.1002/ecy.2542.

230. W. M. Knapp, A. Frances, R. Noss, R. F. C. Naczi, A. Weakley, G. D. Gann, B. G. Baldwin, J. Miller, P. McIntyre, B. D. Mishler, G. Moore, R. G. Olmstead, A. Strong, K. Kennedy, B. Heidel, D. Gluesenkamp, Vascular plant extinction in the continental United States and Canada. *Conservation Biology*. **35**, 360–368 (2020).

231. Kodric-Brown, C. Wilcox, J. G. Bragg, J. H. Brown, Dynamics of fish in Australian desert springs: role of large-mammal disturbance. *Diversity and Distributions*. **13**, 789–798 (2007).

232. Kolesnikova, T. Konakova, A. Taskaeva, A. Kudrin, Soil invertebrates of coniferous forests along a gradient of air pollution (Komi Republic). *Biodiversity Data Journal*. **9** (2021), doi:10.3897/bdj.9.e75586.

233. J. Larkin, A. L. Hipp, J. Kattge, W. Prescott, R. K. Tonietto, S. K. Jacobi, M. L. Bowles, Phylogenetic measures of plant communities show long-term change and impacts of fire management in tallgrass prairie remnants. *Journal of Applied Ecology*. **52**, 1638–1648 (2015).

234. D. J. Larkin, A. L. Hipp, J. Kattge, W. Prescott, R. K. Tonietto, S. K. Jacobi, M. L. Bowles, Data from: Phylogenetic measures of plant communities show long-term change and impacts of fire management in tallgrass prairie remnants (2016), doi:10.5061/DRYAD.763V6.

235. Lelli, J. Nascimbene, D. Alberti, N. Agostini, A. Zoccola, G. Piovesan, A. Chiarucci, Long-term changes in Italian mountain forests detected by resurvey of historical vegetation data. *Journal of Vegetation Science*. **32** (2020), doi:10.1111/jvs.12939.

236. C. Lightfoot, W. G. Whitford, Lizard pitfall trap data from 11 NPP study locations at the Jornada Basin LTER site, 1989-2006 (2022), doi:10.6073/PASTA/51814FA39F87AEA44629A5BE8602EC49.

237. S. B. C. LTER, J. E. Dugan, SBC LTER: Beach: Time series of abundance of birds and stranded kelp on selected beaches, ongoing since 2008 (2021), doi:10.6073/PASTA/06C6B9983A5F0A44349E027A002F5040.

238. S. B. C. LTER, D. C. Reed, R. J. Miller, SBC LTER: Reef: Annual time series of biomass for kelp forest species, ongoing since 2000 (2023), doi:10.6073/PASTA/F2D0BEB83CE7ED6949364AC28DF790EA.

239. Maleki, P. Marchand, D. Charron, B. Lafleur, Y. Bergeron, A 249-year chronosequence of forest plots from eight successive fires in the eastern Canada boreal mixedwoods (2020), doi:10.5061/DRYAD.TQJQ2BVWZ.

240. M. Marshall, T. E. Link, G. N. Flerchinger, D. J. Nicolsky, M. S. Lucash, Ecohydrological modelling in a deciduous boreal forest: Model evaluation for application in non-stationary climates. *Hydrological Processes*. **35** (2021), doi:10.1002/hyp.14251.

241. W. J. Matthews, E. Marsh-Matthews, Dynamics of an upland stream fish community over forty years: trajectories and support for the loose equilibrium concept. *Ecology* (2015),
242. doi:10.1890/14-2179.1.

243. Mendieta-Leiva, H. L. Buckley, G. Zotz, Directional changes over time in the species composition of tropical vascular epiphyte assemblages. *Journal of Ecology*. **110**, 553–568 (2021).

244. Mendieta-Leiva, K. Wagner, G. Zotz, Vascular epiphyte census data at the San Lorenzo Crane plot (2021), doi:10.5281/ZENODO.5645774.

245. M. M. Moore, J. S. Jenness, D. C. Laughlin, R. T. Strahan, J. D. Bakker, H. E. Dowling, J. D. Springer, Cover and density of southwestern ponderosa pine understory plants in permanent chart quadrats (2002–2020). *Ecology*. **103** (2022), doi:10.1002/ecy.3661.

246. M. Mushet, N. Euliss, M. Solensky, Cottonwood Lake Study Area - Invertebrate Counts (2017), doi:10.5066/F7BK1B77.

247. M. Mushet, M. J. Solensky, Cottonwood Lake Study Area - Amphibians (2017), , doi:10.5066/F7X9297Q.

248. R. Muthukrishnan, D. Larkin, Invasive species and biotic homogenization in temperate aquatic plant communities (2020), doi:10.5061/DRYAD.15DV41NT2.

249. R. Muthukrishnan, D. J. Larkin, Invasive species and biotic homogenization in temperate aquatic plant communities. *Global Ecology and Biogeography*. **29**, 656–667 (2020).

250. H. Myers-Smith, ShrubHub/QikiqtarukHub: QikiqtarukHub_v1.0 (2018), doi:10.5281/ZENODO.2397996.

251. Occdownload Gbif.Org, Occurrence Download (2022), doi:10.15468/DL.UEFCY6.

252. Ø. H. Opedal, M. von Numers, G. Tikhonov, O. Ovaskainen, Refining predictions of metacommunity dynamics by modeling species non-independence. *Ecology*. **101** (2020), doi:10.1002/ecy.3067.

253. T. P. Parks, M. C. Quist, C. L. Pierce, Historical Changes in Fish Assemblage Structure in Midwestern Nonwadeable Rivers. *The American Midland Naturalist*. **171**, 27–53 (2014).

254. M. M. Pilarczyk, P. M. Stewart, D. N. Shelton, H. N. Blalock-Herod, J. D. Williams, Current and Recent Historical Freshwater Mussel Assemblages in the Gulf Coastal Plains. *Southeastern Naturalist*. **5**, 205–226 (2006).

255. P. F. Price, G. Spyreas, J. Matthews, Biotic homogenization of regional wetland plant communities within short timescales in the presence of an aggressive invader (2017), doi:10.13012/B2IDB-0478588_V2.

256. P. F. Price, G. Spyreas, J. W. Matthews, Biotic homogenization of regional wetland plant communities within short time-scales in the presence of an aggressive invader. *Journal of Ecology*. **106**, 1180–1190 (2017).

257. C. E. L. Project, M. Alber, Long-term Mollusc Population Abundance and Size Data from the Georgia Coastal Ecosystems LTER Fall Marsh Monitoring Program (2022), doi:10.6073/PASTA/651D603E2930D7FF608D7325230418E8.

258. C. Rosenblad, D. F. Sax, Data from: A new framework for investigating biotic homogenization and exploring future trajectories: oceanic island plant and bird assemblages as a case study (2016), doi:10.5061/DRYAD.C9S61.

259. C. Rosenblad, D. F. Sax, A new framework for investigating biotic homogenization and exploring future trajectories: oceanic island plant and bird assemblages as a case study. *Ecography*. **40**, 1040–1049 (2016).

260. Russell-Smith, P. Jacklyn, Three Parks Savanna Fire-effects Plot Network: Plot-based Vegetation Sampling Data, Northern Territory, Australia, 1994-2016 (2017), doi:10.25911/5C3D75BBCA1C0.

261. Santana, M. Porto, L. Reino, F. Moreira, P. F. Ribeiro, J. L. Santo, J. T. Rotenberry, P. Beja, Data from: Using beta diversity to inform agricultural policies and conservation actions on Mediterranean farmland (2017), doi:10.5061/DRYAD.KP3FV.

262. Santana, M. Porto, L. Reino, F. Moreira, P. F. Ribeiro, J. L. Santos, J. T. Rotenberry, P. Beja, Using beta diversity to inform agricultural policies and conservation actions on Mediterranean farmland. *Journal of Applied Ecology*. **54**, 1825–1835 (2017).

263. Sarnat, B. Blanchard, B. Guénard, J. Fasi, E. Economo, Checklist of the ants (Hymenoptera, Formicidae) of the Solomon Islands and a new survey of Makira Island. *ZooKeys*. **257**, 47–88 (2013).

264. Sonnier, R. Whittington, E. H. Boughton, Long-term response of wetland plant communities to management intensity, grazing abandonment, and prescribed fire (2022), doi:10.6073/PASTA/F20622C01B40E1E08E72F01E29F59302.

265. J. B. Sorte, V. E. Davidson, M. C. Franklin, K. M. Benes, M. M. Doellman, R. J. Etter, R. E. Hannigan, J. Lubchenco, B. A. Menge, Long-term declines in an intertidal foundation species parallel shifts in community composition. *Global Change Biology*. **23**, 341–352 (2016).

266. G. Sperandii, I. Prisco, A. Stanisci, A. T. R. Acosta, RanVegDunes - A random plot database of Italian coastal dunes. *Phytocoenologia*. **47**, 231–232 (2017).

267. G. Sperandii, A. T. R. Acosta, Back into the past: Resurveying random plots to track community changes in Italian coastal dunes (2020), , doi:10.5061/DRYAD.NP5HQBZR8.

268. G. Sperandii, M. Bazzichetto, F. Gatti, A. T. R. Acosta, Back into the past: Resurveying random plots to track community changes in Italian coastal dunes. *Ecological Indicators*. **96**, 572–578 (2019).

269. T. Sperle, H. Bruelheide, Climate change aggravates bog species extinctions in the Black Forest (Germany). *Diversity and Distributions*. **27**, 282–295 (2020).

270. S. Starko, L. A. Bailey, E. Creviston, K. A. James, A. Warren, M. K. Brophy, A. Danasel, M. P. Fass, J. A. Townsend, C. J. Neufeld, Environmental heterogeneity mediates scale-dependent declines in kelp diversity on intertidal rocky shores. *PLOS ONE*. **14**, e0213191 (2019).

271. Swenson, C. Hulshof, M. Katabuchi, B. Enquist, Long-term shifts in the functional composition and diversity of a tropical dry forest: a 30-yr study (2020), doi:10.5061/DRYAD.H44J0ZPG3.

272. K. Szydlowski, A. K. Elgin, D. M. Lodge, J. S. Tiemann, E. R. Larson, Aquatic snail and macrophyte abundance and richness data for ten lakes in Vilas County, WI, USA, 1987-2020 (2022), doi:10.6073/PASTA/29733B5269EFE990C3D2D916453FE4DD.

273. J. E. Tanner, J. H. Connell, Heron Island exposed (north) crest coral community data (2022), doi:10.6084/M9.FIGSHARE.21114061.V1.

274. K. Van Cleve, F. S. Chapin, R. Ruess, Bonanza Creek LTER, Bonanza Creek LTER: Tree Inventory Data from 1989 to present at Core research sites in Interior Alaska (2021), doi:10.6073/PASTA/93067176968C707AC8491CE98B3C9DCA.

275. L. Vernon, T. A. Ranker, Current Status of the Ferns and Lycophytes of the Hawaiian Islands. *American Fern Journal*. **103**, 59–111 (2013).

276. Vojík, K. Boublík, Fear of the dark: decline in plant diversity and invasion of alien species due to increased tree canopy density and eutrophication in lowland woodlands. *Plant Ecology*. **219**, 749–758 (2018).

277. Wardle, C. Dickman, A. Greenville, B. Tamayo, Desert Ecology Plot Network data packages, 1990-2018 (2018), , doi:10.25911/5C13171D944FE.

278. E. Werner, C. J. Davis, D. K. Skelly, R. A. Relyea, M. F. Benard, S. J. McCauley, Cross-Scale Interactions and the Distribution-Abundance Relationship. *PLoS ONE*. **9**, e97387 (2014).

279. E. Werner, C. Davis, D. K. Skelly, R. A. Relyea, M. F. Benard, S. J. McCauley, C. J. Davis, Data from: Cross-scale interactions and the distribution-abundance relationship (2015), , doi:10.5061/DRYAD.JS47K.

280. Wiemers, E. Balletto, V. Dincă, Z. F. Fric, G. Lamas, V. Lukhtanov, M. L. Munguira, C. A. M. van Swaay, R. Vila, A. Vliegenthart, N. Wahlberg, R. Verovnik, An updated checklist of the European Butterflies (Lepidoptera, Papilionoidea). *ZooKeys*. **811**, 9–45 (2018).

281. M. R. Willig, El Verde long-term invertebrate data - Luquillo Forest Dynamics Plot (LFDP) (2020), , doi:10.6073/PASTA/45E3A90ED462F66ACDDE83636746F87F.

282. M. Wood, S. M. Smart, R. G. H. Bunce, L. R. Norton, L. C. Maskell, D. C. Howard, W. A. Scott, P. A. Henrys, Long-term vegetation monitoring in Great Britain – the Countryside Survey 1978–2007 and beyond. *Earth System Science Data*. **9**, 445–459 (2017).

283. K. W. Wright, M. R. Kazenel, J. Bettinelli, T. L. Griswold, K. D. Whitney, J. A. Rudgers, Bee species abundance and composition in three ecosystem types at the Sevilleta National Wildlife Refuge, New Mexico, USA (2021), , doi:10.6073/PASTA/CBE04A94B5F6F3859A3D9C98F5BE0FC8.

284. Prendergast, E. Bazeley-White, O. Smith, J. Lawton, P. Inchausti, E. Al., The Global Population Dynamics Database. *Knowl. Netw. Biocomplexity* (2010), , doi:10.5063/F1BZ63Z8.

285. R. Van Klink, D. E. Bowler, J. M. Chase, O. Comay, M. M. Driessen, S. K. M. Ernest, A. Gentile, F. Gilbert, K. B. Gongalky, G. Pe'er, I. Pe'er, Vincent. H. Resh, A. B. Swengel, S. R. Swengel, T. J. Valone, R. Vermeulen, T. Wepprich, J. Wiedmann, A global database of long-term changes in insect assemblages. *Knowl. Netw. Biocomplexity* (2020), , doi:https://doi.org/10.5063/F1ZC817H.

286. Valtonen, A. Hirka, L. Szőcs, M. P. Ayres, H. Roininen, G. Csóka, Long-term species loss and homogenization of moth communities in Central Europe. *J. Anim. Ecol.* **86**, 730–738 (2017).

287. Magnuson, C. S, E. Stanley, North Temperate Lakes LTER: Benthic Macroinvertebrates 1981 - current. *Environ. Data Initiat.* (2021), , doi:https://doi.org/10.6073/pasta/e34b247937277b35905018f728849a10.

288. S. C. Pennings, Long-term mid-marsh grasshopper abundance and species diversity at eight GCE-LTER sampling sites. *Ga. Coast. Ecosyst. LTER Proj. Univ. Ga. Long Term Ecol. Res. Netw.* (2016), (available at http://dx.doi.org/10.6073/pasta/ec9d524b8f13c000e8e8a225d5a23c7b).

289. R. Pizzolotto, M. Gobbi, P. Brandmayr, Changes in ground beetle assemblages above and below the treeline of the Dolomites after almost 30 years (1980 / 2009). *Ecol. Evol.* **4**, 1284–1294 (2014).

290. K.-L. Huttunen, H. Mykrä, J. Oksanen, A. Astorga, R. Paavola, T. Muotka, Habitat connectivity and in-stream vegetation control temporal variability of benthic invertebrate communities. *Sci. Rep.* **7**, 1448 (2017).

291. Groker, National River Water Quality Network Database (Macro-invertebrates). *GBIF* (2018), , doi:10.15468/MFJETU.

292. S. Schuch, J. Bock, B. Krause, K. Wesche, M. Schaefer, Long-term population trends in three grassland insect groups: A comparative analysis of 1951 and 2009. *J. Appl. Entomol.* **136**, 321–331 (2012).

293. S. Schuch, K. Wesche, M. Schaefer, Long-term decline in the abundance of leafhoppers and planthoppers (Auchenorrhyncha) in Central European protected dry grasslands. *Biol. Conserv.* **149**, 75–83 (2012).

294. SLU, Miljödata MVM. version 2.15.00 (2021), (available at https://miljodata.slu.se/mvm/Default.aspx).

295. W. Pereira, L. Carneiro, R. B. Gonçalves, More losses than gains in ground-nesting bees over 60 years of urbanization. *Urban Ecosyst.* **24**, 233–242 (2021).

296. Environment Agency, Ecology & Fish Bulk Downloads. *UK Dep. Environ. Food Rural Aff.* (2021), (available at https://environment.data.gov.uk/ecology/explorer/downloads/).

297. S.-W. Choi, Long-term (2005–2017) macromoth community monitoring at Mt. Jirisan National Park, South Korea, (available at https://db.cger.nies.go.jp/JaLTER/metacat/metacat?action=read&qformat=jalter-en&sessionid=&docid=ERDP-2019-02.1).

298. S.-W. Choi, J.-S. An, N.-H. Kim, S. Lee, N. Ahn, Long-term (2005–2017) macromoth community monitoring at Mt. Jirisan National Park, South Korea. *Ecol. Res.* **34**, 443–443 (2019).

299. Rennie S., Adamson, J., Anderson, R. Andrews, C. Bater, J. Bayfield, N. Beaton, K. Beaumont, D. Benham, S. Bowmaker, V. Britt, C. Brooker, R. Brooks, D. Brunt, J. Common, G. Cooper, R. Corbett, S. Critchley, N. Dennis, P. Dick, J. Dodd, B. Dodd, N. Donovan, N. Easter, J. Flexen, M. Gardiner, A. Hamilton, D. Hargreaves, P. Hatton-Ellis, M. Howe, M. Kahl, J. Lane, M. Langan, S. Lloyd, D. McCarney, B. McElarney, Y. McKenna, C. McMillan, S. Milne, F. Milne, L. Morecroft, M. Murphy, M. Nelson, A. Nicholson, H. Pallett, D. Parry, D. Pearce, I. Pozsgai, G. Rose, R. Schafer, S. Scott, T. Sherrin, L. Shortall, C. Smith, R. Smith, P. Tait, R. Taylor, C. Taylor, M. Thurlow, M. Tilbury, C. Turner, A. Tyson, K. Watson, H. Whittaker, M. Wood, UK Environmental

Change Network (ECN) butterfly data: 1993-2015 (2017), , doi:10.5285/5aeda581-b4f2-4e51-b1a6-890b6b3403a3.

300. Alignier, Two decades of change in a field margin vegetation metacommunity as a result of field margin structure and management practice changes. *Agriculture, Ecosystems & Environment*. **251**, 1–10 (2018).

301. S. V. D. Berge, S. Tessens, L. Baeten, C. Vanderschaeve, K. Verheyen, Contrasting vegetation change (1974–2015) in hedgerows and forests in an intensively used agricultural landscape. *Applied Vegetation Science*. **22**, 269–281 (2019).

302. Hassall, J. Hollinshead, A. Hull, Temporal dynamics of aquatic communities and implications for pond conservation. *Biodiversity and Conservation*. **21**, 829–852 (2012).

303. Hibit, C. C. Daehler, Long-term decline of native tropical dry forest remnants in an invaded Hawaiian landscape. *Biodiversity and Conservation*. **28**, 1699–1716 (2019).

304. T. H. M. Kolari, P. Korpelainen, T. Kumpula, T. Tahvanainen, Accelerated vegetation succession but no hydrological change in a boreal fen during 20 years of recent climate change. *Ecology and Evolution*. **11**, 7602–7621 (2021).

305. S. Larsen, J. M. Chase, I. Durance, S. J. Ormerod, Lifting the veil: richness measurements fail to detect systematic biodiversity change over three decades. *Ecology*. **99**, 1316–1326 (2018).

306. Litza, M. Diekmann, Resurveying hedgerows in Northern Germany: Plant community shifts over the past 50 years. *Biological Conservation*. **206**, 226–235 (2017).

307. Molina-Martínez, J. L. León-Cortés, H. M. Regan, O. T. Lewis, D. Navarrete, U. Caballero, A. Luis-Martínez, Changes in butterfly distributions and species assemblages on a Neotropical mountain range in response to global warming and anthropogenic land use. *Diversity and Distributions*. **22**, 1085–1098 (2016).

308. J. Prach, M. Kopecký, Landscape-scale vegetation homogenization in Central European sub-montane forests over the past 50 years. *Applied Vegetation Science*. **21**, 373–384 (2018).

309. B. Scarpitta, J. Bardat, A. Lalanne, M. Vellend, Long-term community change: bryophytes are more responsive than vascular plants to nitrogen deposition and warming. *Journal of Vegetation Science*. **28**, 1220–1229 (2017).

310. J. O. Zeni, D. J. Hoeinghaus, C. A. Roa-Fuentes, L. Casatti, Stochastic species loss and dispersal limitation drive patterns of spatial and temporal beta diversity of fish assemblages in tropical agroecosystem streams. *Hydrobiologia*. **847**, 3829–3843 (2020).

311. N.J. Gotelli, R. K. Colwell, Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. *Ecol Lett*. **4**, 379–391 (2001).

312. Becker-Scarpitta, S. Vissault, M. Vellend, Four decades of plant community change along a continental gradient of warming. *Global Change Biology*. **25**, 1629–1641 (2019).

313. O. Hill, Diversity and Evenness: A unifying notation and its consequences. *Ecology*. **54**, 427–432 (1973).

314. Carpenter, A. Gelman, M. D. Hoffman, D. Lee, B. Goodrich, M. Betancourt, M. Brubaker, J. Guo, P. Li, A. Riddell, Stan: A probabilistic programming language. *Journal of statistical software*. **76** (2017).

315. P.-C. Bürkner, brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*. **80**, 1–28 (2017).

Acknowledgments: SAB, TE, AS, RvK, WBX, JMC gratefully acknowledge the support of the German Centre of Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (funded by the German Research Foundation; FZT 118). MD acknowledges funding by the European Union (CoralINT, GA 101044975). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. MD thanks Marten Winter for chocolate, and the Leverhulme Trust Research Centre – the Leverhulme Centre for Anthropocene Biodiversity. TE was supported by the German Research Foundation (DFG) within the project "Establishment of the National Research Data Infrastructure (NFDI)" in the consortium NFDI4Biodiversity (project number 442032008). AFE acknowledges the Fisheries Society of the British Isles Studentship. ISM received funding from the European Union Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 894644. BJM acknowledges support from USDA Hatch grant MAFES #1011538 and NSF EPSCOR Track II grant #2019470.

Funding: German Research Foundation; FZT 118; SAB, TE, AS, RvK, WBX, JMC.

ERC GA 101044975 and the Leverhulme Centre for Anthropocene Biodiversity: MD

Author contributions:

Conceptualization: SAB, BM, TE, ISM, DM, HS, NJG, AM, MD, JMC

Methodology: SAB, BM, VB, CFYC, TE, AFE, ISM, DM, FM, AS, HS, RvK, WBX, NJG, AM, MD, JMC

Investigation: SAB, BM, VB, CFYC, TE, AFE, ISM, DM, FM, AS, HS, RvK, WBX, NJG, AM, MD, JMC

Visualization: SAB, BM, TE, ISM, DM, HS, NJG, AM, MD, JMC

Writing – original draft: SAB, BM, MD, JMC

Writing – review & editing: SAB, BM, VB, CFYC, TE, AFE, ISM, DM, FM, AS, HS, RvK, WBX, NJG, AM, MD, JMC

Competing interests: The authors declare that they have no competing interests.

Data and materials availability: All data used in this study are open access. R code used for data compilation (https://github.com/chase-lab/metacommunity_surveys, https://github.com/chase-lab/checklist_change, https://github.com/chase-lab/homogenisation-richness) and all analyses (https://github.com/sablowes/WhittakerBetaChange) are available, and will be archived in Zenodo prior to publication.

Supplementary Materials

Materials and Methods
Figures S1-S6
Table S1
References *40-316*

Materials and Methods

Data compilation: Our conceptual typology requires estimates of species richness changes at two scales. We refer to them as local (α) and regional (γ), the exact definition of which varies among data sources. To make our data search and synthesis as comprehensive as possible, we searched broadly for data that met these criteria, where regions had at least four plots or locations, and where richness changes were estimated over a period of at least ten years. We started by identifying 80 relevant datasets within the BioTIME database (*20*) that monitored patterns of species abundances within assemblages. To this, we added: (1) similar assemblage-level time series of studies not (yet) included in BioTIME (e.g., *21, 22*); (2) data from studies using 'resurveys', where sites associated with a historical dataset were revisited and re-surveyed using similar methodology in more recent times; (3) data from 'checklist' studies where species known to be present in a given locality (and region) at a 'historical' point in time were indicated together with species present in that locality at a later point in time (minus those that went extinct from a site plus those that newly colonized that site); and, (4) data from studies that reported changes in species richness at two spatial scales, but for which the underlying raw data were not available. Because of the relatively specific data requirements, literature searches were conducted in an ad-hoc fashion, rather than using a formal literature search. In all, we compiled a total of 337 regions and a total of 20,470 locations that met our criteria; 283 regions documented repeated samples of species assemblages through time; 54 regions were compiled from checklist studies (Fig. S4; *40-311*).

Data standardization: To quantify changes in β-diversity that emerged from combined changes occurring at the local- and regional-scale, we required that the starting and end years for all locations within a given region were the same. This ensured that change estimated across the different locations within a region covered the same period of time, and meant that regional changes estimated by aggregating all species across all locations within regions also covered the same time period. Additionally, to ensure that our analyses did not quantify changes in species richness due to variation in sampling effort, we needed to standardize sampling effort (e.g., the

number of plots or transects) across all locations for each time point within regions. The heterogeneous nature of the data that we compiled meant that we needed slightly different procedures to identify combinations of locations and years for different data sources. For clarity, we delineate broad categories of data structures, and describe separately how locations and years were selected and sample-effort standardization needed for the different structures.

Checklist data: Checklist data typically consisted of species lists for locations within regions, compiled from a historical time period and from a more contemporary time period (mean = 273 years; median = 258 years; range = 10 - 501 years). These lists were compiled either from samples and/or observations collected during the two periods, or more frequently, by counting native species only to determine the richness of the historical period, with the contemporary species richness calculated as the sum of native and introduced species (minus any species that went extinct). For our analyses, we selected regions that had at least four locations, removed locations that documented species lists for only one period, and finally, ensured that all locations within each region had data from the same time period for both the historical and contemporary species lists.

Resurvey data: We distinguish three different data structures that we refer collectively to as resurvey data:

(i) Compiled time series data that document repeated samples of assemblages documenting species abundances, i.e., data from the BioTIME (20), RivFishTime (21), and InsectChange (22), plus similarly structured data that we compiled for this and related studies. We first filtered data to ensure that samples from all locations within regions had a temporal duration of at least ten years, and that a minimum of four locations within a region were sampled per year (allowing us to track diversity of the same locations through time within regions). Locations within regions were identified using geographic coordinates in the data, although we also included regions with only one geographic coordinate where discrete, unique samples could be identified (e.g., multiple plots within a site).

After applying these filters, the number of locations sampled per year often varied considerably within regions, and we sought to identify locations, as well as start and end years that balanced a trade-off between the number of locations and the duration of the sampling period for each region. To do this, we first identified all year-pairs -- combinations of start and end year with at least ten years separating them -- for all locations within a given region. We then determined different thresholds for what proportion of the total number of locations we wanted to retain, using a combination of the total number of locations in a region, and visual inspection of locations sampled in each year. For example, for resurvey data newly collated for this study, we selected starting and end years where the proportion of the maximum locations was at least 90% for regions with fewer than 20 locations, 50% for regions with more than 20 locations, and 25% for the NERC Countryside survey data, which had between 60 and 300 locations across the UK (and where the lower threshold meant that the temporal duration of the surveys

increased by more than ten years). For regions in the BioTIME and RivFishTime databases, we identified year-pairs with at least 75% and 90% of the maximum number of locations, respectively. Multiple year-pairs often remained following this, and we selected the pair of years with the longest duration, and finally, broke any remaining ties by selecting the pair of years with the most locations. For mosquito data sourced from Vectorbase (https://vectorbase.org/vectorbase/app) and compiled in InsectChange there were frequently fewer sites sampled monthly, and we visually selected locations and the start and end years for each region to ensure that we would be able to standardize the sampling of the same months for each location through time.

Next, we ensured that sampling effort was consistent across all years and locations within regions, using sample-based rarefaction (*312*) where required to standardize effort. Note that for many data (e.g., data from InsectChange and other invertebrate data) where sampling took place across multiple months within years, we used sample-based rarefaction to resample equal numbers of samples across the same months for all locations within a region, which were then compiled to provide one sample per year for each location. Additionally, for data collected using multiple sampling methodologies (e.g., mosquitoes sampled using different attractants, or freshwater fishes collected with different techniques), we identified the methodology that ensured the maximum number of time series, and standardized sampling effort using data collected with only one method.

(ii) We collated data from studies where sites associated with a historical dataset were revisited and re-surveyed using the same methodology in more recent times, sometimes referred to as "legacy" studies (e.g., *313*). Again, we required each region to have at least four locations and ten years or more between the historical and contemporary samples.

(iii) Finally, we collated studies that estimated species richness changes at two scales, where there were at least four sites at the smaller scale and ten years between the first and last sample. For these studies raw data were not available (n = 15), but available data provided an estimate of the average local richness at two time points, and a single value for regional richness at two time points.

Estimating richness, diversity and its change: For the majority of the data, we calculated species richness from the effort-standardized locations and years as the number of distinct species, though higher classifications, such as genera, were sometimes used where studies only classified organisms to genus. We calculated species richness for each location within each region for every available year to document changes in α-scale species richness. γ-scale richness was calculated as the number of species in all sites combined for each region and each year. This method of calculating regional richness yields a single number for each region at each time point, and we calculated two types of resamples for regional richness. For datasets where sample-based rarefaction was not required to standardize effort, jackknife resamples were calculated by

systematically leaving each location out of the regional richness calculation once. For where effort-standardization was more complex and required the use of sample-based rarefaction, we used 200 bootstrap resamples (i.e., richness resamples were estimated using all locations, not $n_{\text{locations}}$-1); and then, to prevent these resampled data dominating the data to which models were fit, we subsampled the bootstrap resamples down to the same size as a jackknife would have been (i.e., we used a random subset of the bootstrap resamples equal to $n_{\text{locations}} - 1$ for the given dataset). Finally, we summarized both the jackknife and bootstrap resamples by calculating the median regional richness, to which models were fit.

Many data sources, including the 54 datasets with checklist data and 118 regions in the resurvey data, had only two years of data available (e.g., a historical and more contemporary sample). As a result, to maximize the number of regions in our complete analysis, we calculated richness change using the log-ratio of species richness in the most recent time point and species richness in the initial sample, divided by the number of years between the two samples (i.e., $log\left(\frac{S_{t2}}{S_{t1}}\right).t^{-1}$, where S_{t2} is species richness in the most recent sample (t2 = year), S_{t1} is species richness in the first sample (t1 = year), and t = t2 – t1 + 1 is the number of years between the samples. This was done separately for each location in each region. These same data were aggregated and used to calculate concomitant changes in regional diversity through time, quantified as the log-ratio of resamples (either jackknife or bootstrap) of species richness at the regional scale in the most recent sample and the resample of species richness in the initial sample, divided by the number of years between the two samples.

In addition, because many of our data sources included both information on the abundance of individual species, as well as time series of more than two years, we also calculated diversity metrics that differ in their sensitivity to common and rare species (*28, 314*) for all years having effort-standardized data, and estimated rates of change using statistical models. Specifically, we calculated richness and the inverse of Simpson's concentration (*28*). These two metrics are equal to diversity with order $q = \{0, 2\}$, where increasing q decreases the influence of rare species, and ${}^{q}D = (\sum_{i=1}^{S} p_i^q)^{1/(1-q)}$; p_i is the frequency (relative abundance) of species i (*27*). These diversity measures are sometimes referred to as Hill numbers, numbers equivalents, or effective numbers (27, *314*), here we refer to them as species richness and diversity for simplicity.

Statistical models: To estimate α- and γ-scale richness changes, we fit multilevel (also called mixed effects or hierarchical) models to data from each scale separately. For our initial analysis of the changes calculated using log-ratios (n_{regions} = 337), these models took the form:

$$ES_{ij} \sim N(\mu, \sigma),$$

$$\mu = \alpha + \alpha_i,$$

$$\log(\sigma) \sim sample_type_i * logdt_i,$$

where ES_{ij} is assumed to have a Gaussian error distribution and is the jth local-scale estimate of species richness change in region i, or at the regional-scale the j subscript is dropped and ES_i is the median of the regional richness resamples for region i; α is the overall intercept and equal to the average rate of change estimated for each scale, and α_i is the departure from the overall intercept for each region (i.e., the varying intercept for regions). Because variation in the log-ratio estimates of change was a decreasing function of the duration between samples, we

included covariates for residual variation (σ), where $sample_type_i$ estimated a separate intercept according to whether region *i* were resurvey or checklist data, and $logdt_i$ was the natural logarithm of the number of years between the first and last samples in region *i.* We fit models using Bayesian methods and we assumed the following, weakly regularizing priors:

$$\alpha \sim N(0,1),$$
$$\alpha_i \sim N(0,1),$$
$$sample_type_i \sim N(0,1),$$
$$logdt_i \sim N(0,1).$$

For the time series data of species richness and diversity (i.e., ${}^{q}D, \{q = 0, 2\}$; $n_{\text{regions}} = 165$), we estimated rates of change using statistical models (rather than change being calculated using log-ratios as was done in the initial analysis). Time series data of diversity metrics were constrained to be positive values, but due to effort standardization were not always integer values, so we fit models that assumed lognormal error distributions and identity link functions. Overall rates of change were estimated by including (mean centered) year as a predictor, and we allowed rates of change to vary among regions by including varying slopes (for year) and intercepts for regions in the regional scale model, and both regions and locations within regions for the local scale model.

We fit all models using the Hamiltonian Monte Carlo (HMC) sampler Stan (*315*), and coded using the brms package (*316*). We fit models with variable numbers of chains and iterations to ensure posterior distributions had sufficient effective sample sizes. Visual inspection of the HMC chains and Rhat summaries showed model convergence (all Rhats < 1.05).

We used models fit to the α- and γ-scale data (described above) to quantify changes in β-diversity ($\Delta\beta$). Estimates of $\Delta\alpha$ and $\Delta\gamma$ were used as x- and y-coordinates, respectively, and then the distance of these points from the 1:1 line was calculated (Fig. 1). Specifically, we extracted 1000 draws from the posterior distribution of the α-scale estimate and designated them as the x-coordinate, and combined this with 1000 draws from the corresponding γ-scale estimate as the y-coordinate, and then calculated the distance from the 1:1 line for each point. This means the units of our estimate of β-diversity is effective numbers of communities (*27*); and as rates of change in the x- and y-values are on a log-scale, $\Delta\beta$ is also describes proportional changes. Variation among regions in $\Delta\beta$ were calculated similarly: estimates of change for individual regions used the varying intercepts (initial analysis of log-ratios) or varying slopes (time series data) from models fit to data at the α- and γ-scales.

Supplementary Figures

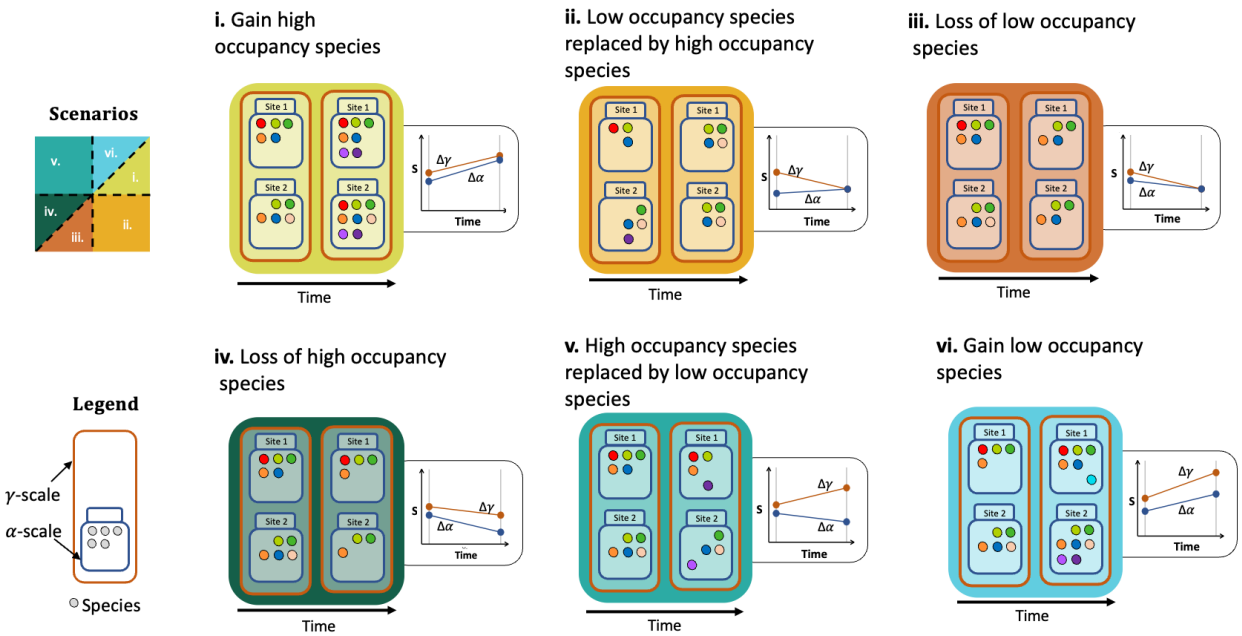

Figure S1: Simplified illustrations of species occupancy and richness changes underpinning each of the scenarios in Figure 1. *Each panel shows a simplified scenario of richness changes at smaller (α) and larger (γ) scales between two time points, accompanied by a regression showing richness at the two scales as a function time (slopes are labeled* Δα and Δγ for each scale).

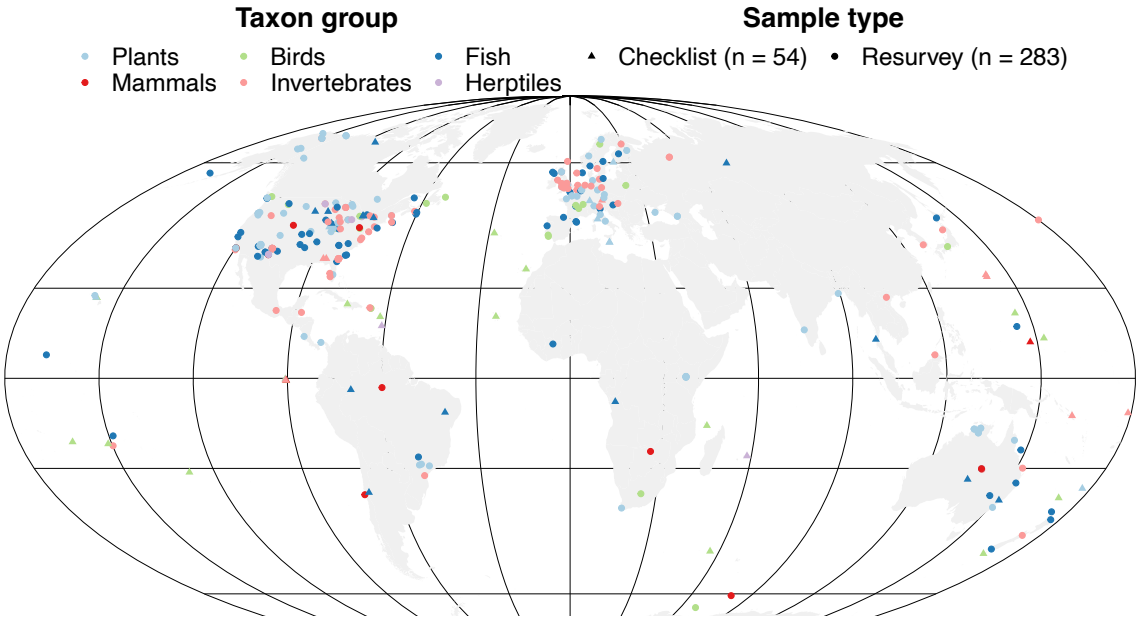

Figure S2: Map showing the central coordinate of each dataset (region) in our compiled data ($n_{regions}$ = 337).

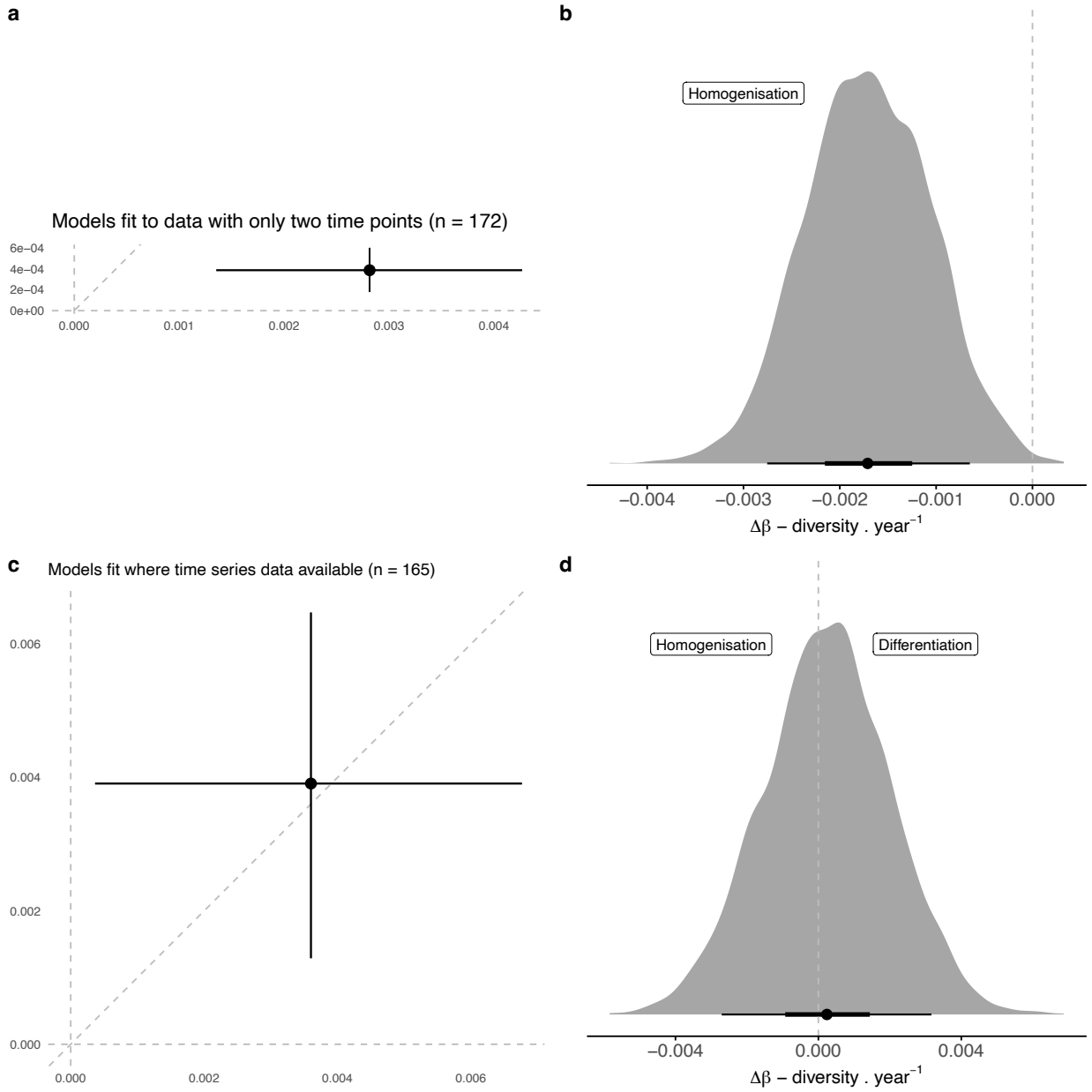

Figure S3: The tendency towards biotic homogenization is strongest in data where only two time points were available. *(a) Change in γ-diversity as a function of change in α-diversity, and (b) change in beta-diversity estimated by models fit to data with only two time points; (c) change in γ-diversity as a function of change in α-diversity, and (d) change in beta-diversity estimated by models fit to data where time series were available. Δβ was calculated as the distance from 1:1 line (left = homogenization, right = differentiation) of 1000 draws of α- and γ-scale intercept posterior distributions; black point shows median, bar represents 50% (thick) and 90% (thin) credible intervals. Note all model results shown here were fit to duration standardized log-ratios as per Fig. 2 in the main text.*

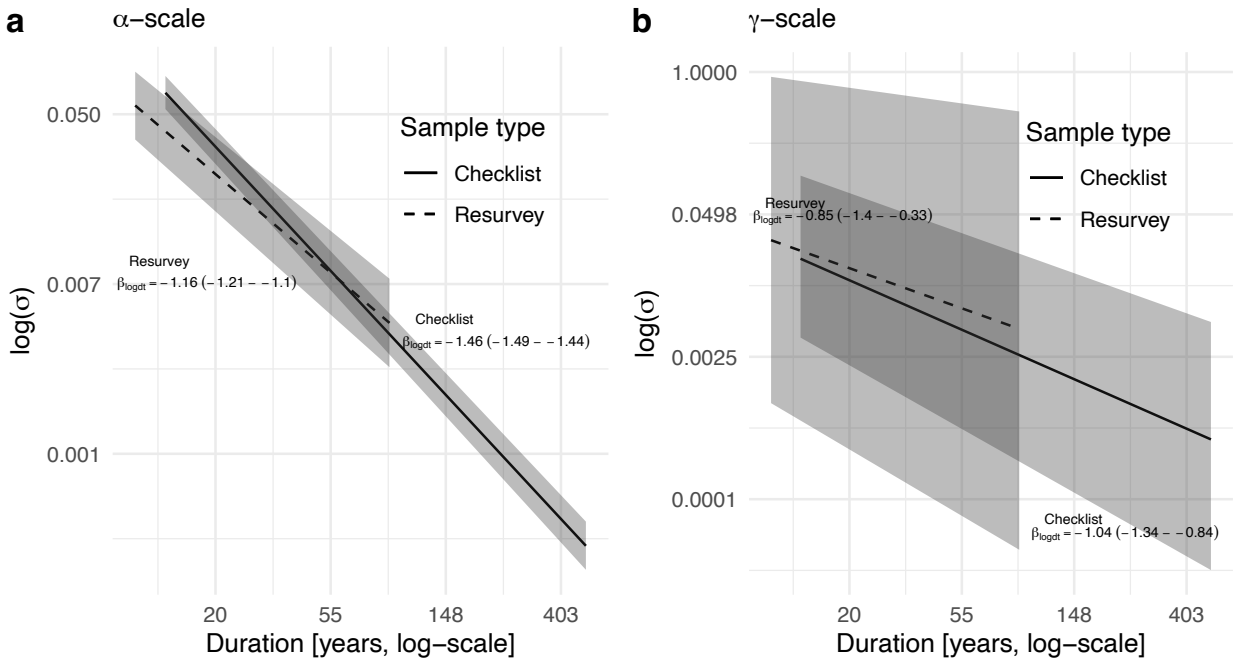

Figure S4: Scale-dependent residual variation as a function of temporal duration for the two sample types. *Models fit to the full data set adjusted for residual variation being a decreasing function of temporal duration for both types of samples (checklists and resurveys) at the (a) α- and (b) γ-scales.*

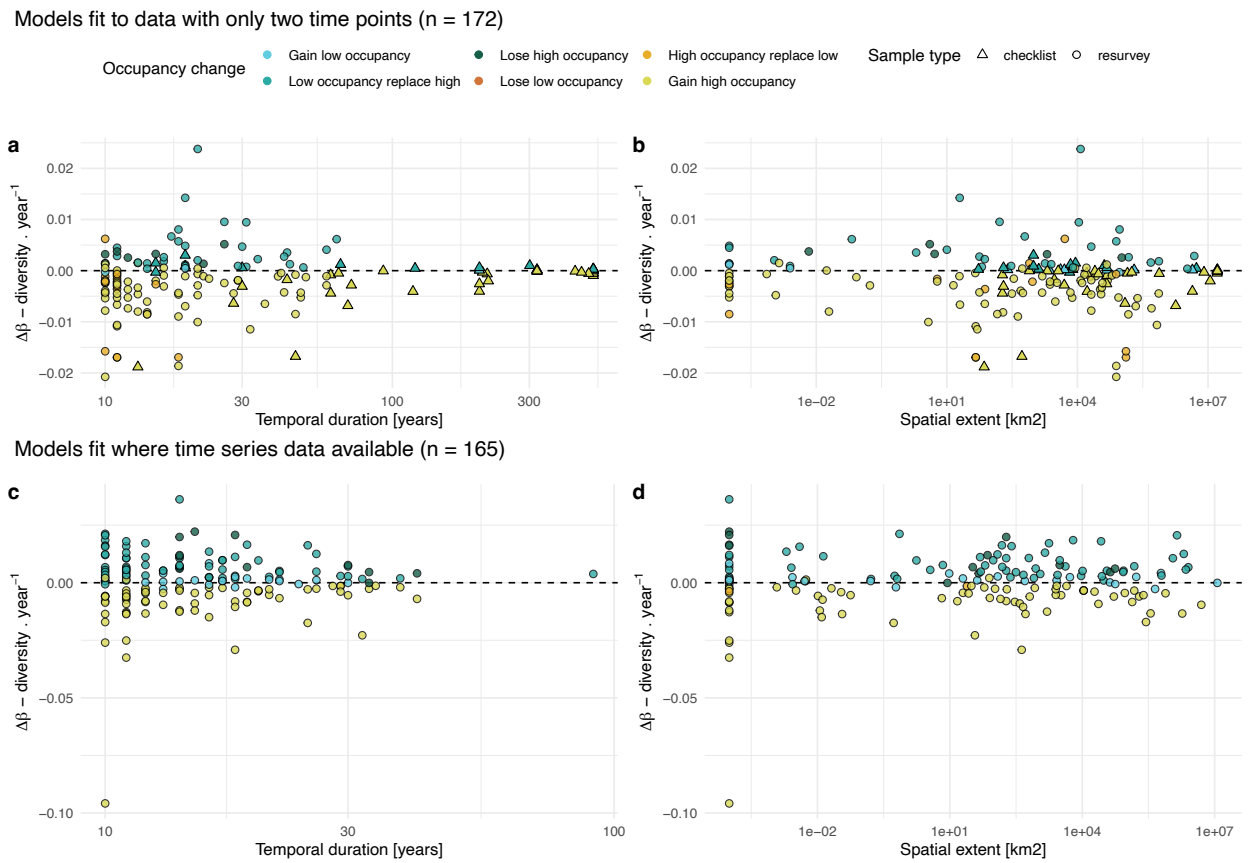

Figure S5: Biotic homogenization is strongly associated with data sets that had only two time points, and more common at intermediate to large temporal and spatial scales. *Changes in beta-diversity as a function of (a) temporal duration and (b) spatial extent estimated using models fit to data with only two time points available; and, changes in beta-diversity as a function of (c) temporal duration and (d) spatial extent estimated using models fit to data where time series were available. Each point shows Δβ for an individual dataset (region) calculated as the mean distance from the 1:1 line (< 0 = homogenization, > 0 = differentiation) of 1000 draws of each α- and γ-scale regional estimate (i.e., overall intercept plus regional random intercept). Both x-axes are on a logarithmic scale.*

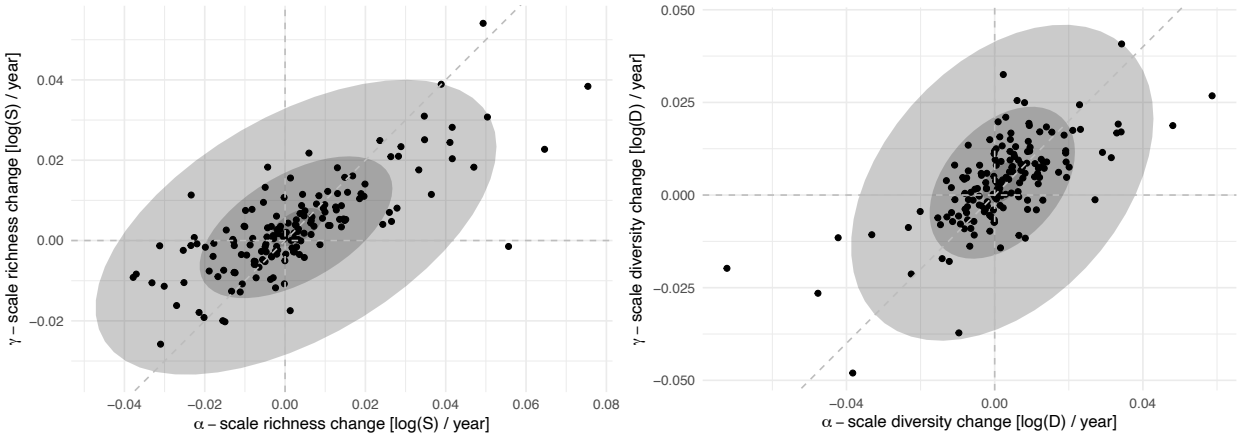

Figure S6: Scale-dependent variation in diversity change in the subset of datasets with species abundance time series. *Changes in α- and γ-scale diversity of (a) species richness, and (b) diversity (the inverse of Simpson's concentration (28), and more influenced by numerically abundant species). Shading on each panel shows the 50% and 90% quantiles of variation in the posterior distribution describing the varying rates of changes among the datasets from multi-level models fit to the α- and γ-scales separately. Each point represents a dataset (n = 165) and shows the median of the posterior of the γ-scale as a function of the α-scale. In (a), for richness, greater variation at the α-scale (relative to the γ-scale), shows how local species richness gains outpacing regional richness gains frequently results in homogenization, and richness losses (i.e., $\Delta\alpha$ and $\Delta\gamma < 0$) are more often associated with differentiation (i.e., $\Delta\gamma > \Delta\alpha$) than homogenization. Variation in α- and γ-scale changes are more balanced among the datasets for diversity (b). The greatest rates of species gains (q = 0) were found for datasets at the α-scale. In contrast, the greatest rates of diversity loss were found for datasets at the α-scale for q = 2.*