Supplementary of: Changes in Taxonomic and Phylogenetic Diversity in the Anthropocene

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This supplementary information file includes:

Phylogeny building process
Table S1 to S5
Figs. S1 to S9
Text S1

**Phylogenies**

For plants, we generated the phylogeny using Phylomatic v4.2 [1] based on the synthesis phylogeny zanne2014 [2], which was constructed and time-calibrated from seven gene regions for \(>32000\) plant species using maximum-likelihood. We chose this phylogeny because it is one of the most up-to-date phylogenies for plants.

For birds, because we had extinct birds in the historical data period [3], we used the 100 augmented phylogenies constructed by Baiser et al [4]. They augmented 100 randomly selected global bird phylogenies generated by Jetz et al [5] by inserting extinct birds into the phylogenies in a position from the stem branch preceding the most recent common ancestor of species from the same family. The branch length of the inserted species extended to the present time to make the augmented phylogenies ultrametric. We analyzed each dataset with all 100 augmented phylogenies and then used the average values as final measurements. Previous studies [4,6] suggested that 100 phylogenies were enough to get stable phylogenetic diversity values.

For fishes, we were unable to find a phylogeny built with gene sequences that was large enough to contain most of the species in our datasets. The most recent large fish phylogeny [7] had 11,638 species. However, only 6,115 out of 13,236 fishes in our datasets were included in this phylogeny. Therefore, we instead extracted a phylogeny for our fishes from the Open Tree of Life [8], which is a comprehensive phylogeny with \(~2.3\) million tips by synthesizing published phylogenies. However, the phylogeny extracted from the Open Tree of Life did not have branch lengths (i.e., not a chronogram), which is required for most phylogenetic diversity measures. To calculate branch length, for each of the 3,404 internal nodes, we first derived its descendants and then searched for their divergence time through the TimeTree of Life database [9]. The TimeTree database was
compiled based on 3,163 studies and 97,085 species (as of October 10, 2017). For each pair of species included in their database, we extracted their average divergence time from all previous studies. In the end, we extracted divergence time for 767 internal nodes. With the phylogeny from the Open Tree of Life and the divergence date of internal nodes from the TimeTree database, we then solved the branch length using Phylocom \cite{10} and its \texttt{b1adj} function. The \texttt{b1adj} algorithm placed estimated node ages onto the phylogeny. Ages of nodes without dates were then estimated by equally placing ages between nodes with dates to minimize variance in branch lengths.

These final phylogenies, however, still did not cover all species in our datasets. This was because there were taxa not identified to species level or species that were not included in the Open Tree of Life database. In the end, we had 31,131 out of 32,382 (96.14\%) plant species, 2,399 out of 2,903 (95.66\%) bird species, and 12,448 out of 13,236 (94.05\%) fish species in their corresponding phylogenies. Therefore, we calculated the proportion of species in the phylogeny for each dataset.

We removed datasets that had less than 80\% of their species covered in the phylogeny from any ‘time period’ (\texttt{dat}_1 and \texttt{dat}_2), resulting in 162 out of 189 datasets for final analyses (Supplementary Table S5). For these 162 datasets, we removed the small fraction of species that were not in the phylogeny prior to analyses.

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Table S1. Summary of LMM output for effect sizes of $\alpha$ and $\beta$ diversity for different taxonomic groups. Significant changes (i.e., 95% confidence interval does not include zero) are in bold. Abbreviations: SR, species richness; PD, Faith’s phylogenetic diversity (without root); PSV: phylogenetic species variation; Sorensen_tur, Turnover component of Sorensen dissimilarity; pSorensen_tur, Turnover component of Phylogenetic Sorensen dissimilarity; PCDp, phylogenetic component of phylogenetic community dissimilarity.

| index | Changes in diversity | Estimate | Std. Error | 2.5 % | 97.5 % | Random Terms |
|-------|----------------------|----------|------------|-------|--------|--------------|
| $\alpha$: Bird (54) | | | | | | |
| SR | 6.18 % | 0.060 | 0.061 | -0.059 | 0.179 | study; grain_size |
| PD | 3.37 % | 0.033 | 0.051 | -0.066 | 0.132 | study; grain_size |
| PSV | -2.08 % | -0.021 | 0.013 | -0.047 | 0.005 | study; grain_size |
| $\alpha$: Fish (55) | | | | | | |
| SR | 10.62 % | **0.101** | **0.049** | **0.005** | **0.197** | study |
| PD | 8.21 % | 0.079 | 0.037 | **0.007** | **0.151** | study |
| PSV | -0.11 % | -0.001 | 0.000 | -0.002 | 0.000 | study |
| $\alpha$: Plant (50) | | | | | | |
| SR | 4.69 % | 0.046 | 0.065 | -0.081 | 0.173 | study |
| PD | 2.84 % | 0.028 | 0.101 | -0.170 | 0.226 | study; data_type |
| PSV | -0.77 % | -0.008 | 0.003 | -0.014 | -0.002 | study |
| $\beta$: Bird (54) | | | | | | |
| Sorensen_tur | -4.58 % | -0.047 | 0.092 | -0.228 | 0.134 | study; data_type; driver |
| pSorensen_tur | -5.16 % | -0.053 | 0.063 | -0.177 | 0.071 | study; data_type; driver |
| PCDp | 1 % | 0.010 | 0.014 | -0.018 | 0.038 | study |
| $\beta$: Fish (55) | | | | | | |
| Sorensen_tur | -8.89 % | **-0.093** | **0.047** | **-0.185** | **-0.002** | study |
| pSorensen_tur | -2.43 % | -0.025 | 0.037 | -0.098 | 0.049 | study |
| PCDp | **0.6 %** | **0.006** | **0.001** | **0.004** | **0.008** | study |
| $\beta$: Plant (50) | | | | | | |
| Sorensen_tur | -6.37 % | -0.066 | 0.031 | -0.126 | -0.005 | study |
| pSorensen_tur | -5.47 % | -0.056 | 0.028 | -0.112 | -0.001 | study |
| PCDp | -0.44 % | -0.004 | 0.009 | -0.022 | 0.013 | study |
Table S2. Summary of LMM output for effect sizes of $\alpha$ and $\beta$ diversity for different sampling methods. Significant changes (i.e., 95% confidence interval does not include zero) are in bold. Abbreviations: SR, species richness; PD, Faith’s phylogenetic diversity (without root); PSV: phylogenetic species variation; Sorensen_tur, Turnover component of Sorensen dissimilarity; pSorensen_tur, Turnover component of Phylogenetic Sorensen dissimilarity; PCDp, phylogenetic component of phylogenetic community dissimilarity.

| index | Changes in diversity | Estimate | Std. Error | 2.5 % | 97.5 % | Random Terms |
|-------|----------------------|----------|------------|-------|--------|---------------|
| $\alpha$: Land Use Data (66); land use gradient approach | | | | | | |
| SR | -10.22 % | -0.108 | 0.052 | -0.209 | -0.007 | study |
| PD | -12.29 % | -0.131 | 0.041 | -0.212 | -0.050 | study |
| PSV | -3.31 % | -0.034 | 0.011 | -0.055 | -0.013 | study |
| $\alpha$: Land Use Data (66); landscape approach | | | | | | |
| SR | -1.04 % | -0.011 | 0.025 | -0.060 | 0.039 | study; taxa; driver |
| PD | -2.35 % | -0.024 | 0.024 | -0.070 | 0.023 | study; taxa; driver |
| PSV | -1.05 % | -0.011 | 0.003 | -0.017 | -0.004 | study; taxa; driver |
| $\alpha$: Resample Data (18) | | | | | | |
| SR | 17.09 % | 0.158 | 0.093 | -0.024 | 0.339 | study |
| PD | 15.18 % | 0.141 | 0.074 | -0.003 | 0.286 | study |
| PSV | 1.19 % | 0.012 | 0.012 | -0.012 | 0.036 | study |
| $\alpha$: Species List Data (78) | | | | | | |
| SR | 6.93 % | 0.067 | 0.016 | 0.036 | 0.098 | study |
| PD | 4.59 % | 0.045 | 0.010 | 0.025 | 0.064 | study |
| PSV | -0.25 % | -0.002 | 0.001 | -0.005 | 0.000 | study |
| $\beta$: Land Use Data (66); land use gradient approach | | | | | | |
| Sorensen_tur | -6.24 % | -0.064 | 0.095 | -0.251 | 0.122 | study; taxa; driver |
| pSorensen_tur | -5.56 % | -0.057 | 0.071 | -0.197 | 0.083 | study; taxa; driver |
| PCDp | 0.55 % | 0.005 | 0.006 | -0.006 | 0.017 | study; taxa; driver |
| $\beta$: Land Use Data (66); landscape approach | | | | | | |
| Sorensen_tur | 7.88 % | 0.076 | 0.035 | 0.008 | 0.144 | study; taxa; driver |
| pSorensen_tur | 5.88 % | 0.057 | 0.034 | -0.010 | 0.124 | study; driver |
| PCDp | 1.24 % | 0.012 | 0.012 | -0.012 | 0.037 | study |
| $\beta$: Species List Data (78) | | | | | | |
| Sorensen_tur | -4.17 % | -0.043 | 0.026 | -0.094 | 0.009 | study |
| pSorensen_tur | -0.09 % | -0.001 | 0.010 | -0.021 | 0.020 | study |
| PCDp | -0.08 % | -0.001 | 0.006 | -0.013 | 0.011 | study |
| $\beta$: Resample Data (18) | | | | | | |
| Sorensen_tur | -9.6 % | -0.101 | 0.046 | -0.191 | -0.011 | study |
| pSorensen_tur | -7.71 % | -0.080 | 0.032 | -0.144 | -0.017 | study |
| PCDp | -1.41 % | -0.014 | 0.010 | -0.034 | 0.006 | study |
Table S3. Summary of LMM output for effect sizes of $\alpha$ and $\beta$ diversity for different continents. Significant changes (i.e., 95% confidence interval does not include zero) are in bold. Abbreviations: SR, species richness; PD, Faith’s phylogenetic diversity (without root); PSV: phylogenetic species variation; Sorensen_tur, Turnover component of Sorensen dissimilarity; pSorensen_tur, Turnover component of Phylogenetic Sorensen dissimilarity; PCDp, phylogenetic component of phylogenetic community dissimilarity.

| index | Changes in diversity | Estimate | Std. Error | 2.5% | 97.5% | Random Terms |
|-------|----------------------|----------|------------|------|-------|--------------|
| $\alpha$: Africa (22) | | | | | | |
| SR | $-14.16\%$ | $-0.153$ | $0.100$ | $-0.349$ | $0.044$ | study |
| PD | $-11.48\%$ | $-0.122$ | $0.082$ | $-0.282$ | $0.038$ | study |
| PSV | $0.01\%$ | $0.000$ | $0.000$ | $-0.001$ | $0.001$ | study |
| $\alpha$: Asia (27) | | | | | | |
| SR | $4.38\%$ | $0.043$ | $0.006$ | $0.031$ | $0.055$ | study |
| PD | $3.16\%$ | $0.031$ | $0.005$ | $0.022$ | $0.040$ | study |
| PSV | $-0.12\%$ | $-0.001$ | $0.001$ | $-0.002$ | $0.000$ | study |
| $\alpha$: Europe (29) | | | | | | |
| SR | $6.45\%$ | $0.062$ | $0.010$ | $0.044$ | $0.081$ | study |
| PD | $3.5\%$ | $0.034$ | $0.005$ | $0.024$ | $0.044$ | study |
| PSV | $-0.49\%$ | $-0.005$ | $0.003$ | $-0.010$ | $0.000$ | study |
| $\alpha$: North America (33) | | | | | | |
| SR | $6.68\%$ | $0.083$ | $0.081$ | $-0.075$ | $0.241$ | study |
| PD | $3.17\%$ | $0.031$ | $0.066$ | $-0.098$ | $0.160$ | study |
| PSV | $-1.45\%$ | $-0.015$ | $0.010$ | $-0.034$ | $0.005$ | study |
| $\alpha$: Oceania (39) | | | | | | |
| SR | $6.5\%$ | $0.063$ | $0.021$ | $0.023$ | $0.103$ | study |
| PD | $4.78\%$ | $0.047$ | $0.010$ | $0.027$ | $0.067$ | study |
| PSV | $-2.46\%$ | $-0.025$ | $0.029$ | $-0.082$ | $0.032$ | study; grain_size; data_type; driver |
| $\alpha$: South America (12) | | | | | | |
| SR | $24.28\%$ | $0.217$ | $0.086$ | $0.048$ | $0.387$ | study |
| PD | $15.78\%$ | $0.147$ | $0.062$ | $0.025$ | $0.269$ | study |
| PSV | $0.14\%$ | $0.001$ | $0.002$ | $-0.002$ | $0.004$ | study |
| $\beta$: Africa (22) | | | | | | |
| Sorensen_tur | $-4.96\%$ | $-0.051$ | $0.046$ | $-0.142$ | $0.040$ | study |
| pSorensen_tur | $-8.09\%$ | $-0.084$ | $0.044$ | $-0.170$ | $0.002$ | study |
| PCDp | $-0.92\%$ | $-0.009$ | $0.015$ | $-0.039$ | $0.021$ | study |
| $\beta$: Asia (27) | | | | | | |
| Sorensen_tur | $-9.46\%$ | $-0.099$ | $0.053$ | $-0.203$ | $0.005$ | study |
| pSorensen_tur | $-5.2\%$ | $-0.053$ | $0.039$ | $-0.129$ | $0.022$ | study |
| PCDp | $-0.4\%$ | $-0.004$ | $0.009$ | $-0.021$ | $0.013$ | study |
| $\beta$: Europe (29) | | | | | | |
| Sorensen_tur | $-3.47\%$ | $-0.035$ | $0.056$ | $-0.146$ | $0.075$ | study; grain_size |
| pSorensen_tur | $1.62\%$ | $0.016$ | $0.004$ | $0.009$ | $0.023$ | study |
| PCDp | $-0.05\%$ | $0.000$ | $0.011$ | $-0.022$ | $0.021$ | study |
| $\beta$: North America (33) | | | | | | |
| Sorensen_tur | $-10.23\%$ | $-0.108$ | $0.045$ | $-0.197$ | $0.019$ | study |
| pSorensen_tur | $-6.43\%$ | $-0.066$ | $0.026$ | $-0.118$ | $0.015$ | study |
| PCDp | $1.14\%$ | $0.011$ | $0.012$ | $-0.012$ | $0.035$ | study |
| $\beta$: Oceania (39) | | | | | | |
| Sorensen_tur | $-0.54\%$ | $-0.005$ | $0.007$ | $-0.018$ | $0.008$ | study |
| pSorensen_tur | $2.22\%$ | $0.022$ | $0.046$ | $-0.069$ | $0.113$ | study |
| PCDp | $1.11\%$ | $0.011$ | $0.016$ | $-0.021$ | $0.043$ | study |
| $\beta$: South America (12) | | | | | | |
| Sorensen_tur | $-0.38\%$ | $-0.004$ | $0.004$ | $-0.012$ | $0.004$ | study |
| pSorensen_tur | $0.6\%$ | $0.006$ | $0.005$ | $-0.003$ | $0.015$ | study |
| PCDp | $2.79\%$ | $0.028$ | $0.024$ | $-0.075$ | $0.018$ | study |
Table S4. Changes in pairwise taxonomic $\beta$ diversity when measured with Sorensen dissimilarity or its nestedness component. Both measurements gave qualitatively similar results, albeit the smaller numbers from Sorensen dissimilarity.

| Groups                    | Sorensen | Turnover |
|---------------------------|----------|----------|
| Bird (54)                 | -2.73 %  | -4.58 %  |
| Fish (55)                 | -4.95 %  | -8.89 %  |
| Plant (53)                | -4.88 %  | -6.37 %  |
| Land Use Data (66)        | -4.74 %  | -6.24 %  |
| Species List Data (78)    | -1.65 %  | -4.17 %  |
| Resample Data (18)        | -6.37 %  | -9.6 %   |
**Table S5.** Sources and characteristics of datasets collected in the study. Detailed reference information see Text S1.

| Ref | location               | n_site | sp_in_phy_dat1 | sp_in_phy_dat2 | taxa      | spatial_extent | grain_size | data_type | driver          | decision        |
|-----|------------------------|--------|----------------|----------------|-----------|----------------|------------|-----------|-----------------|-----------------|
| 1   | united_states          | 93     | 0.639          | 0.979          | plant     | region         | small      | old_new   | ongoing disturbance |
| 2   | canada                 | 133    | 0.660          | 0.955          | plant     | region         | small      | old_new   | ongoing disturbance |
| 3   | united_states          | 3      | 0.662          | 0.938          | bird      | continent      | moderate   | land_use  | urbanization          |
| 4   | india                  | 3      | 0.776          | 0.718          | bird      | region         | small      | land_use  | urbanization          |
| 5   | archipelago_Antarctic  | 4      | 1.000          | 1.000          | bird      | continent      | high       | native_exotic | invasion         |
| 6   | archipelago_Azores     | 9      | 1.000          | 1.000          | bird      | region         | high       | native_exotic | invasion         |
| 7   | archipelago_CapeVerdes | 13     | 1.000          | 1.000          | bird      | region         | high       | native_exotic | invasion         |
| 8   | archipelago_Comoros    | 4      | 1.000          | 1.000          | bird      | region         | high       | native_exotic | invasion         |
| 9   | archipelago_CookIslands| 15     | 1.000          | 1.000          | bird      | region         | moderate   | native_exotic | invasion         |
| 10  | archipelago_Galapagos  | 11     | 1.000          | 1.000          | bird      | region         | high       | native_exotic | invasion         |
| 11  | archipelago_GreaterAntilles| 4     | 1.000          | 1.000          | bird      | region         | very_high  | native_exotic | invasion         |
| 12  | archipelago_Hawaii     | 6      | 1.000          | 1.000          | bird      | region         | very_high  | native_exotic | invasion         |
| 13  | archipelago_LesserAntilles| 12    | 1.000          | 1.000          | bird      | region         | high       | native_exotic | invasion         |
| 14  | archipelago_Marianas   | 15     | 1.000          | 1.000          | bird      | region         | moderate   | native_exotic | invasion         |
| 15  | archipelago_NewZealand | 10     | 1.000          | 1.000          | bird      | region         | moderate   | native_exotic | invasion         |
| 16  | archipelago_Pitcairns  | 4      | 1.000          | 1.000          | bird      | region         | moderate   | native_exotic | invasion         |
| 17  | archipelago_SocietyIslands| 11    | 1.000          | 1.000          | bird      | region         | moderate   | native_exotic | invasion         |
| 18  | world_ocean            | 152    | 1.000          | 1.000          | bird      | continent      | very_high  | native_exotic | invasion         |
| 19  | ocean_Atlantic         | 45     | 1.000          | 1.000          | bird      | region         | moderate   | native_exotic | invasion         |
| 20  | ocean_Caribbean        | 21     | 1.000          | 1.000          | bird      | continent      | high       | native_exotic | invasion         |
| 21  | ocean_Indian           | 11     | 1.000          | 1.000          | bird      | continent      | high       | native_exotic | invasion         |
| 22  | ocean_Pacific          | 75     | 1.000          | 1.000          | bird      | continent      | moderate   | native_exotic | invasion         |
| 23  | iberian_peninsula      | 10     | 0.919          | 0.817          | fish      | region         | very_high  | native_exotic | invasion         |
| 24  | solomon_islands        | 16     | 0.820          | 0.941          | plant     | region         | small      | land_use  | grazing          |
| 25  | solomon_islands        | 16     | 0.820          | 0.917          | plant     | region         | small      | land_use  | management       |
| 26  | italy                  | 9      | 0.240          | 0.250          | plant     | region         | small      | land_use  | urbanization     |
| 27  | uganda                 | 35     | 0.907          | 0.980          | bird      | region         | small      | land_use  | agriculture       |
| 28  | papua_new_guinea       | 6      | 0.934          | 0.940          | bird      | region         | small      | land_use  | agriculture       |
| 29  | south_africa           | 24     | 0.938          | 0.979          | bird      | region         | small      | land_use  | agriculture       |
| 30  | costa_rica             | 8      | 0.902          | 0.975          | bird      | region         | small      | land_use  | management       |
| 31  | malaysia               | 20     | 0.929          | 0.964          | bird      | region         | small      | land_use  | agriculture       |
| 32  | malaysia               | 20     | 0.929          | 0.970          | bird      | region         | small      | land_use  | management       |
| 33  | sao_tome_and_principe  | 40     | 0.941          | 0.949          | bird      | region         | small      | land_use  | agriculture       |
| 34  | sao_tome_and_principe  | 40     | 0.941          | 0.926          | bird      | region         | small      | land_use  | management       |
| 35  | sao_tome_and_principe  | 40     | 1.000          | 1.000          | plant     | region         | small      | land_use  | agriculture       |
| 36  | sao_tome_and_principe  | 40     | 1.000          | 1.000          | plant     | region         | small      | land_use  | management       |
| 37  | china                  | 15     | 0.864          | 0.835          | fish      | region         | moderate   | native_exotic | invasion         |
| 38  | australia              | 95     | 0.964          | 1.000          | bird      | region         | small      | land_use  | grazing          |
| 39  | portugal               | 9      | 1.000          | 1.000          | plant     | region         | small      | land_use  | management       |
| 40  | philippines            | 8      | 0.951          | 0.938          | bird      | region         | small      | land_use  | agriculture       |
| 41  | sao_tome_and_principe  | 6      | 0.955          | 0.889          | bird      | region         | small      | land_use  | management       |
| 42  | south_africa           | 56     | 0.990          | 1.000          | plant     | region         | small      | land_use  | agriculture       |
| Region          | Value | Similarity | Land Use | Area | Management       |
|-----------------|-------|------------|----------|------|------------------|
| South Africa    | 0.990 | 0.983      | Grazing  | Small| Land Use         |
| South Africa    | 0.990 | 0.990      | Urbanization | Small| Land Use         |
| France          | 0.881 | 0.881      | Urbanization | Moderate| Land Use         |
| Costa Rica      | 0.981 | 1.000      | Agriculture | Small| Land Use         |
| Costa Rica      | 0.980 | 0.977      | Agriculture | Small| Land Use         |
| Burkina Faso    | 0.975 | 0.993      | Agriculture | Small| Land Use         |
| Germany         | 1.000 | 1.000      | Old New | Management | Land Use         |
| Germany         | 0.977 | 0.977      | Old New | Management | Land Use         |
| United States   | 0.825 | 0.773      | Very High| Native Exotic| Invasion | Excluded |
| Mexico          | 0.850 | 0.829      | Management | Land Use | Land Use         |
| Indonesia       | 0.976 | 0.988      | Management | Land Use | Land Use         |
| Costa Rica      | 0.963 | 1.000      | Agriculture | Small| Land Use         |
| Panama          | 0.963 | 1.000      | Agriculture | Small| Land Use         |
| Costa Rica      | 0.963 | 0.984      | Grazing   | Small| Land Use         |
| Panama          | 0.963 | 0.984      | Grazing   | Small| Land Use         |
| Costa Rica      | 0.963 | 0.988      | Management | Land Use | Land Use         |
| Panama          | 0.963 | 0.988      | Management | Land Use | Land Use         |
| Kenya           | 0.887 | 0.901      | Management | Land Use | Land Use         |
| Costa Rica      | 0.982 | 0.976      | Grazing   | Small| Land Use         |
| India           | 0.964 | 0.944      | Management | Land Use | Land Use         |
| Ethiopia        | 0.918 | 0.943      | Management | Land Use | Land Use         |
| Ethiopia        | 0.973 | 1.000      | Management | Land Use | Land Use         |
| Ethiopia        | 0.900 | 0.020      | Management | Land Use | Land Use         |
| Ethiopia        | 0.552 | 0.633      | Management | Land Use | Land Use         |
| Indonesia       | 0.731 | 0.855      | Management | Land Use | Land Use         |
| Indonesia       | 0.938 | 0.943      | Management | Land Use | Land Use         |
| Ethiopia        | 1.000 | 0.989      | Management | Land Use | Land Use         |
| Ethiopia        | 0.778 | 0.887      | Management | Land Use | Land Use         |
| Ethiopia        | 0.762 | 0.722      | Management | Land Use | Land Use         |
| United States   | 0.989 | 0.984      | Agriculture | Land Use | Land Use         |
| United States   | 0.989 | 0.980      | Grazing   | Small| Land Use         |
| United States   | 0.989 | 0.966      | Management | Land Use | Land Use         |
| United States   | 0.989 | 0.983      | Urbanization | Land Use | Land Use         |
| Argentina       | 1.000 | 1.000      | Management | Land Use | Land Use         |
| Australia       | 1.000 | 1.000      | Management | Land Use | Land Use         |
| United Kingdom  | 0.990 | 0.991      | Ongoing Disturbance | Old New| Land Use         |
| Germany         | 0.990 | 0.990      | Urbanization | Land Use | Land Use         |
| Germany         | 0.989 | 0.990      | Urbanization | Land Use | Land Use         |
| United States   | 1.000 | 0.987      | Management | Land Use | Land Use         |
| China           | 0.921 | 0.906      | Native Exotic| Invasion | Native Exotic| Invasion |
| Brazil          | 0.994 | 0.988      | Post Disturbance | Old New| Land Use         |
| North Atlantic  | 0.885 | 0.866      | Climate Change | Old New| Land Use         |
| United States   | 0.820 | 0.810      | Native Exotic| Invasion | Native Exotic| Invasion |
| United States   | 0.820 | 0.810      | Native Exotic| Invasion | Native Exotic| Invasion |
| United States   | 0.784 | 0.797      | Native Exotic| Invasion | Native Exotic| Invasion |
| United States   | 0.731 | 0.740      | Native Exotic| Invasion | Native Exotic| Invasion |
| Country            | Continent | Region | Land Use | Management | Native Exotic | Invasion | Excluded |
|--------------------|-----------|--------|----------|------------|---------------|----------|----------|
| United States      | North America | Moderate | Native Exotic | Invasion | Excluded |
| Canada             | North America | Small | Old/New | Ongoing Disturbance | |
| Ghana              | Africa | Small | Land Use | Management | |
| Kenya              | Africa | Small | Land Use | Management | |
| Australia          | Oceania | Very High | Native Exotic | Invasion | Excluded |
| Spain              | Europe | Moderate | Native Exotic | Invasion | |
| France             | Europe | Small | Land Use | Urbanization | |
| United States      | North America | Small | Land Use | Management | |
| Argentina          | South America | Small | Land Use | Grazing | |
| Greece             | Europe | Small | Land Use | Agriculture | |
| North America      | North America | Moderate | Old/New | Ongoing Disturbance | |
| United States      | North America | High | Native Exotic | Invasion | |
| Indonesia          | Southeast Asia | Small | Land Use | Agriculture | |
| Indonesia          | Southeast Asia | Small | Land Use | Management | |
| South Africa       | Africa | Small | Land Use | Grazing | |
| Spain              | Europe | Small | Land Use | Grazing | Excluded |
| France             | Europe | Small | Land Use | Grazing | Excluded |
| Philippines        | Asia | Small | Land Use | Agriculture | |
| Egypt              | Africa | Small | Land Use | Management | |
| Egypt              | Africa | Small | Land Use | Urbanization | |
| Argentina          | South America | Small | Land Use | Grazing | |
| Argentina          | South America | Small | Land Use | Grazing | |
| United Kingdom     | Europe | Moderate | Old/New | Ongoing Disturbance | |
| Afghanistan        | Asia | High | Native Exotic | Invasion | Excluded |
| Argentina          | South America | High | Native Exotic | Invasion | |
| Australia          | Oceania | High | Native Exotic | Invasion | |
| Country              | Score | Probability | Region | High | Native Exotic | Invasion |
|----------------------|-------|-------------|--------|------|---------------|----------|
| Belgium              | 3     | 0.875       | Fish   | High | Native Exotic | Invasion |
| Brazil               | 92    | 0.963       | Fish   | High | Native Exotic | Invasion |
| Bulgaria             | 4     | 0.915       | Fish   | High | Native Exotic | Invasion |
| Canada               | 80    | 0.900       | Continent | High | Native Exotic | Invasion |
| Chile                | 21    | 0.985       | Fish   | High | Native Exotic | Invasion |
| China                | 72    | 0.933       | Fish   | High | Native Exotic | Invasion |
| Colombia             | 9     | 0.962       | Fish   | High | Native Exotic | Invasion |
| Congo                | 3     | 0.985       | Fish   | High | Native Exotic | Invasion |
| Denmark              | 4     | 0.862       | Fish   | High | Native Exotic | Invasion |
| Finland              | 6     | 0.857       | Fish   | High | Native Exotic | Invasion |
| France               | 50    | 0.868       | Fish   | High | Native Exotic | Invasion |
| French Polynesia     | 17    | 1.000       | Fish   | High | Native Exotic | Invasion |
| Germany              | 4     | 0.887       | Fish   | High | Native Exotic | Invasion |
| Greece               | 18    | 0.966       | Fish   | High | Native Exotic | Invasion |
| India                | 44    | 0.951       | Fish   | Continent | High | Native Exotic | Invasion |
| Indonesia            | 72    | 0.924       | Fish   | High | Native Exotic | Invasion |
| Iran                 | 42    | 0.897       | Fish   | High | Native Exotic | Invasion |
| Ireland              | 4     | 0.857       | Fish   | High | Native Exotic | Invasion |
| Italy                | 43    | 0.938       | Fish   | High | Native Exotic | Invasion |
| Japan                | 138   | 0.931       | Fish   | High | Native Exotic | Invasion |
| Kenya                | 8     | 0.972       | Fish   | High | Native Exotic | Invasion |
| Madagascar           | 11    | 0.938       | Fish   | High | Native Exotic | Invasion |
| Malaysia             | 61    | 0.954       | Fish   | High | Native Exotic | Invasion |
| Martinique           | 5     | 0.929       | Fish   | High | Native Exotic | Invasion |
| Mexico               | 83    | 0.944       | Fish   | High | Native Exotic | Invasion |
| Morocco              | 12    | 0.923       | Fish   | High | Native Exotic | Invasion |
| New Caledonia        | 11    | 0.969       | Fish   | High | Native Exotic | Invasion |
| New Zealand          | 195   | 1.000       | Fish   | High | Native Exotic | Invasion |
| Norway               | 8     | 0.905       | Fish   | High | Native Exotic | Invasion |
| Panama               | 18    | 0.950       | Fish   | High | Native Exotic | Invasion |
| Papua New Guinea     | 26    | 0.853       | Fish   | High | Native Exotic | Invasion |
| Philippines          | 6     | 0.892       | Fish   | High | Native Exotic | Invasion |
| Poland               | 4     | 0.889       | Fish   | High | Native Exotic | Invasion |
| Portugal             | 9     | 0.848       | Fish   | High | Native Exotic | Invasion |
| Russia               | 104   | 0.926       | Fish   | Continent | High | Native Exotic | Invasion |
| South Africa         | 53    | 0.953       | Fish   | High | Native Exotic | Invasion |
| South Korea          | 195   | 0.922       | Fish   | High | Native Exotic | Invasion |
| Spain                | 22    | 0.789       | Fish   | High | Native Exotic | Invasion |
| Sri Lanka            | 91    | 0.956       | Fish   | High | Native Exotic | Invasion |
| Sweden               | 22    | 0.886       | Fish   | High | Native Exotic | Invasion |
| Tanzania             | 13    | 0.979       | Fish   | High | Native Exotic | Invasion |
| Thailand             | 19    | 0.948       | Fish   | High | Native Exotic | Invasion |
| Tunisia              | 13    | 0.923       | Fish   | High | Native Exotic | Invasion |
| Turkey               | 46    | 0.933       | Fish   | High | Native Exotic | Invasion |
| United Kingdom       | 43    | 0.892       | Fish   | High | Native Exotic | Invasion |
| United States        | 193   | 0.959       | Fish   | Continent | High | Native Exotic | Invasion |
| Venezuela            | 17    | 0.943       | Fish   | High | Native Exotic | Invasion |
|   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|
| 74 | vietnam | 25 | 0.927 | 0.922 | fish | region | high | native_exotic | invasion |
| 75 | ecuador | 49 | 0.961 | 0.958 | bird | region | small | land_use | agriculture |
| 76 | south_africa | 13 | 0.866 | 0.820 | bird | region | small | land_use | urbanization |
| 77 | north_america | 60 | 0.974 | 0.977 | plant | continent | very_high | native_exotic | invasion |
| 77 | eu | 30 | 0.990 | 0.990 | plant | continent | very_high | native_exotic | invasion |
Figure S1. Sampling methods, grain sizes, and continents of datasets for the three taxonomic groups we collected. a: 54 out of 55 fish datasets were native-non-native ones; the majority of resurvey studies were about plants. b: none of the fish datasets had small grain size locales; the majority of bird and plant datasets were at small scale.
Figure S2. Partition of Sorensen dissimilarity into nestedness and turnover. Sorensen is a measure of pairwise dissimilarity of species (taxonomic) composition of assemblages.
Figure S3. Changes in taxonomic diversity vs. changes in phylogenetic diversity across all datasets. A: changes in $\alpha$ diversity. B: changes in $\beta$ diversity. Positive effect size suggests increases in site dissimilarity while negative effect size suggests decreases in site dissimilarity. Therefore, the grey area indicates both species homogenization and phylogenetic homogenization. Note that effect sizes of PSV and PCDp are independent from the effect sizes of species richness and Sorensen dissimilarity, respectively. This is not the case for $pd_{unroot}$ (Faith’s PD without root) and $psor\_turnover$ (turnover part of PhyloSor). Consequently, to examine patterns of “pure” phylogenetic diversity, metrics that are independent with species diversity should be used.
**Figure S4.** Changes in taxonomic and phylogenetic diversity of datasets from different continents.
Figure S5. Histogram of log ratio effect size.
Figure S6. The average number (a) and average proportion of site occupation (b) of species that were lost and gained within datasets of different taxonomic groups. Each colored dot represents the average value of a dataset while each black dot represents mean values across all datasets. Values from the same dataset were connected with lines. Plant and fish on average have more gained species than lost ones, resulting in higher alpha diversity; gained species also occupied more sites than lost species, resulting in lower beta diversity. Note that the values in this figure were observed ones while statistics in Fig. 2 were based on weighted linear mixed models, therefore, their patterns were not exactly the same.
**Figure S7.** The average number (a) and average proportion of site occupation (b) of species that were lost and gained within datasets of different data types. Each colored dot represents the average value of a dataset while each black dot represents mean values across all datasets. Values from the same dataset were connected with lines. Datasets from Resample Data and Species List Data on average have more gained species than lost ones, resulting in higher alpha diversity; gained species also occupied more sites than lost species, resulting in lower beta diversity. Note that the values in this figure were observed ones while statistics in Fig. 3 were based on weighted linear mixed models, therefore, their patterns were not exactly the same.
Figure S8. Site level changes in mean pairwise phylogenetic distances between gained/lost species and species that maintained of different taxonomic groups. Each colored dot represents the average value of a dataset while each black dot represents mean values across all datasets. MPDs: mean pairwise phylogenetic distance among shared species in both ‘time periods’; MPDsl: mean pairwise phylogenetic distance between shared species and lost species.; MPDsg: mean pairwise phylogenetic distance between shared species and gained species. To account for differences of MPDs among datasets, we compared MPDsl − MPDs and MPDsg − MPDs for each dataset. For Species List Data, we set MPDsg − MPDs to NA (not available) for datasets did not have any lost species; and we only connected datasets that have lost and gained species with lines.
Figure S9. Site level changes in mean pairwise phylogenetic distances between gained/lost species and species that maintained of different data types. Each colored dot represents the average value of a dataset while each black dot represents mean values across all datasets. MPDs: mean pairwise phylogenetic distance among shared species in both ‘time periods’; MPDsl: mean pairwise phylogenetic distance between shared species and lost species.; MPDsg: mean pairwise phylogenetic distance between shared species and gained species. To account for differences of MPDs among datasets, we compared MPDsl - MPDs and MPDsg - MPDs for each dataset. For Species List Data, we set MPDsg - MPDs to NA (not available) for datasets without any lost species; and we only connected datasets that have lost and gained species with lines.
Text S1: References for original studies used in this study. Numbers correspond to the “Ref” column in Supplementary Table S5.

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