Supplementary Materials

Loss of morphologically unique avian frugivores diminishes seed dispersal function and natural restoration potential pan-tropically

Jun Ying Lim[1,2,*], Wei Qiang Lee[1,2], Charles J. Marsh[1,2], Rachakonda Sreekar[3], Joseph A. Tobias[4], Iago Ferreiro Arias[5,6], David P. Edwards[7,8]

[1] Department of Biological Sciences, National University of Singapore, Singapore

[2] Center for Nature-based Climate Solutions, National University of Singapore, Singapore

[3] Centre for Biodiversity and Conservation Science, School of the Environment, University of Queensland, Queensland, Australia

[4] Department of Life Sciences, Imperial College London, Ascot, United Kingdom

[5] Department of Conservation Biology and Global Change, Estación Biológica de Doñana, CSIC, Sevilla, Spain

[6] Department of Biogeography and Global Change, Museo Nacional de Ciencias Naturales, CSIC, Madrid, Spain

[7] Department of Plant Sciences and Centre for Global Wood Security, University of Cambridge, Cambridge, UK

[8] Conservation Research Institute, University of Cambridge, Cambridge, UK

* corresponding author

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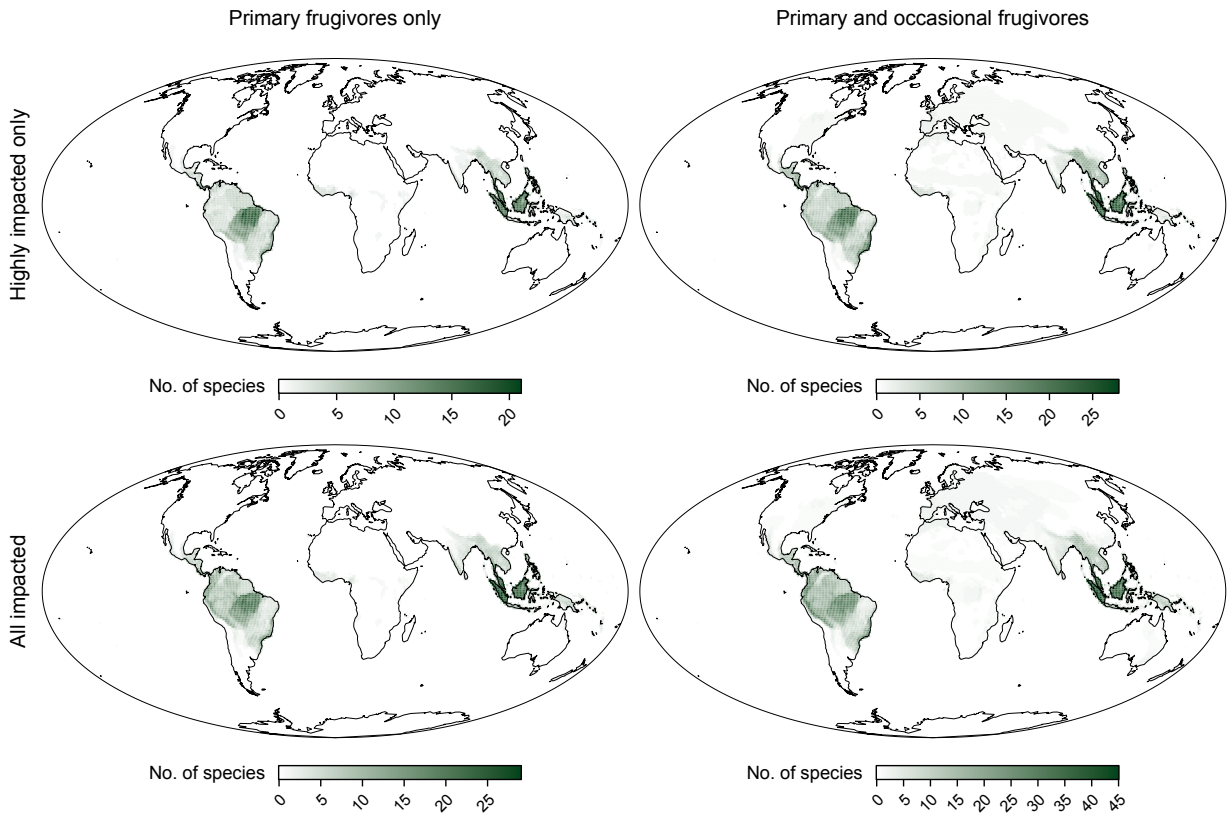
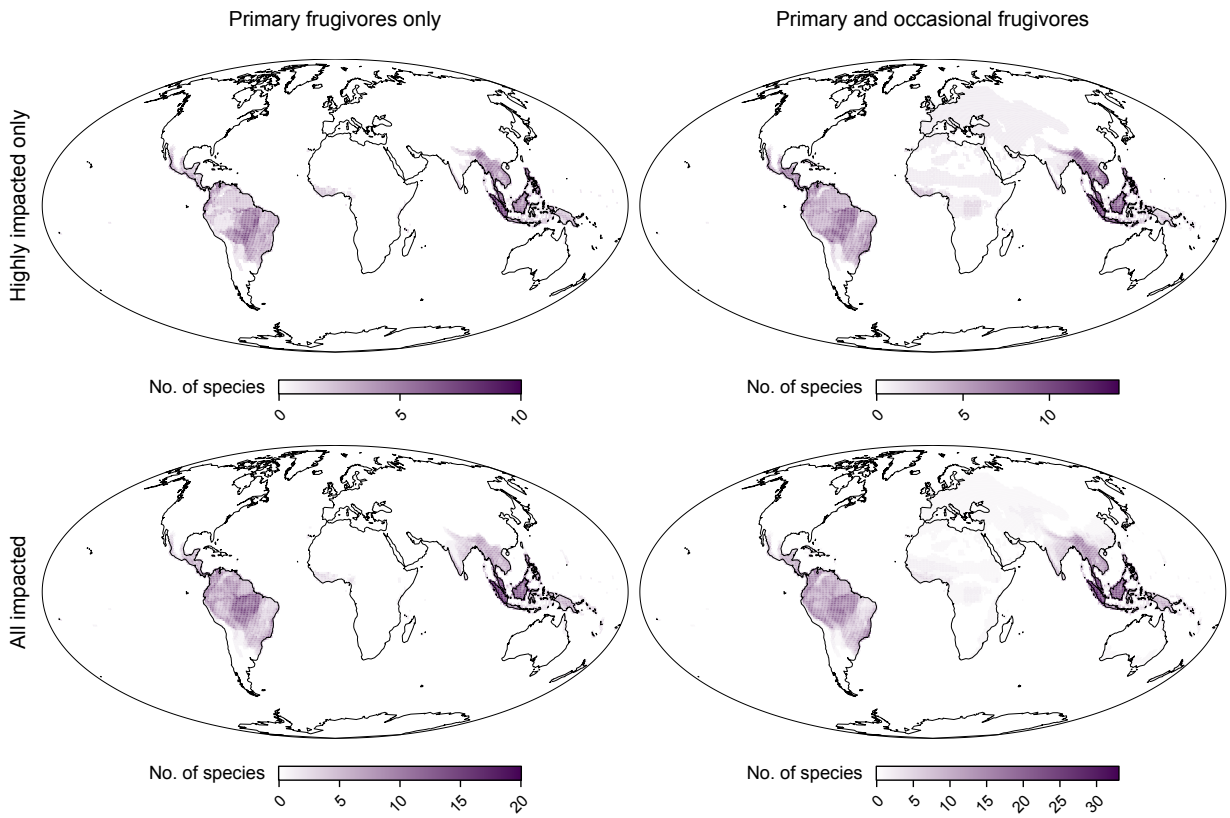
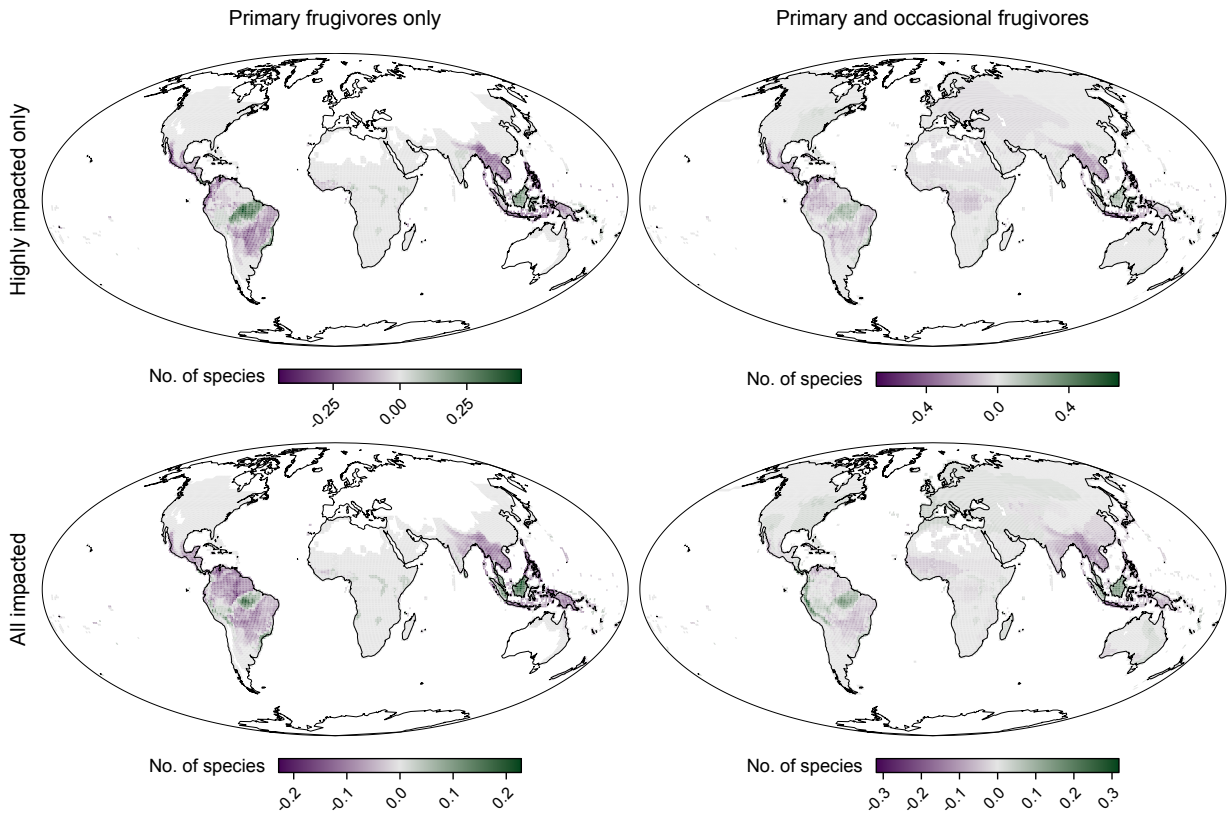
Supplementary Figures



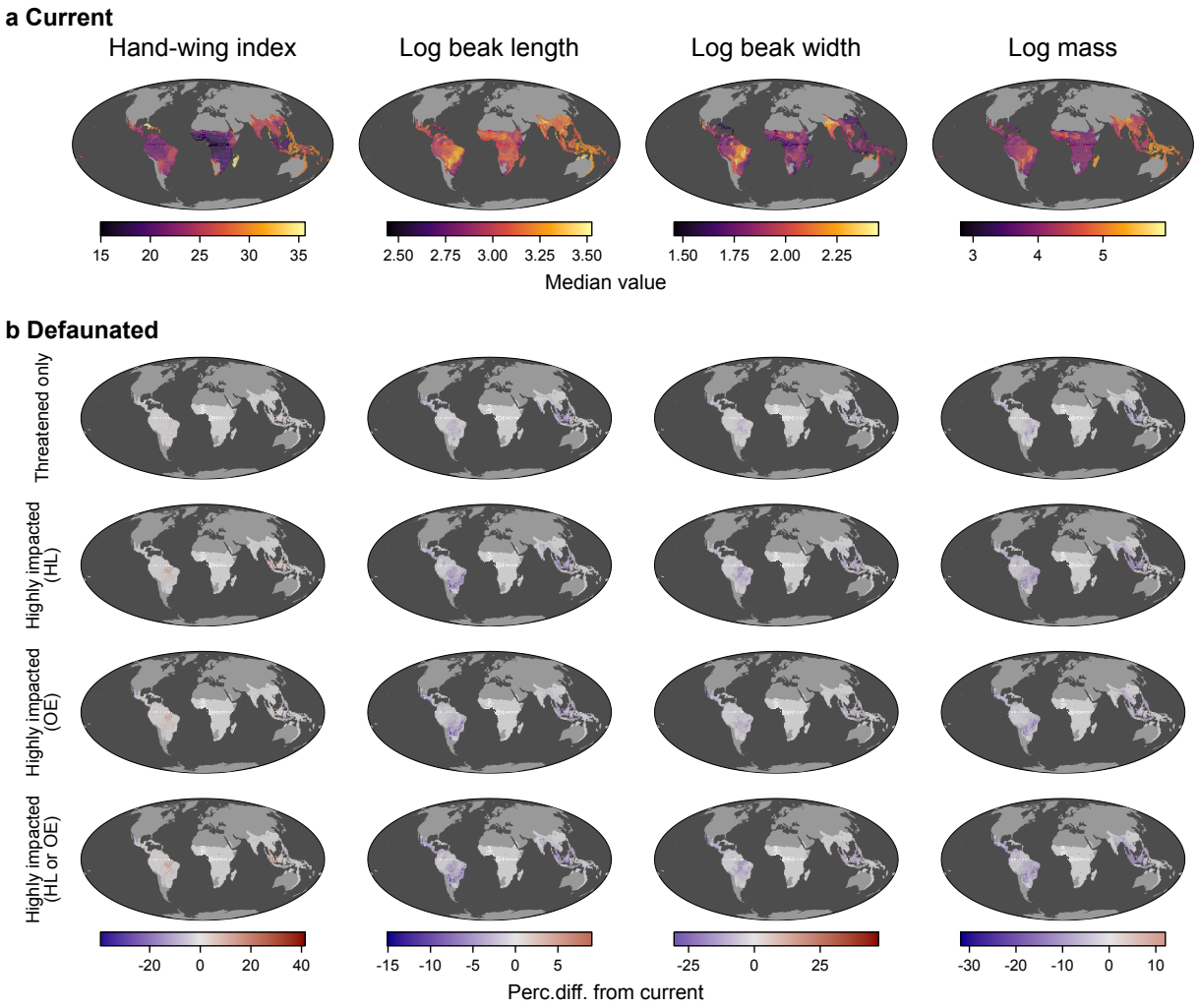
Supplementary Figure 1 | Distribution of frugivorous birds impacted by habitat loss and degradation (HL). Species richness maps were generated by overlaying the extant, native and full (resident and seasonal) geographic ranges of species (see Methods). Frugivores were categorised as either primary ($\geq$ 60% fruit in diet; n = 1,188 species) or occasional (30–60 % fruit in diet; n = 1,275 species). IUCN threat scores were used to define species as either impacted (any threat score, or where the threat score was unknown) or as highly impacted species (threat scores $\geq$ 6). Map in Molleweide projection, 100 x 100 km grid cells. White areas do not have any species meeting the frugivory criteria.



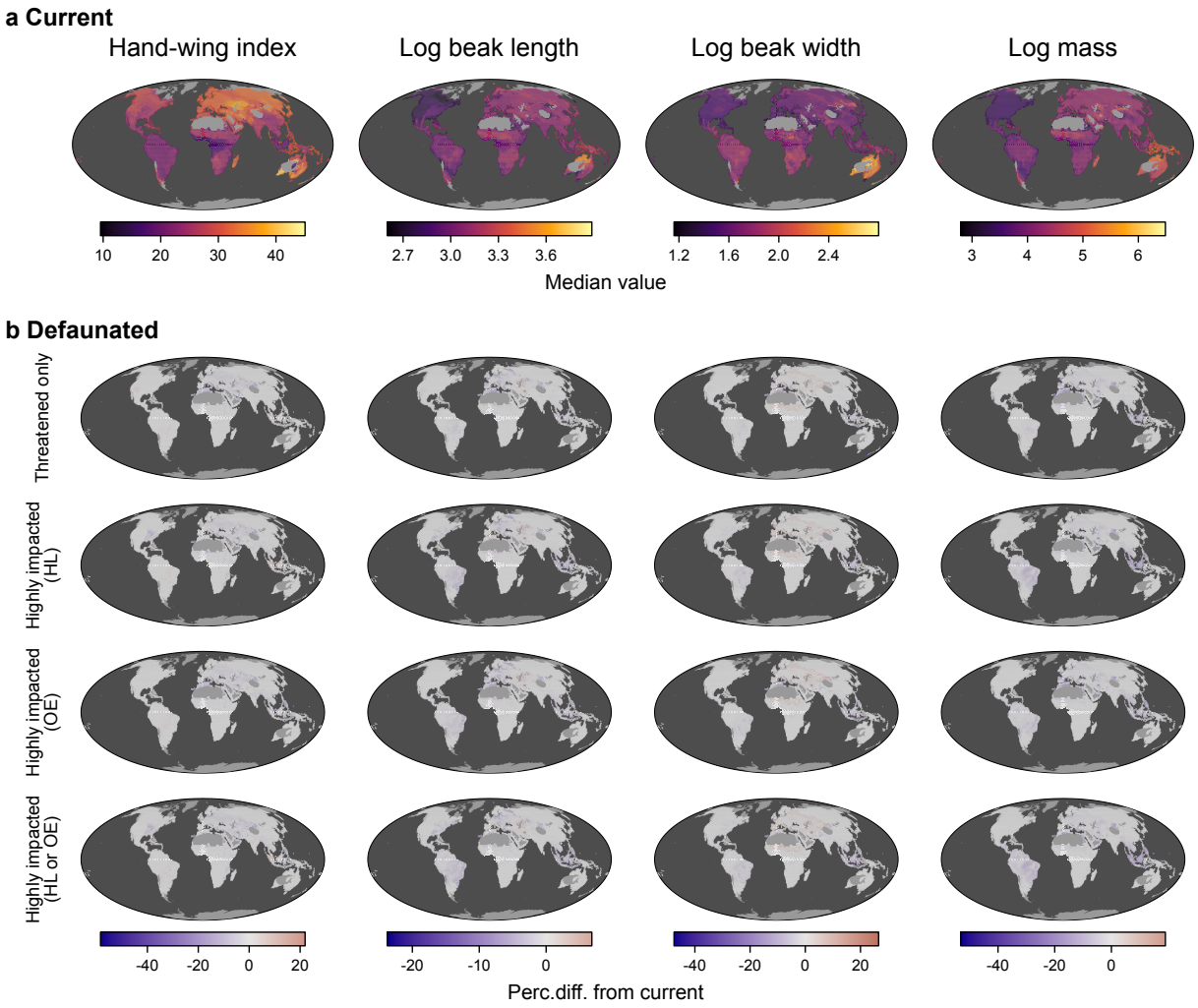
Supplementary Figure 2 | Distribution of frugivorous birds impacted by overexploitation (OE). Species richness maps were generated by overlaying the extant, native and full (resident and seasonal) geographic ranges of species (see Methods). Frugivores were categorised as either primary ($\geq$ 60% fruit in diet; n = 1,188 species) or occasional (30–60 % fruit in diet; n = 1,275 species). IUCN threat scores were used to define species as either impacted (any threat score, or where the threat score was unknown) or as highly impacted species (threat scores $\geq$ 6). Map in Molleweide projection, 100 x 100 km grid cells. White areas do not have any species meeting the frugivory criteria.



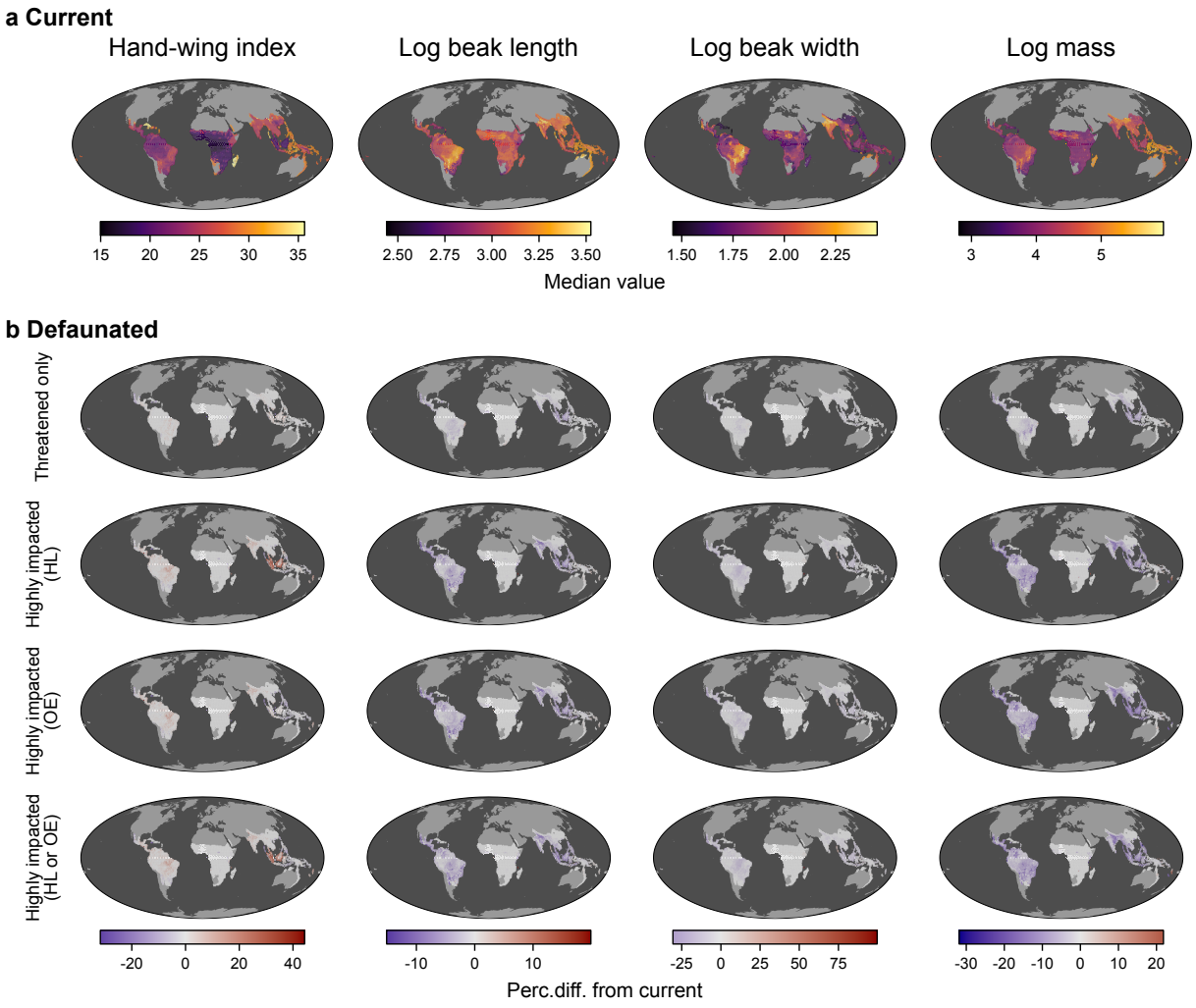
Supplementary Figure 3 | Relative species richness difference between frugivorous birds impacted by habitat loss and degradation and those affected by overexploitation. Species richness maps were generated by overlaying the extant, native and full (resident and seasonal) geographic ranges of species (see Methods). Frugivores were categorised as either primary ($\geq$ 60% fruit in diet; n = 1,188 species) or occasional (30–60 % fruit in diet; n = 1,275 species). IUCN threat scores were used to define species as either impacted (any threat score, or where the threat score was unknown) or as highly impacted species (threat scores $\geq$ 6). The relative difference between the two threat types was calculated as the number of species proportional to the cell with the maximum number of species for each threat type. Green areas have relatively more species impacted by habitat loss than by overexploitation, and vice versa for purple areas. Map in Molleweide projection, 100 x 100 km grid cells. White areas do not have any species meeting the frugivory criteria.



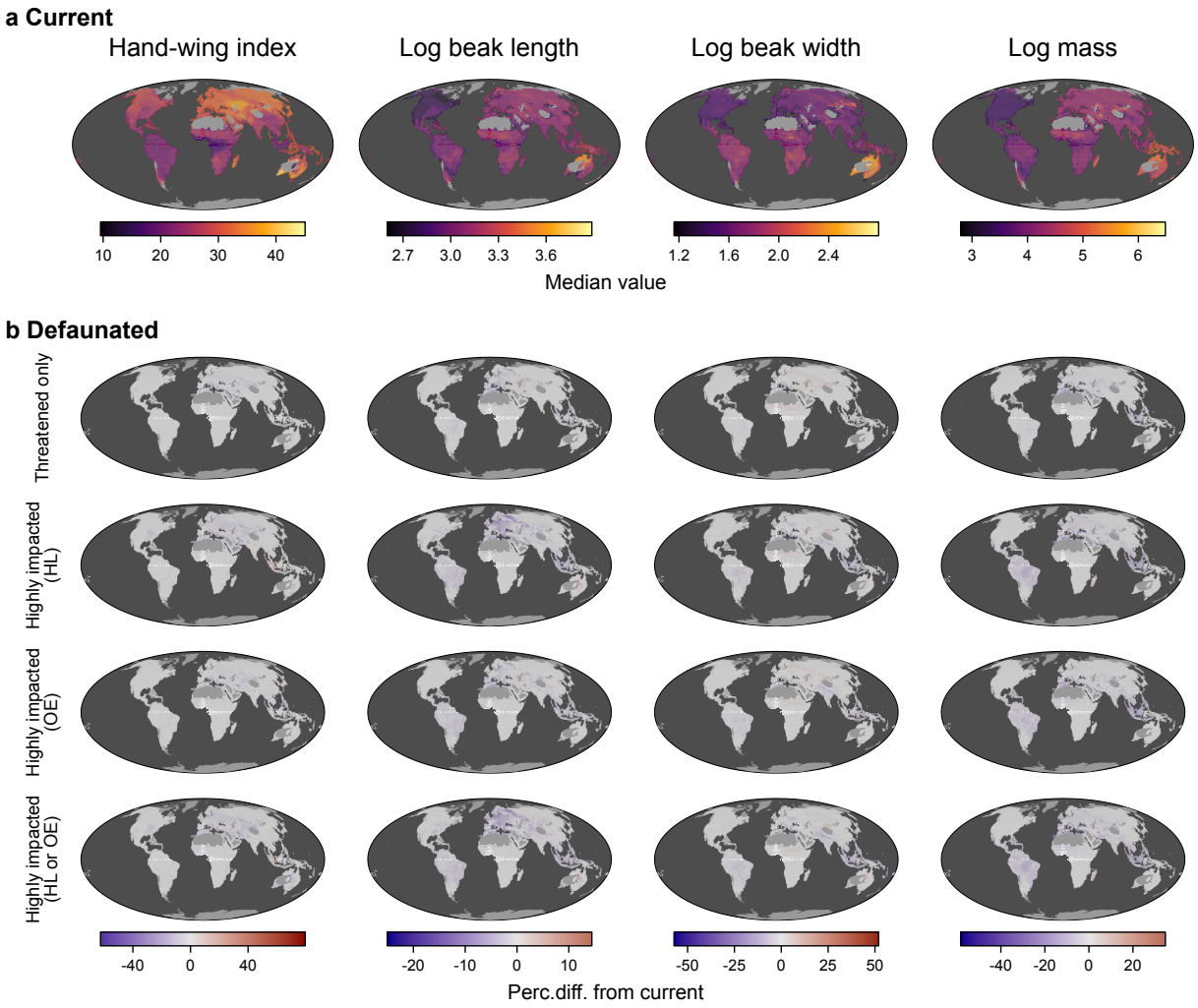
Supplementary Figure 4 | Trait values of primary frugivore assemblages after defaunation of threatened or highly impacted primary avian frugivore species. a) Median trait value of primary frugivore (diet consists of $\geq 60\%$ fruit, $n = 1{,}188$ species) assemblages under current conditions. b) Percentage change in median trait values after removal of species considered threatened by IUCN (threatened only), and species considered highly impacted (threat score ≥ 6) by habitat loss (HL), overexploitation (OE) or either (HL or OE).



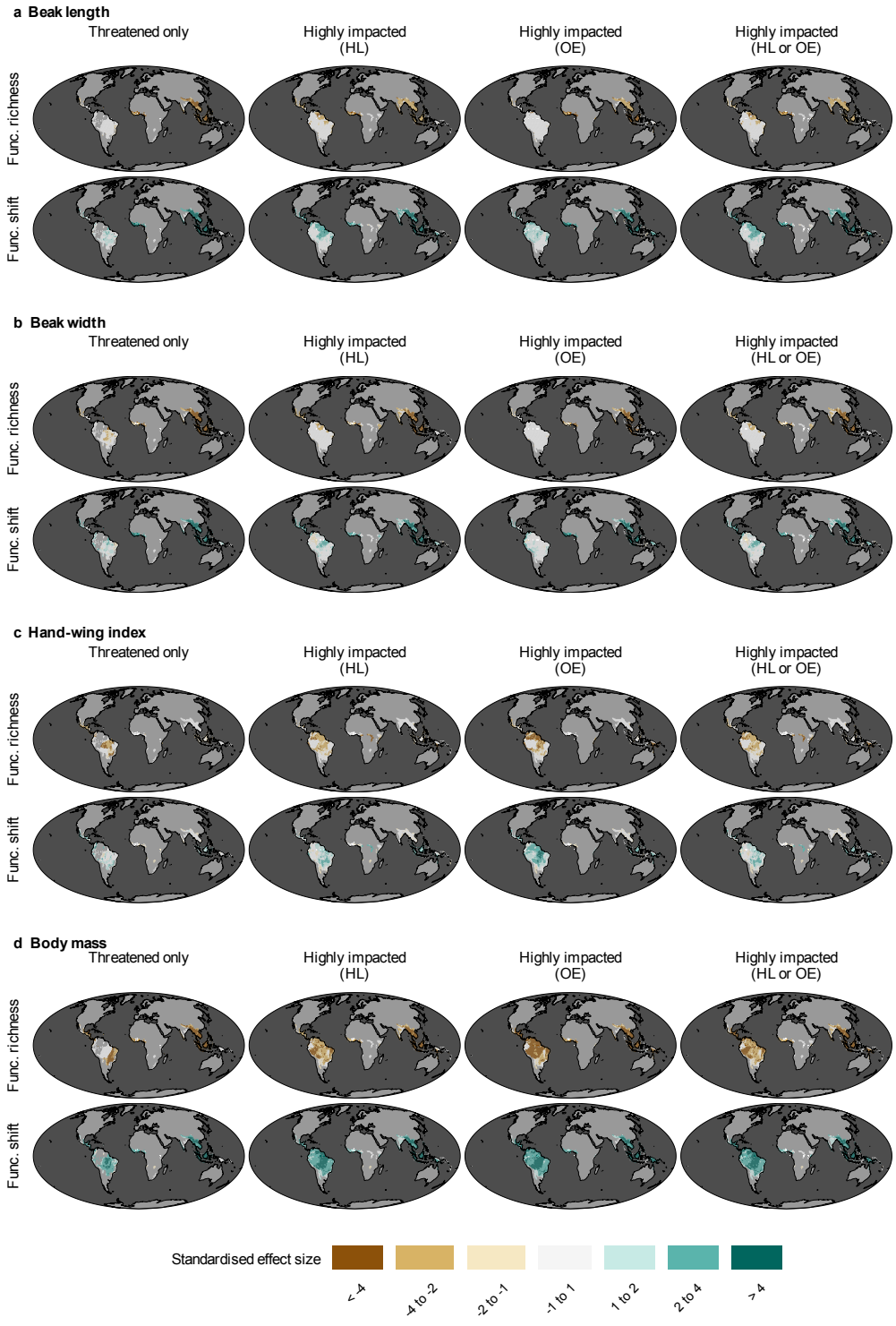
Supplementary Figure 5 | Trait change in primary and occasional frugivore assemblages after defaunation of threatened species and species highly impacted by habitat loss or overexploitation. a) Median trait value of primary and occasional frugivore (diet consists of $\geq 30\%$ fruit, $n = 2{,}463$ species) assemblages under current conditions. b) Percentage change in median trait value after removal of species considered threatened by IUCN (threatened only), and species considered highly impacted (threat score ≥ 6) by habitat loss (HL), overexploitation (OE) or either (HL or OE).



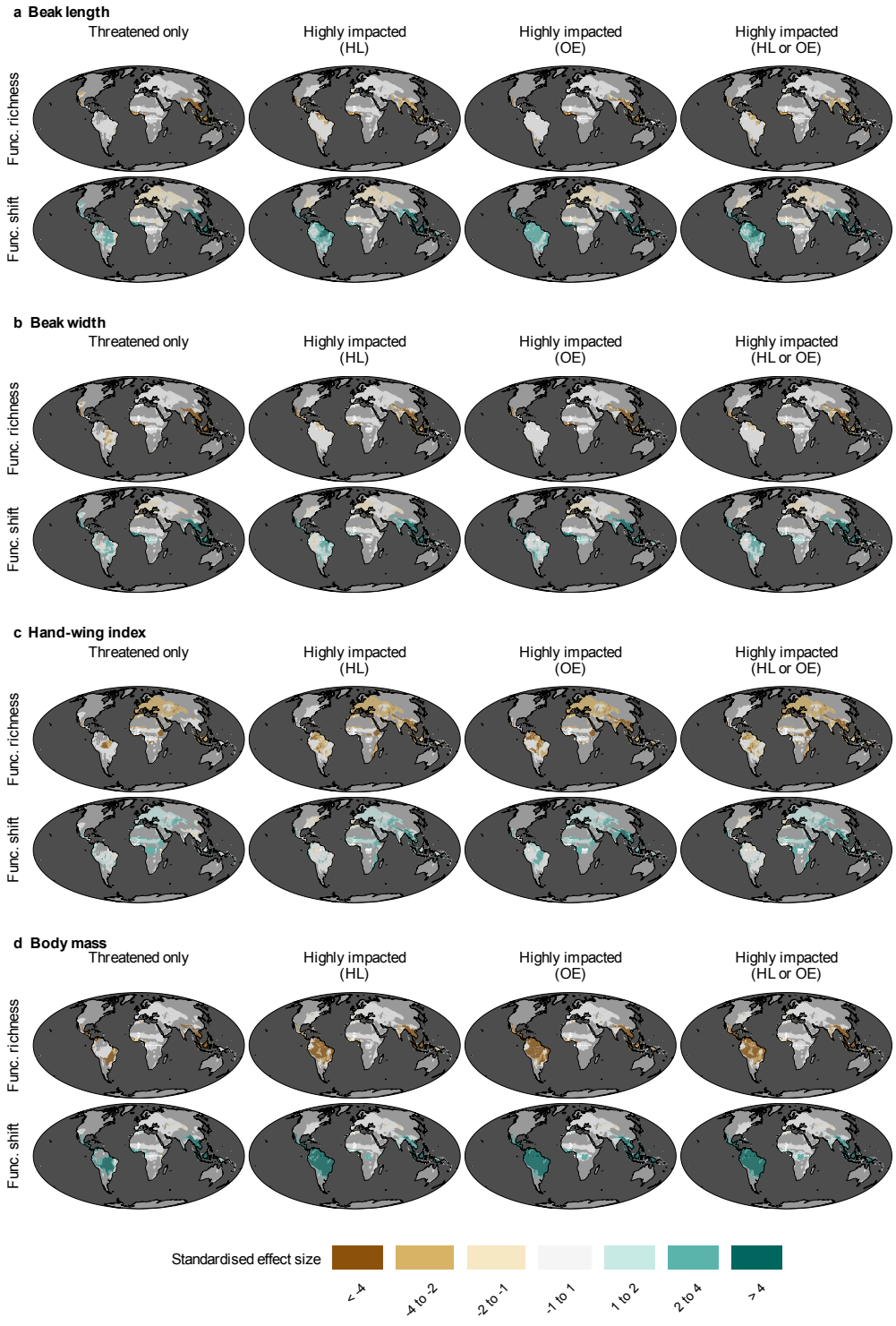
Supplementary Figure 6 | Trait change in primary frugivore assemblages after defaunation of threatened species and species impacted by habitat loss or overexploitation. a) Median trait value of primary frugivore (diet consists of $\geq 60\%$ fruit, $n = 1{,}188$ specie) assemblages under current conditions. b) Percentage change in median trait value after removal of species considered threatened by IUCN (threatened only), and species considered impacted (with any threat score or threat score is unknown) by habitat loss (HL), overexploitation (OE) or either (HL or OE).



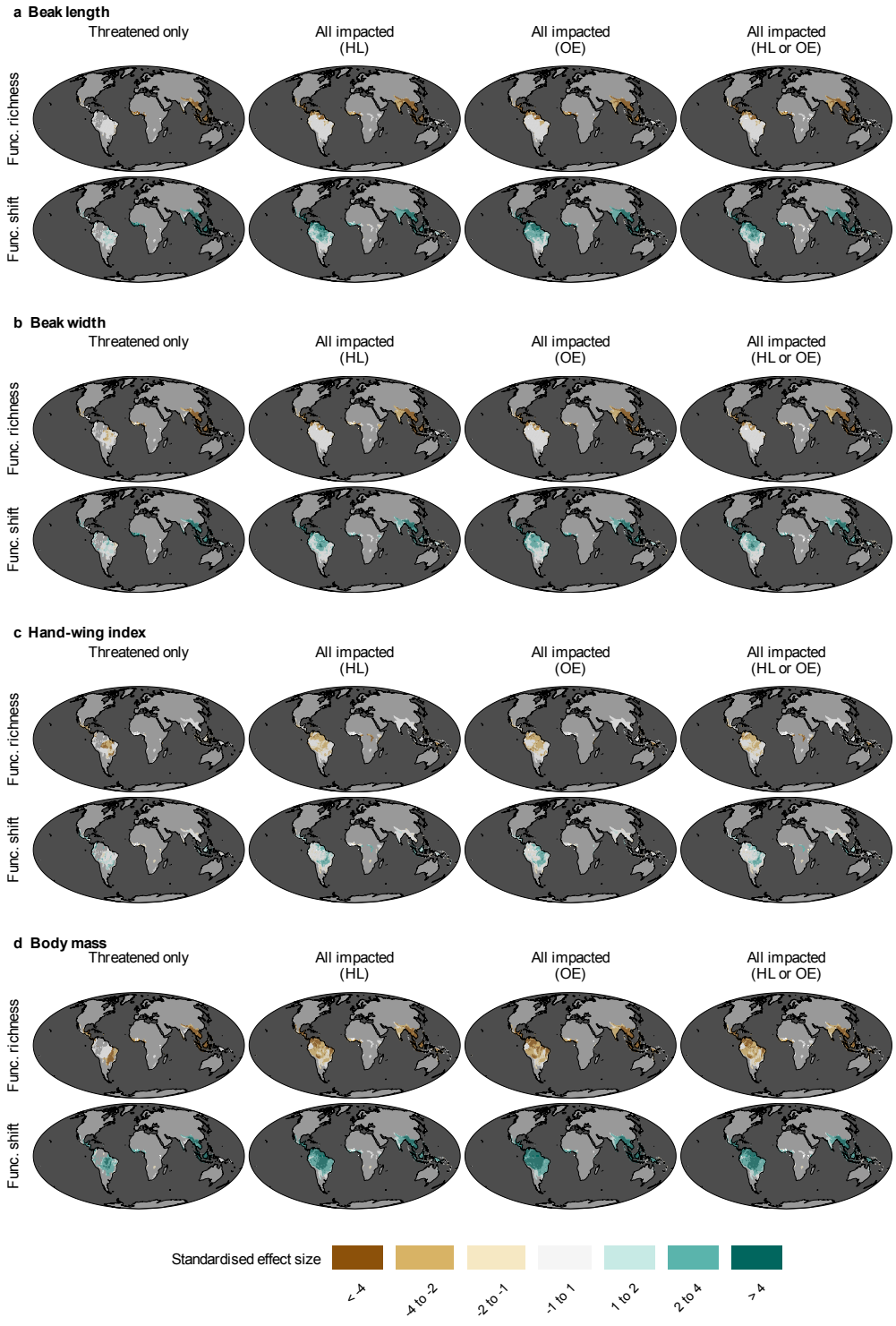
Supplementary Figure 7 | Trait change in primary and occasional frugivore assemblages after defaunation of threatened species and species impacted by habitat loss or overexploitation. a) Median trait value of primary and occasional frugivore (diet consists of $\geq 30\%$ fruit, $n = 2{,}463$ species) assemblages under current conditions. b) Percentage change in median trait value after removal of species considered threatened by IUCN (threatened only), and species considered impacted (with any threat score or threat score is unknown) by habitat loss (HL), overexploitation (OE) or either (HL or OE).



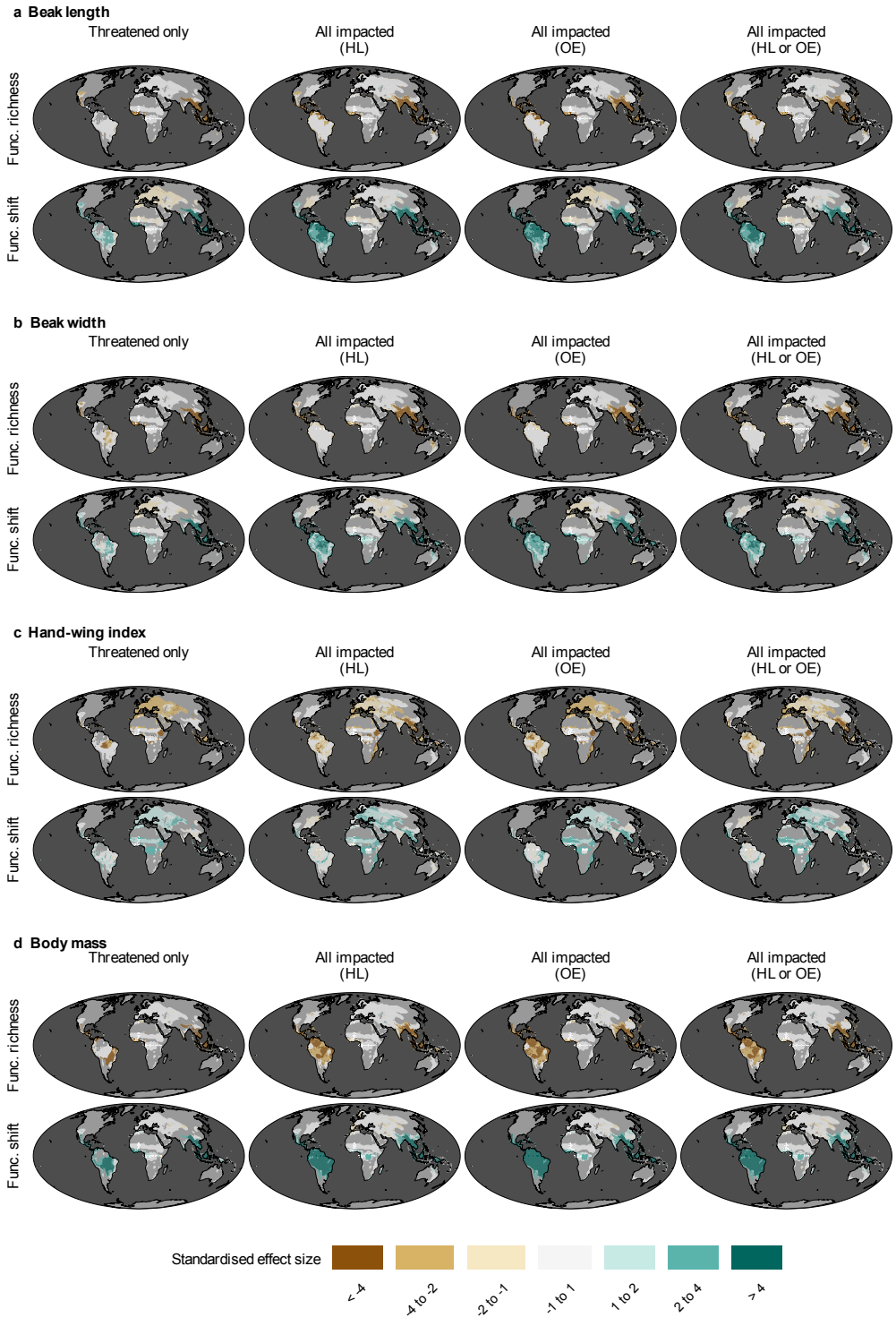
Supplementary Figure 8 | Standardised effect of defaunation of threatened species and species highly impacted by habitat loss or overexploitation on the functional diversity of individual traits of primary frugivore assemblages. Primary frugivores are those whose diet consists of $\geq 60\%$ fruit and species considered highly impacted by habitat loss (HL), overexploitation (OE) or either (HL or OE) have threat scores ≥ 6 for the respective threat. Functional richness was calculated as the range of trait values of a defaunated assemblage. Functional shift was calculated as the difference in mean trait value between an intact assemblage and the defaunated assemblage. Standardised effect sizes were calculated by comparing functional diversity values with null assemblages with random losses (see Methods).



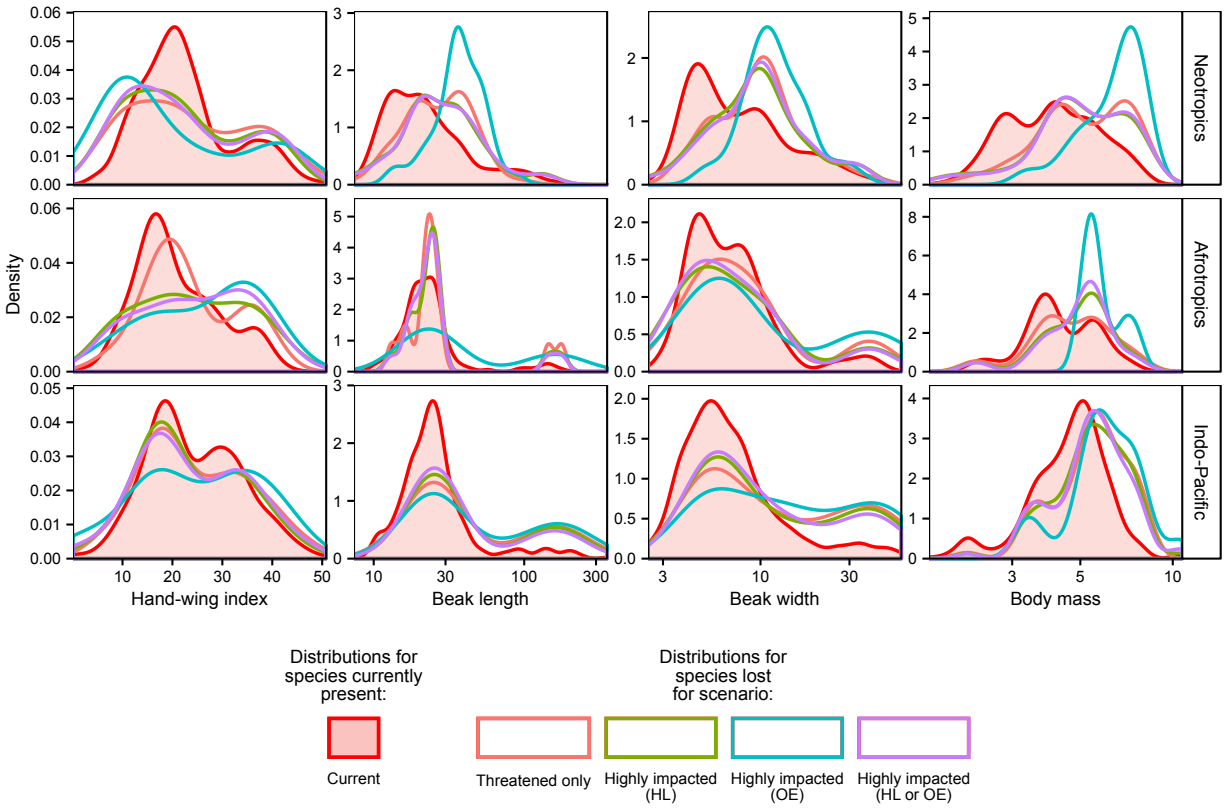
Supplementary Figure 9 | Standardised effect of defaunation of threatened species and species highly impacted by habitat loss or overexploitation on the functional diversity of individual traits of primary and occasional frugivore assemblages. Primary and occasional frugivores are those whose diet consists of $\geq 30\%$ fruit and species considered highly impacted by habitat loss (HL), overexploitation (OE) or either (HL or OE) have threat scores ≥ 6 for the respective threat. Functional richness was calculated as the range of trait values of a defaunated assemblage. Functional shift was calculated as the difference in mean trait value between an intact assemblage and the defaunated assemblage. Standardised effect sizes were calculated by comparing functional diversity values with null assemblages with random losses (see Methods).



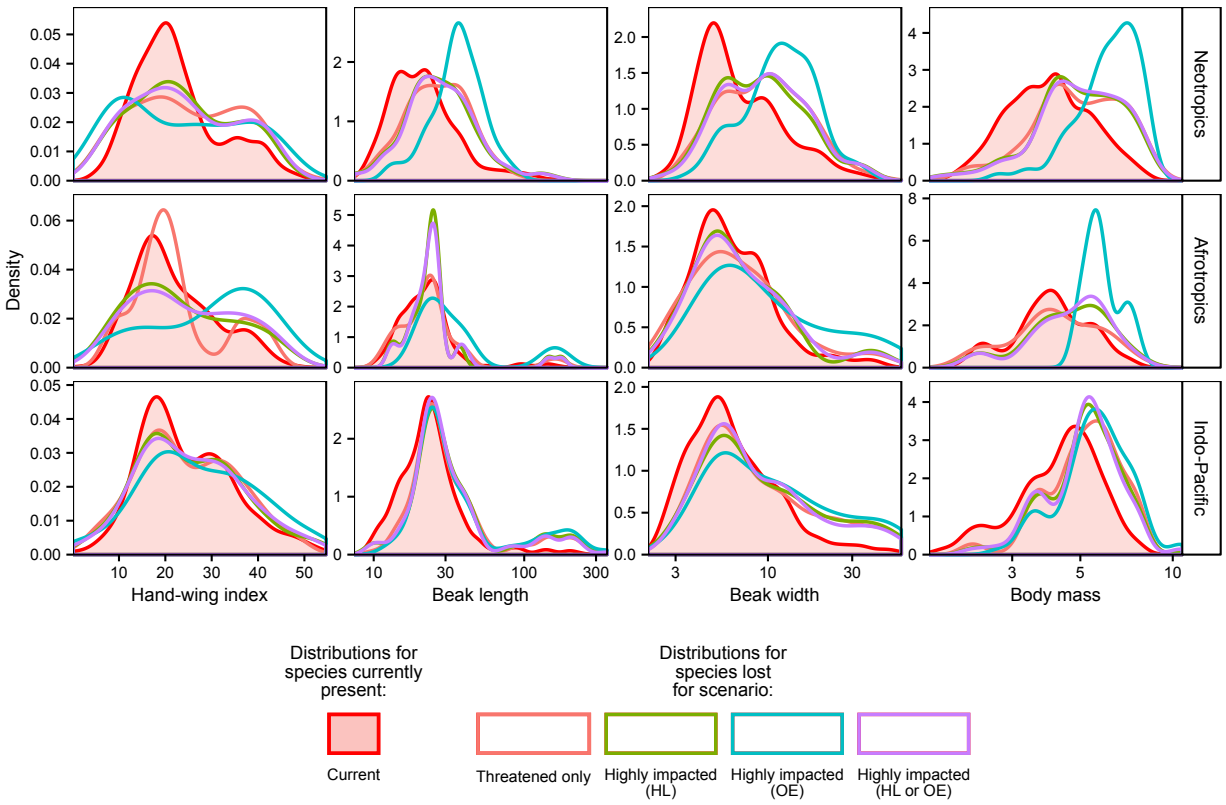
Supplementary Figure 10 | Standardised effect of defaunation of threatened species and species impacted by habitat loss or overexploitation on the functional diversity of individual traits of primary frugivore assemblages. Primary frugivores are those whose diet consists of $\geq 60\%$ fruit and species considered highly impacted by habitat loss (HL), overexploitation (OE) or either (HL or OE) have any threat score, or the threat score was unknown, for the respective threat. Functional richness was calculated as the range of trait values of a defaunated assemblage. Functional shift was calculated as the difference in mean trait value between an intact assemblage and the defaunated assemblage. Standardised effect sizes were calculated by comparing functional diversity values with null assemblages with random losses (see Methods).



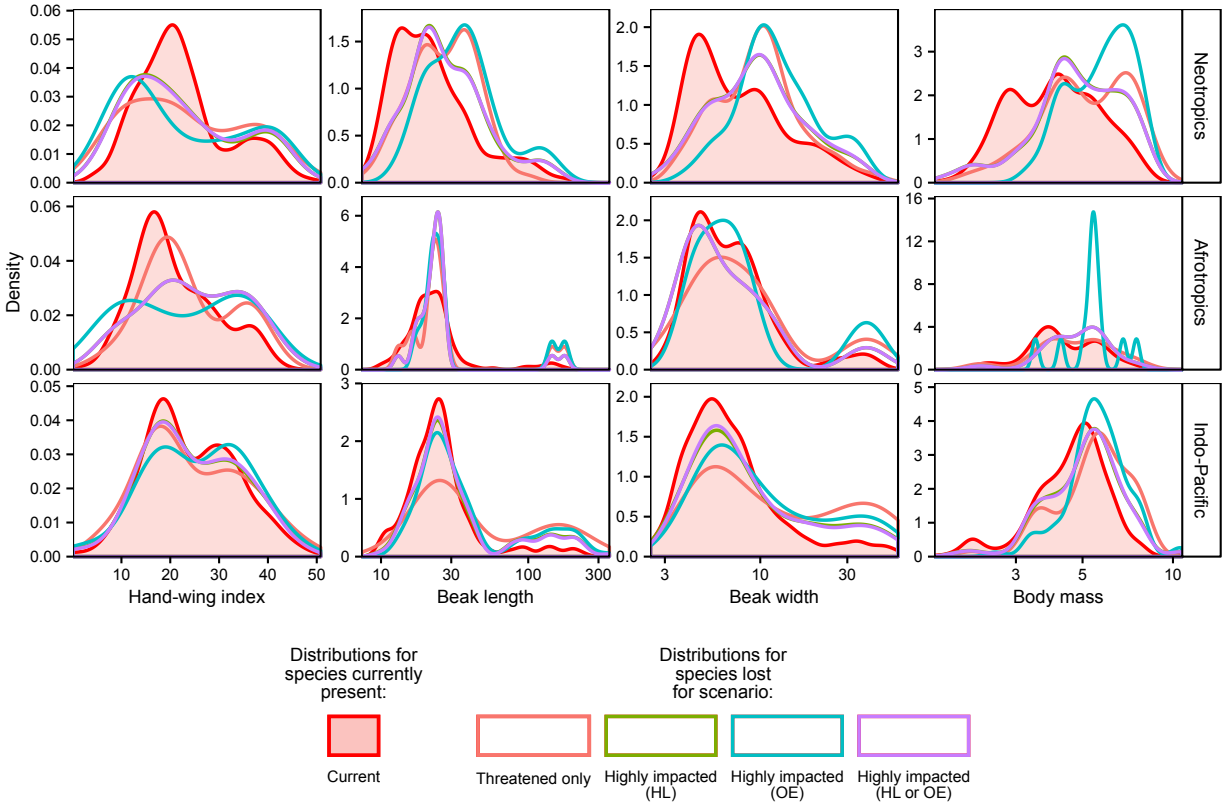
Supplementary Figure 11 | Standardised effect of defaunation of threatened species and species impacted by habitat loss or overexploitation on the functional diversity of individual traits of primary and occasional frugivore assemblages. Primary and occasional frugivores are those whose diet consists of $\geq$ 30% fruit and species considered highly impacted by habitat loss (HL), overexploitation (OE) or either (HL or OE) have any threat score, or the threat score was unknown, for the respective threat. Functional richness was calculated as the range of trait values of a defaunated assemblage. Functional shift was calculated as the difference in mean trait value between an intact assemblage and the defaunated assemblage. Standardised effect sizes were calculated by comparing functional diversity values with null assemblages with random losses (see Methods).



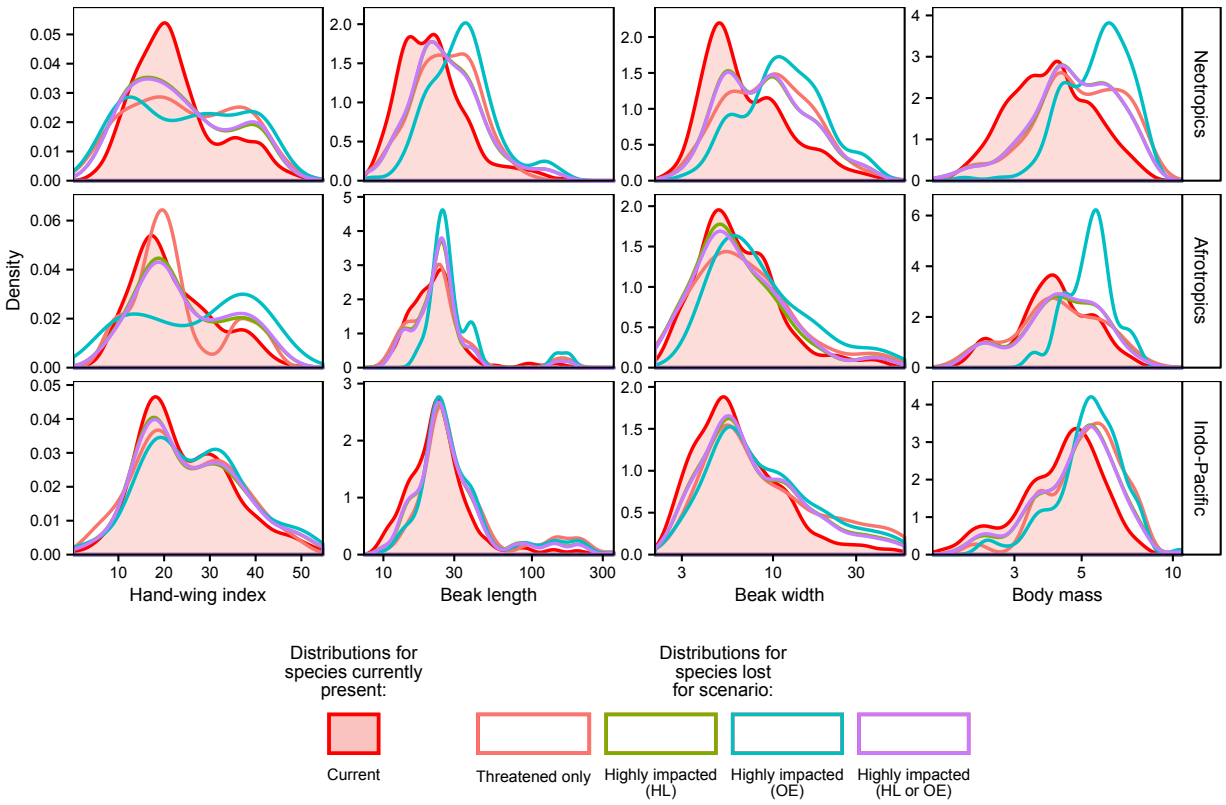
Supplementary Figure 12 | Trait distribution of threatened and highly impacted primary frugivores. Red polygons represent the trait distributions of primary frugivore species (diet consists of $\geq 60\%$ fruit, $n = 1{,}188$ species) present within each region. Coloured lines represent the trait distributions of species that would be removed in eligible grid cells under "Threatened only", "HL", "OE" and "HL or OE" scenarios (see Methods; Fig. 2).



Supplementary Figure 13 | Trait distributions of threatened and highly impacted primary and occasional frugivores. Red polygons represent the trait distributions of primary and occasional frugivore species (diet consists of $\geq$ 30% fruit, n = 2,463 species) present within the region. Coloured lines represent the trait distributions of species that would be removed in eligible grid cells under "Threatened only", "HL", "OE" and "HL or OE" scenarios (see Methods; Extended Data Fig. 5a).



Supplementary Figure 14 | Trait distributions of threatened and all impacted primary frugivores. Red polygons are the trait distributions for primary frugivores species (diet consists of $\geq 60\%$ fruit, $n = 1{,}188$ species) present within each region. Coloured lines represent the trait distributions of species that would be removed in eligible grid cells under "Threatened only", "HL", "OE" and "HL or OE" scenarios (see Methods; Extended Data Fig. 5b)



Supplementary Figure 15 | Trait distributions of threatened and all impacted primary and occasional frugivores. Red polygons are the trait distributions for primary and occasional frugivore species (diet consists of $\geq$ 30% fruit, n = 2,463 species) currently present within the region. Coloured lines represent the trait distributions of species that would be removed in eligible grid cells under "Threatened only", "HL", "OE" and "HL or OE" scenarios (see Methods; Extended Data Fig. 5c)

Supplementary Tables

Supplementary Table 1 | Principal component (PC) loadings for avian frugivore morphological traits.

	PC1	PC2	PC3	PC4
Hand Wing Index	-0.13	-0.97	0.05	0.19
Log Body Mass	-0.56	0.03	0.72	-0.41
Log Beak Width	-0.57	-0.05	-0.69	-0.44
Log Beak Length	-0.59	0.23	-0.03	0.78
Proportion of variance explained	0.63	0.25	0.08	0.03

Supplementary Table 2 | Defaunation impacts on the functional diversity of primary frugivore assemblages (diet ≥ 60% fruit) and potential impacts on natural restoration potential. Magnitude of functional change is based on the 'Threatened only' defaunation scenario. n = total number of eligible grid cells in each tropical realm or globally (see Methods)

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	Functional change	Restoration potential	Functional richness Prop. of cells	Functional shift Prop. of cells
Global	Low	Low	0.506	0.496
(n = 5649)	Low	Medium	0.133	0.129
	Low	High	0.157	0.156
	Medium	Low	0.041	0.048
	Medium	Medium	0.048	0.038
	Medium	High	0.053	0.036
	High	Low	0.016	0.019
	High	Medium	0.025	0.040
	High	High	0.021	0.038
Neotropics	Low	Low	0.385	0.369
(n = 1611)	Low	Medium	0.156	0.168
	Low	High	0.190	0.213
	Medium	Low	0.065	0.106
	Medium	Medium	0.055	0.061
	Medium	High	0.083	0.082
	High	Low	0.025	0.000
	High	Medium	0.018	0.001
	High	High	0.022	0.001
Afrotropics	Low	Low	0.786	0.781
(n = 1841)	Low	Medium	0.118	0.107
	Low	High	0.067	0.049
	Medium	Low	0.008	0.014
	Medium	Medium	0.003	0.008
	Medium	High	0.004	0.010
	High	Low	0.010	0.010
	High	Medium	0.003	0.009
	High	High	0.001	0.012
Indo-Pacific	Low	Low	0.397	0.388
(n = 1336)	Low	Medium	0.111	0.091
	Low	High	0.073	0.066
	Medium	Low	0.065	0.037
	Medium	Medium	0.105	0.060
	Medium	High	0.098	0.030
	High	Low	0.020	0.058
	High	Medium	0.073	0.138
	High	High	0.057	0.132

Supplementary Table 3 | Defaunation impacts on the functional diversity of primary and occasional frugivore assemblages (diet $\geq$ 30% fruit) and potential impacts on natural restoration potential. Magnitude of functional change is based on the 'Threatened only' defaunation scenario. n = total number of eligible grid cells in each tropical realm or globally (see Methods).

	Functional change	Restoration potential	Functional richness Prop. of cells	Functional shift Prop. of cells
Global	Low	Low	0.614	0.616
(n = 13055)	Low	Medium	0.130	0.123
	Low	High	0.139	0.127
	Medium	Low	0.029	0.028
	Medium	Medium	0.026	0.025
	Medium	High	0.010	0.013
	High	Low	0.013	0.027
	High	Medium	0.017	0.010
	High	High	0.022	0.020
Neotropics	Low	Low	0.425	0.368
(n = 1717)	Low	Medium	0.154	0.162
	Low	High	0.052	0.024
	Medium	Low	0.047	0.186
	Medium	Medium	0.086	0.041
	Medium	High	0.031	0.027
	High	Low	0.056	0.092
	High	Medium	0.044	0.066
	High	High	0.105	0.034
Afrotropics	Low	Low	0.079	0.099
(n = 2184)	Low	Medium	0.037	0.034
	Low	High	0.009	0.013
	Medium	Low	0.006	0.003
	Medium	Medium	0.007	0.009
	Medium	High	0.006	0.004
	High	Low	0.037	0.042
	High	Medium	0.035	0.034
	High	High	0.049	0.058
Indo-Pacific	Low	Low	0.465	0.396
(n = 1552)	Low	Medium	0.094	0.055
	Low	High	0.094	0.082
	Medium	Low	0.045	0.047
	Medium	Medium	0.034	0.041
	Medium	High	0.035	0.012
	High	Low	0.021	0.042
	High	Medium	0.095	0.056
	High	High	0.101	0.156

Supplementary Table 4 | Table S4 | Defaunation impacts on the functional diversity of primary frugivore assemblages (diet ≥ 60% fruit) and potential impacts on natural restoration potential. Magnitude of functional change is based on the 'HL or OE' defaunation scenario whereby any species with threat score ≥ 6 in either category is considered highly impacted. n = total number of eligible grid cells in each tropical realm or globally (see Methods).

			Functional richness	Functional shift
	Functional change	Restoration potential	Prop. of cells	Prop. of cells
Global	Low	Low	0.481	0.439
(n = 5647)	Low	Medium	0.139	0.109
	Low	High	0.169	0.127
	Medium	Low	0.069	0.100
	Medium	Medium	0.060	0.106
	Medium	High	0.055	0.058
	High	Low	0.012	0.023
	High	Medium	0.008	0.023
	High	High	0.007	0.049
Neotropics	Low	Low	0.341	0.274
(n = 1611)	Low	Medium	0.184	0.177
	Low	High	0.107	0.217
	Medium	Low	0.032	0.093
	Medium	Medium	0.058	0.142
	Medium	High	0.026	0.071
	High	Low	0.013	0.040
	High	Medium	0.015	0.045
	High	High	0.007	0.041
Afrotropics	Low	Low	0.427	0.358
(n = 1840)	Low	Medium	0.108	0.110
	Low	High	0.066	0.095
	Medium	Low	0.020	0.068
	Medium	Medium	0.013	0.032
	Medium	High	0.009	0.017
	High	Low	0.007	0.012
	High	Medium	0.004	0.010
	High	High	0.002	0.010
Indo-Pacific	Low	Low	0.353	0.307
(n = 1335)	Low	Medium	0.202	0.118
	Low	High	0.172	0.076
	Medium	Low	0.119	0.096
	Medium	Medium	0.139	0.056
	Medium	High	0.012	0.061
	High	Low	0.015	0.131

Supplementary Table 5 | Defaunation impacts on the functional diversity of primary and occasional frugivore assemblages (diet $\geq$ 30% fruit) and potential impacts on natural restoration potential. Magnitude of functional change is based on the 'HL or OE' defaunation scenario whereby any species with threat score ≥ 6 in either category is considered highly impacted. n = total number of eligible grid cells in each tropical realm or globally (see Methods).

	Functional change	Restoration potential	Functional richness Prop. of cells	Functional shift Prop. of cells
Global	Low	Low	0.603	0.573
($n = 13053$)	Low	Medium	0.126	0.109
	Low	High	0.132	0.106
	Medium	Low	0.044	0.053
	Medium	Medium	0.022	0.057
	Medium	High	0.024	0.047
	High	Low	0.022	0.047
	High	Medium	0.014	0.028
	High	High	0.012	0.021
Neotropics	Low	Low	0.573	0.505
($n = 1717$)	Low	Medium	0.160	0.109
	Low	High	0.405	0.096
	Medium	Low	0.094	0.044
	Medium	Medium	0.051	0.075
	Medium	High	0.054	0.084
	High	Low	0.009	0.047
	High	Medium	0.028	0.028
	High	High	0.014	0.052
Afrotropics	Low	Low	0.774	0.736
($n = 2184$)	Low	Medium	0.040	0.043
	Low	High	0.047	0.027
	Medium	Low	0.014	0.014
	Medium	Medium	0.005	0.010
	Medium	High	0.009	0.016
	High	Low	0.016	0.014
	High	Medium	0.019	0.015
	High	High	0.015	0.024
Indo-Pacific	Low	Low	0.416	0.350
($n = 1548$)	Low	Medium	0.078	0.097
	Low	High	0.278	0.082
	Medium	Low	0.105	0.066
	Medium	Medium	0.085	0.048
	Medium	High	0.048	0.049
	High	Low	0.018	0.192
	High	Medium	0.017	0.028
	High	High	0.092	0.088

Supplementary Table 6 | Defaunation impacts on the functional diversity of primary frugivore assemblages (diet $\geq$ 60% fruit) and potential impacts on natural restoration potential. Magnitude of functional change is based on the 'HL or OE' defaunation scenario whereby any species with any threat score, or threat score is unknown, for either category is considered impacted. n = total number of eligible grid cells in each tropical realm or globally (see Methods).

	Functional change	Restoration potential	Functional richness Prop. of cells	Functional shift Prop. of cells
Global	Low	Low	0.483	0.412
(n = 5626)	Low	Medium	0.136	0.099
	Low	High	0.149	0.111
	Medium	Low	0.063	0.100
	Medium	Medium	0.054	0.053
	Medium	High	0.059	0.053
	High	Low	0.015	0.049
	High	Medium	0.017	0.055
	High	High	0.024	0.068
Neotropics	Low	Low	0.327	0.122
(n = 1611)	Low	Medium	0.166	0.076
	Low	High	0.176	0.094
	Medium	Low	0.111	0.222
	Medium	Medium	0.049	0.073
	Medium	High	0.096	0.082
	High	Low	0.037	0.130
	High	Medium	0.015	0.081
	High	High	0.024	0.120
Afrotropics	Low	Low	0.778	0.788
(n =1839)	Low	Medium	0.108	0.111
	Low	High	0.065	0.057
	Medium	Low	0.021	0.016
	Medium	Medium	0.013	0.013
	Medium	High	0.005	0.014
	High	Low	0.005	0.000
	High	Medium	0.004	0.001
	High	High	0.001	0.000
Indo-Pacific	Low	Low	0.382	0.332
(n = 1315)	Low	Medium	0.126	0.079
	Low	High	0.060	0.026
	Medium	Low	0.089	0.106
	Medium	Medium	0.135	0.106
	Medium	High	0.118	0.078
	High	Low	0.005	0.038
	High	Medium	0.031	0.107
	High	High	0.054	0.129

Supplementary Table 7 | Defaunation impacts on the functional diversity of primary and occasional frugivore assemblages (diet $\geq$ 30% fruit) and potential impacts on natural restoration potential. Magnitude of functional change is based on the 'HL or OE' defaunation scenario whereby any species with any threat score, or threat score is unknown, for either category is considered impacted. n = total number of eligible grid cells in each tropical realm or globally (see Methods).

	Functional change	Restoration potential	Functional richness Prop. of cells	Functional shift Prop. of cells
Global	Low	Low	0.593	0.559
(n = 13035)	Low	Medium	0.119	0.105
	Low	High	0.124	0.104
	Medium	Low	0.054	0.049
	Medium	Medium	0.030	0.023
	Medium	High	0.027	0.020
	High	Low	0.013	0.053
	High	Medium	0.018	0.039
	High	High	0.023	0.049
Neotropics	Low	Low	0.366	0.076
(n = 1717)	Low	Medium	0.142	0.023
	Low	High	0.156	0.019
	Medium	Low	0.122	0.141
	Medium	Medium	0.062	0.058
	Medium	High	0.087	0.058
	High	Low	0.016	0.287
	High	Medium	0.015	0.137
	High	High	0.035	0.200
Afrotropics	Low	Low	0.755	0.797
(n = 2184)	Low	Medium	0.075	0.085
	Low	High	0.042	0.042
	Medium	Low	0.054	0.038
	Medium	Medium	0.015	0.019
	Medium	High	0.004	0.015
	High	Low	0.026	0.001
	High	Medium	0.015	0.000
	High	High	0.015	0.003
Indo-Pacific	Low	Low	0.413	0.361
(n = 1536)	Low	Medium	0.080	0.076
	Low	High	0.016	0.020
	Medium	Low	0.102	0.087
	Medium	Medium	0.094	0.042
	Medium	High	0.079	0.025
	High	Low	0.031	0.100
	High	Medium	0.080	0.136
	High	High	0.103	0.154