Unifying latitudinal gradients in range size and richness across marine and terrestrial systems

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Supplementary online material

Supplementary methods

Data. Species range limits for marine bivalves and terrestrial birds are available at Data Dryad at dx.doi.org/10.5061/dryad.p0q25. Temperature gradients in Figure 3 A-C represent the annual mean daily sea-surface and air temperature (the daily mean temperature averaged over a full year) in 1° latitude bands. Sea-surface temperature (SSTs) at a 9*9 km^2 resolution was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) and rescaled to a 1°*1° resolution. Air temperatures were obtained from CliMond database (Kriticos et al. 2012). The tropical-temperate boundaries in the Eastern Pacific are at 6ºS and 23.5ºN and in the Western Atlantic at 23ºS and 28ºN (Spalding et al. 2007). In the global-scale analyses of bivalves, the boundaries are set at 25ºS and 30ºN. In analyses of birds, the boundaries are set at 30ºS and 30ºN.

Relation between latitude and median range size. We use generalized least-squares to compare the relation between latitude and median latitudinal range size between hemispheres and between birds and bivalves. This method minimizes the correlation among the residuals due to the spatial structure of the data (Fig. S2), and is implemented in the function gls in the R package nlme (Pinheiro et al. 2013). We fit five alternative models accounting for the relationship between the variance in the residuals and latitudinal distance among 1º bands in semi-variograms (linear, Gaussian, spherical, exponential, and rational quadratic functions; Begueria and Pueyo 2009), and selected the best-fitting model based on the Akaike information criterion (AIC) for each of the comparisons (Table S1).

Contribution of nestedness to dissimilarity. We subsample 20 bands (without replacement) for 1,000 times from all latitudinal 1º bands within each hemisphere. For each of the 1,000 generated datasets, we then compute species-level and genus-level proportional contribution of nestedness to total dissimilarity (Baselga 2012). We use the function beta.sample in the R package betapart (Balselga and Orme 2012). The proportion of cases in which the species-level contribution to nestedness is higher than the genus-level contribution thus represents the probability that the increase in nestedness from species to genus levels occurs by chance.

Relation between per-genus species range size and genus range size. We use a bootstrapping test to account for the dependence of genus range size on the median latitudinal range size of its species, as well as the mean distance among latitudinal midpoints of its species, because species range size and among-species distance must be less than or equal to genus range size (Novack-Gottshall and Miller 2003). Species range size and genus range size was resampled (with replacement) independently for each genus for 1,000 times, and resulted species range sizes (or among-species distances) were required to be equal to or greater than the corresponding genus range size in each iteration. Using these simulated data, we calculated the rank-order correlations as a null expectation, and compared the 1,000 null correlations with the observed rank correlation.

Supplementary results and discussion

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Species range-size gradients. Marine temperatures vary only slightly over a wide latitudinal range around the equator especially in the Western Atlantic (and Western Pacific) because the Earth‘s rotation drives warm tropical waters toward the poles along the western oceanic margins. In contrast, cold polar water are driven toward the equator in the Eastern Pacific, where the tropics are further truncated by cold-water upwelling at 6º S. Therefore, tropical zones with more or less constant sea-surface temperature (25-27°C) are ~5,000-6,000 km broad along the western margins but only ~2,500-4,000 km broad along the eastern margins. Therefore, tropical waters in the Western Atlantic permit broad geographic ranges even in the absence of large thermal tolerances. In contrast, the cool temperatures just south of the equator in the eastern Pacific restrict the latitudinal span of tropical waters and reduce tropical species range sizes by ~2,000 km relative to the Western Atlantic (Fig. 3D-E). The actual peak in range size in the Eastern Pacific is then located at 10ºS, and is generated by few broad-ranging species inhabiting tropical and temperate latitudes (see also Tomasovych et al. 2015).

Genus range-size gradients. Globally and along the New World coasts, median genus range sizes of bivalves significantly increase from within the tropics to at the highest latitudes. In birds, median genus range size is ≤ ~4,700 km in the tropics and increases significantly to the highest southern latitudes; in the Northern Hemisphere, it peaks at ~8000 km near 55°N but then declines towards higher latitudes. In the New World, the temperate Northern Hemisphere median again exceeds tropical values, but the maximum occurs at ~30°N, with a northerly decline. Nonetheless, narrow-ranging genera (which we define as encompassing < 60° of latitude, i.e., more than ~6,600 km) are concentrated in the tropics for New World birds and bivalves, by a factor of 3-5 relative to 45°N (Fig. S7). For New World birds

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and bivalves, narrow-ranging genera (which we define as encompassing < 60° of latitude, i.e., less than ~6,600 km) are concentrated in the tropics by a factor of 3-5 relative to 45°N (Fig. S7). Broad-ranging genera (> 60° of latitude) show shallower richness gradients in the Eastern Pacific bivalves and New World birds. In contrast, a greater number of broad-ranging bivalve genera occur in the tropical Western Atlantic, likely due to the shallower temperature gradients, resulting in tropical climatic conditions that are latitudinally broader. The increase in median genus range size of New World birds from 0° to 30°N (grey line in Fig. 3F) is produced by the declining richness of broad-ranging genera briefly exceeding the declining richness of narrow-ranging genera, which cluster around the equator. Overall, there is a steep decline in the number of narrow-ranging genera at around 25°N to 30°N both on land and in the sea (Fig. S7). The deserts of Mexico, Argentina, and Chile on land, and strong thermal gradients in the sea apparently restrict many genera to the tropics (Fig. 3A-C).

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Supplementary tables and figures

Table S1 - The generalized least-square estimates of slope of the median latitudinal range size over latitude at the species and genus level, and the selected correlation structures that minimize the spatial correlation among the residuals. The slopes are significantly negative in bivalve species at regional scales and in the Southern Hemisphere at the global scale. The slopes become mostly positive in both groups at the genus level.

	Southern Hemisphere range-size~latitude slope	*p*	Cor. Structure	Northern Hemisphere range-size~latitude slope	*p*	Cor. Structure
Species						
Eastern Pacific bivalves	-50.2	<0.0001	Spherical	-9.9	<0.0001	Spherical
Western Atlantic bivalves	-61.3	<0.0001	Spherical	-25.5	0.0377	Spherical
Global bivalves	-28.8	0.0263	Spherical	-0.7	0.9406	Spherical
New World birds	15.4	0.0824	Spherical	2.4	0.6243	Exponential
Global birds	17.2	0.0315	Spherical	12.1	0.0040	Spherical
Genera						
Eastern Pacific bivalves	59.0	0.1527	Spherical	14.9	0.0452	Spherical
Western Atlantic bivalves	91.0	<0.0001	Spherical	100.4	<0.0001	Spherical
Global bivalves	112.0	<0.0001	Spherical	83.0	<0.0001	Spherical
New World birds	76.7	<0.0001	Ratio	-5.7	0.7233	Spherical
Global birds	82.0	<0.0001	Ratio	25.1	0.0314	Spherical

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Table S2 - Wilcoxon rank-sum test comparing per-genus richness of tropical species belonging to bridge and tropics-only genera (Tropics) and per-genus richness of extratropical species belonging to bridge and extratropics-only genera (Extratropics).

	Mean richness of restricted genera	Mean richness of bridge genera	W stat.	p-value
Tropics-Global bivalves	1.58	3.68	18957.5	<0.0001
Extratropics-Global bivalves	1.67	2.92	17500	<0.0001
Tropics-Global birds	2.59	6.59	196847	<0.0001
Extratropics-Global birds	1.58	2.86	9487	<0.0001
Tropics-Western Atlantic bivalves	1.07	1.48	929.5	0.0111
Extratropics-Western Atlantic bivalves	1.34	2.19	2140	0.0045
Tropics-Eastern Pacific bivalves	1.18	1.50	989	0.0221
Extratropics-Eastern Pacific bivalves	1.54	2.16	3705	0.0038
Tropics-New World birds	2.78	5.47	47801	<0.0001
Extratropics-New World birds	1.86	2.56	3120.5	0.0080

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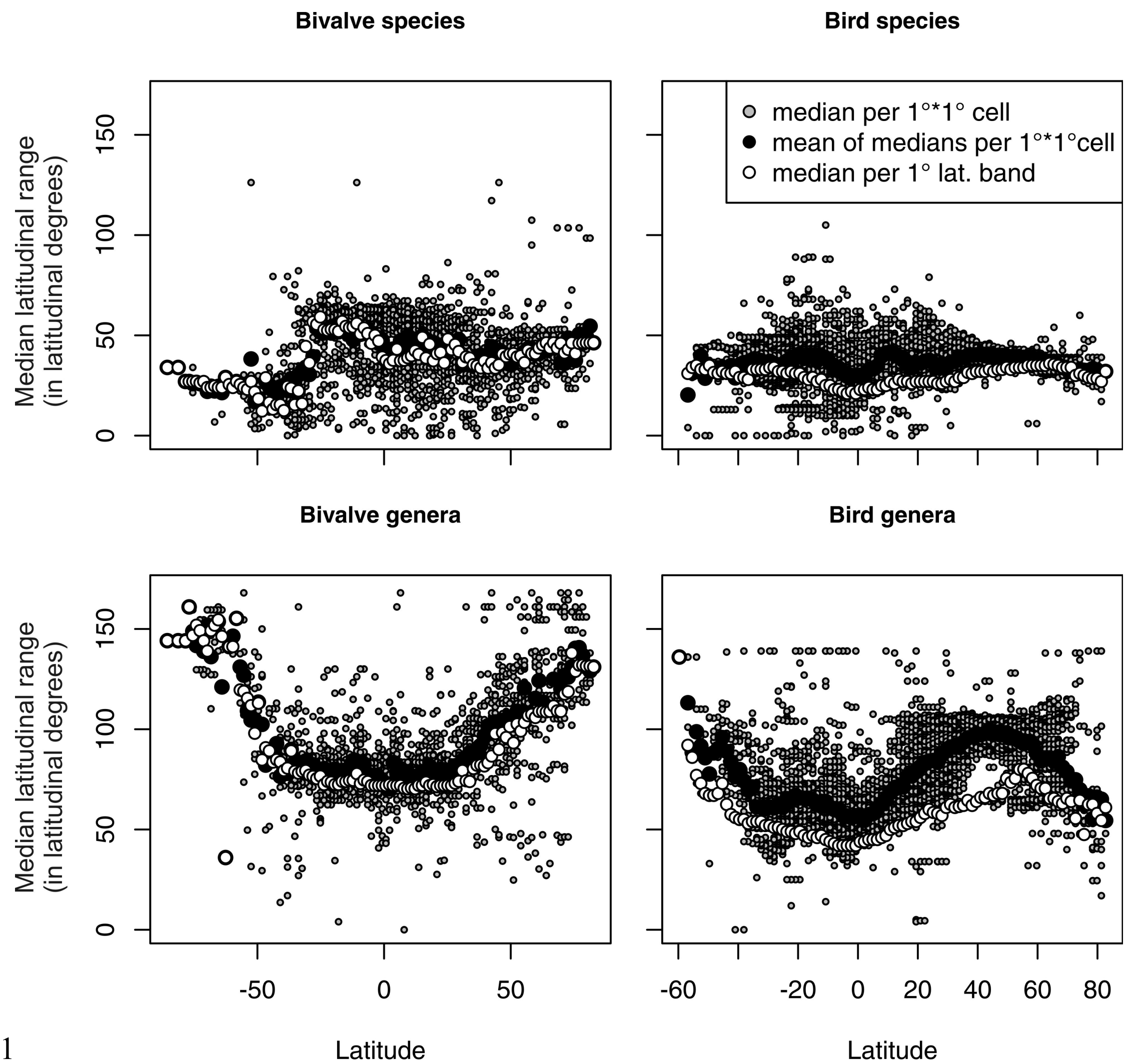

Figure S1 - The effects of spatial resolution on latitudinal gradients in range size of species and genera in bivalves and birds. Median range size per 1° latitudinal band (white points) tends to be lower than the per-band average (black points) of median range size per equal-area ~1° cells (25,000 km^2) because narrow-ranging species contribute less to individual 1° cells than to full 1° bands. This offset is larger in birds than in bivalves. Gray points show individual median range size for all 1° cells. In contrast to the main body of the paper where gaps in species distributions were ignored, i.e., species occurrences were counted in all latitudinal bands that are situated within the latitudinal range limits of the species, these plots show raw data.

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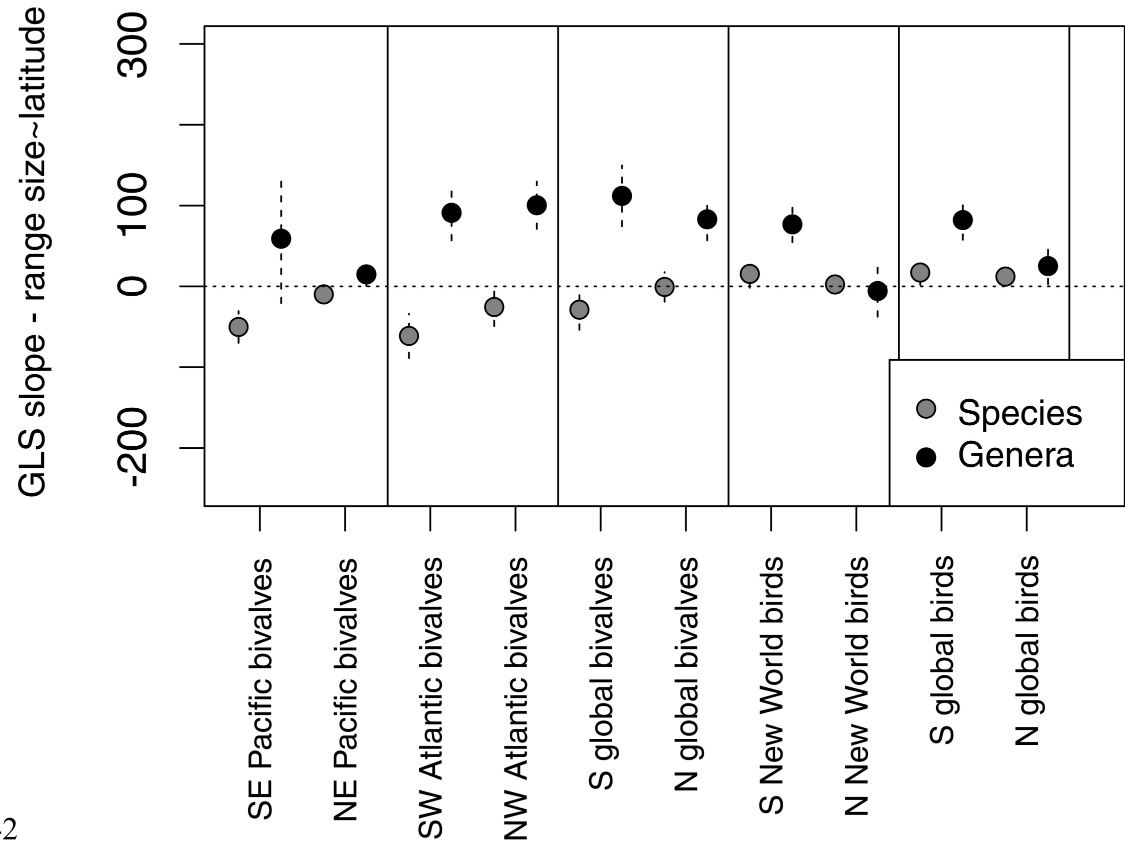

Figure S2 - Slopes of the relation between latitude and latitudinal range size estimated by generalized least-square models are negative in bivalve species (with the exception of the Northern Hemisphere at global scales) and slightly positive in bird species. The slopes become positive in both groups at the genus level. Error bars represent 95% confidence intervals on slope estimates.

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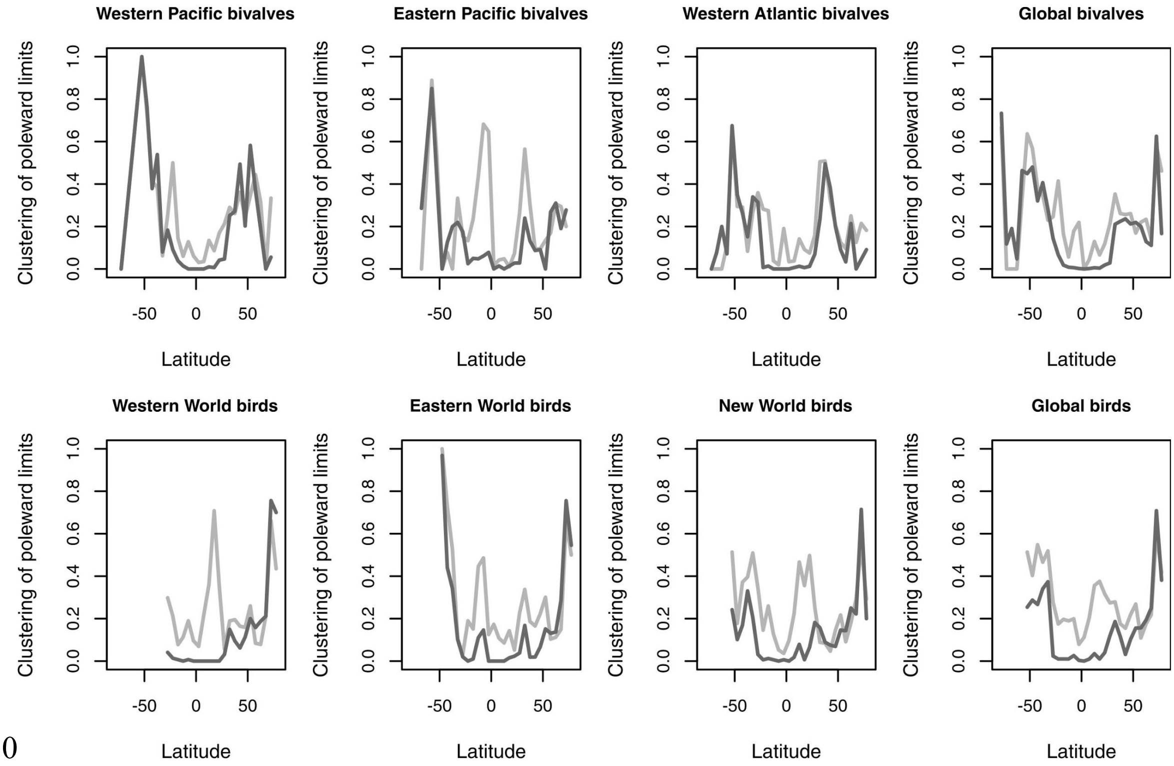

Figure S3 Clustering of poleward range limits of genera at the resolution of 5° bands (i.e., the number of genera with poleward range limits relative to all genera in a given band). In bivalves, genus range limits are rare within the tropics, in contrast to some major clustering of range limits of bird genera. Here three additional regions are included beyond those in the main text, the Western Pacific for bivalves, and the Western Old World (including the western Palearctic, Africa, and Saharo-Arabian areas) and Eastern Old World (including the eastern Palearctic, Oriental, Indo-Pacific, Australia and New Zealand) for birds to separate the tropical areas of Africa and the Indo-Pacific according to the biogeographic divisions suggested by Holt et al. (2013).

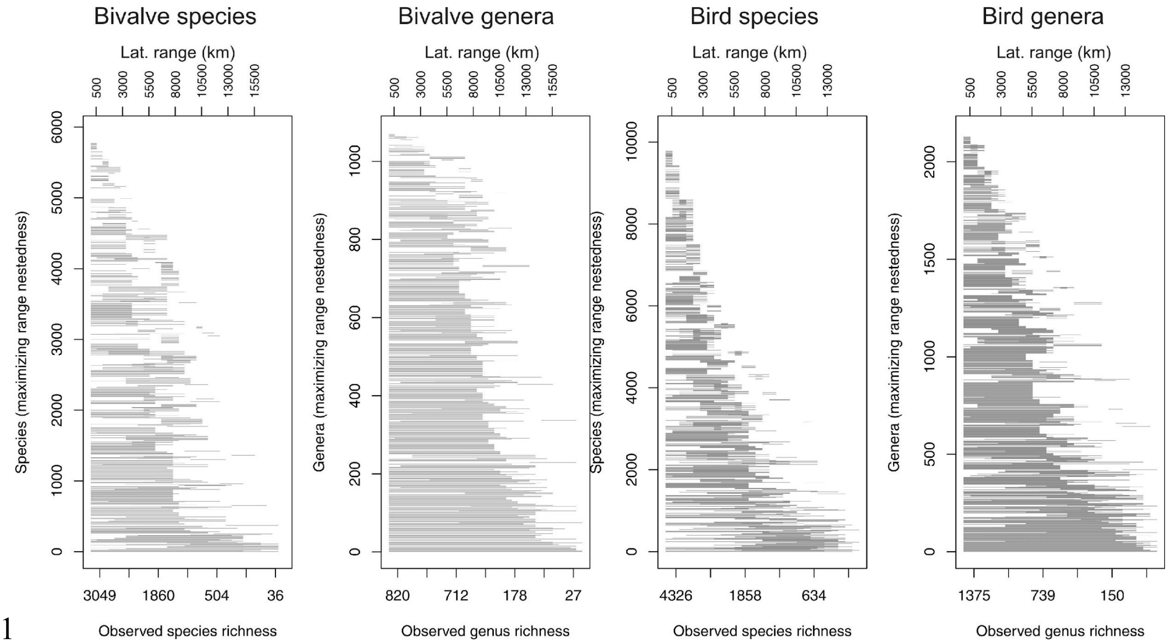

Figure S4. Visualization of range configuration and Rapoport patterns: species show a pattern of turnover, with broad-ranging bivalve species at low latitudes replaced by narrow-ranging bivalve species at high latitudes (inverse Rapoport's pattern), and broad-ranging bird species at higher latitudes replaced by narrow-ranging bird species at low latitudes (Rapoport's pattern). However, bivalve and bird genera show predominantly nested ranges - genera with broad ranges are found at most latitudes whereas narrow-ranging genera are much more common in the tropics. The columns are 5º latitudinal bands (ordered by increasing richness). The rows represent species ordered such that broad-ranging taxa are at the bottom and taxa with narrower ranges are more frequent towards the top (i.e., they are nested within broad-ranging species if they occupy latitudes within their range). This ordering is based on an iterative procedure, attempting to maximize both the gradient in richness and in nestedness of ranges.

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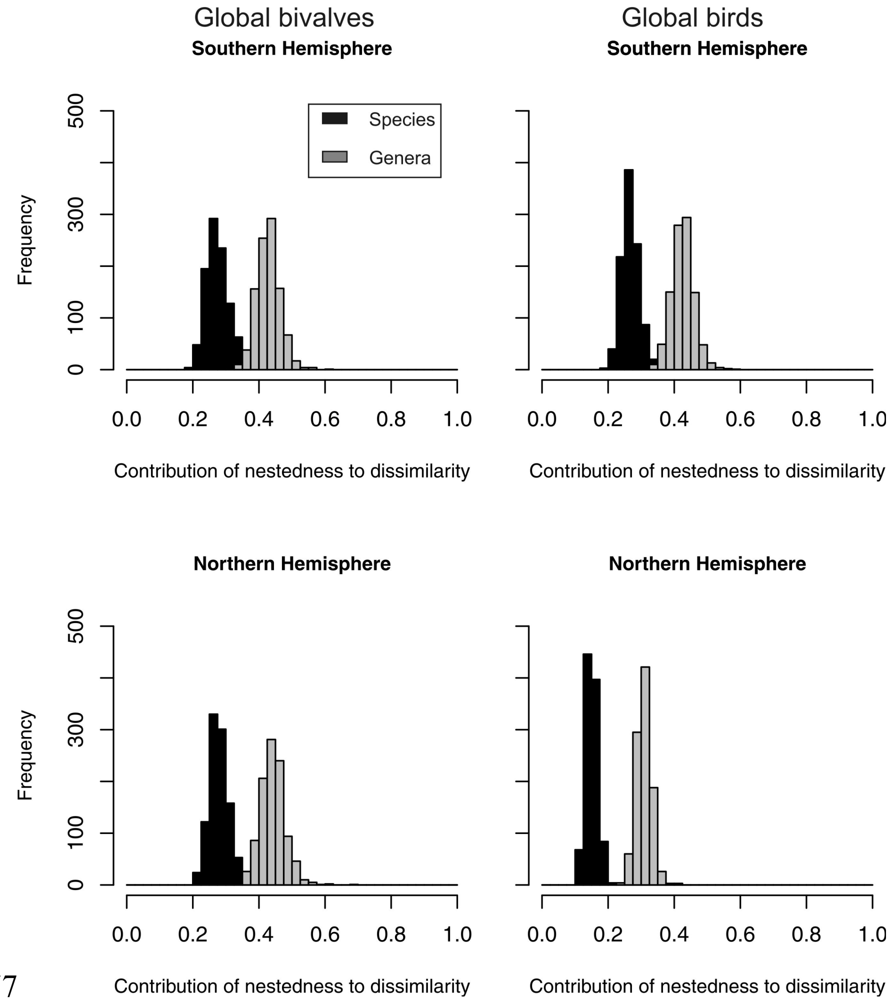

Figure S5 - At species level, turnover (Simpson dissimilarity) contributes with 75% (Southern Hemisphere) and 85% (Northern H.) to total (Sorenson) dissimilarity in birds, and with 73% (Southern H.) and 72% (Northern H.) to total dissimilarity in bivalves. At genus level, turnover contributes with 57% (Southern H.) and 69% (Northern H.) to total dissimilarity in birds, and with 57% (Southern H.) and 55% (Northern H.) to total dissimilarity in bivalves. The mean contribution of nestedness to total dissimilarity is significantly larger at genus than at species level in both hemispheres and in both groups (all $p < 0.001$). In both groups, turnover rather than nestedness thus accounts for species range-size gradients.

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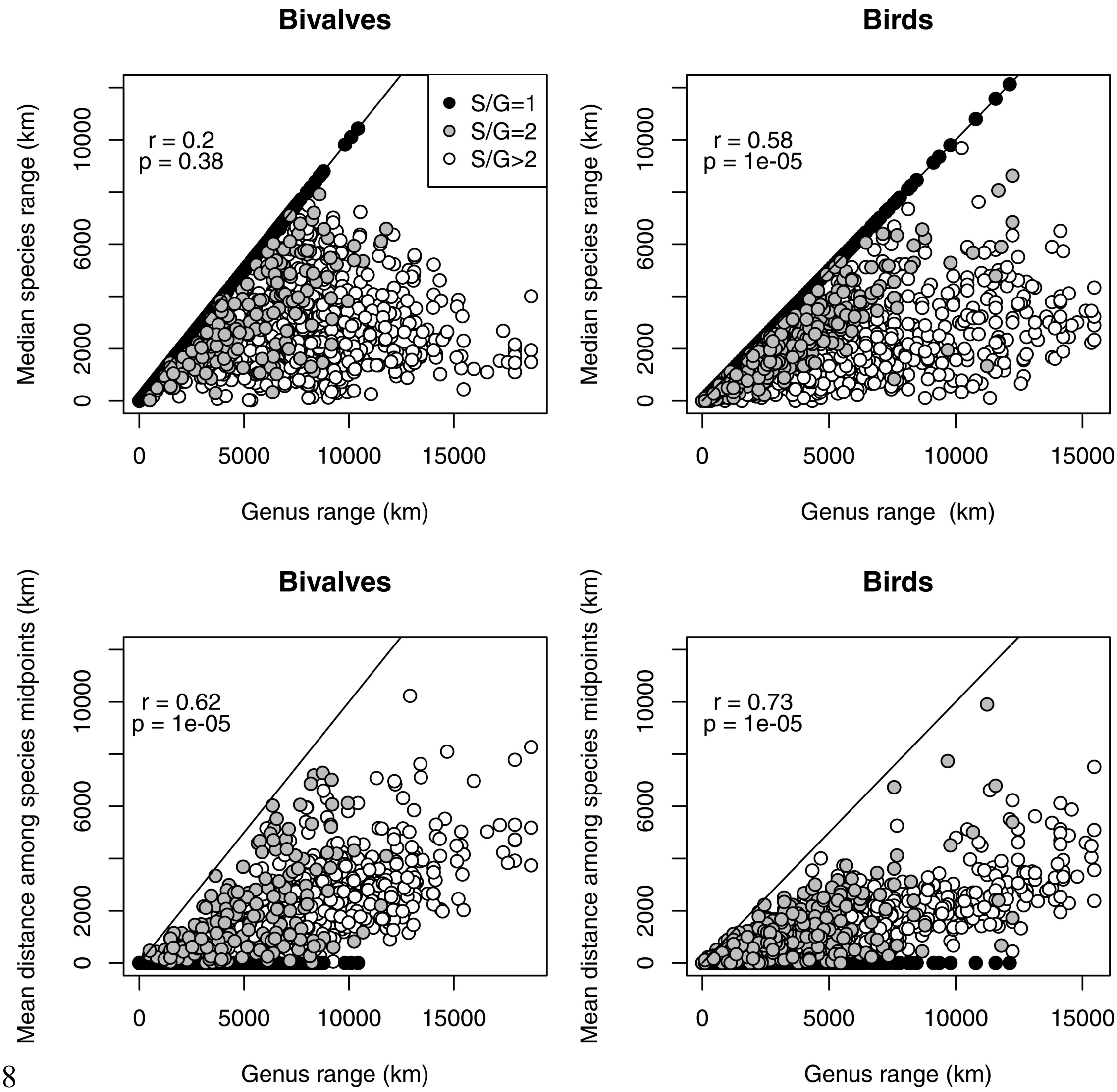

Figure S6 *Top row:* Spearman rank correlation (*r*) between genus latitudinal range size and per-genus median species latitudinal range size for bivalves (left) and birds (right). *Bottom row:* Per-genus mean latitudinal distance among species centroids against genus latitudinal range size for bivalves (left) and birds (right). Similar results apply to three regional datasets. Genera are subdiviced according to their per-genus species richness (S/G) into three categories, including monospecific genera (where species and genus range sizes are the same by default, black points), genera with two species (gray points), and genera with more than two species (white points).

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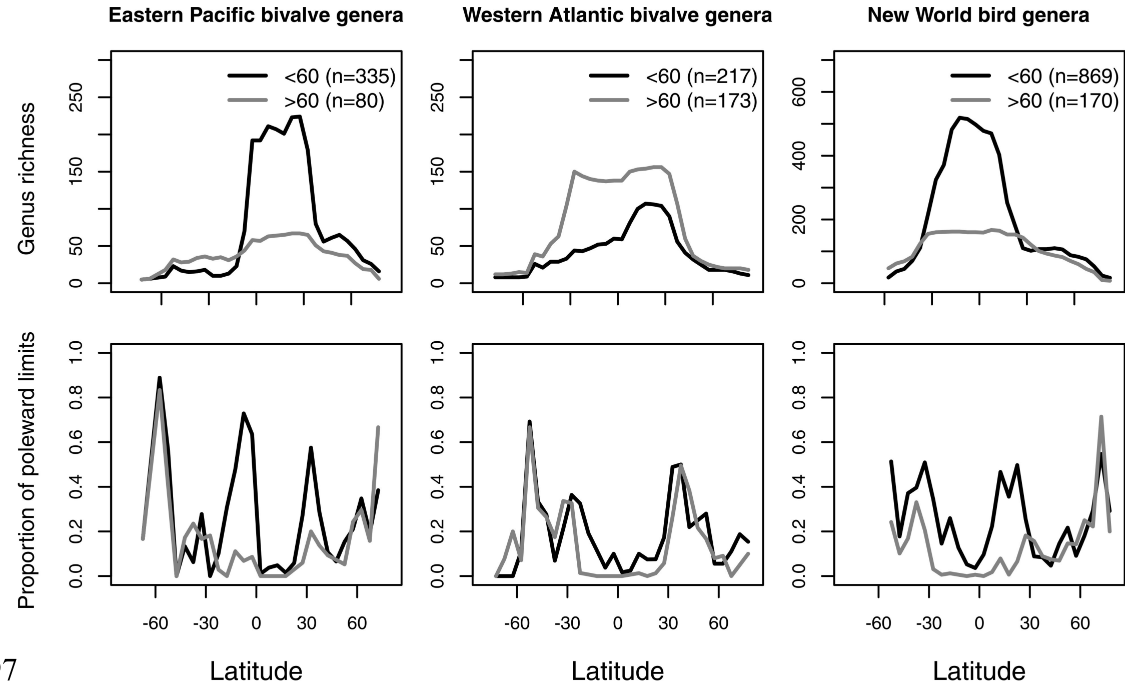

Figure S7 - Latitudinal gradients in genus richness and the proportion of poleward range limits (i.e., the number of genera with poleward range limits relative to all genera in a given band) of two groups of genera delimited by having a range size smaller or larger than 60° (here, at the resolution of 5° bands).

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