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## Supplementary Information for

# Trophically integrated ecometric models as tools for demonstrating spatial and temporal functional changes in mammal communities

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**This PDF file includes:**

Figures S1 to S9

Tables S1 to S9

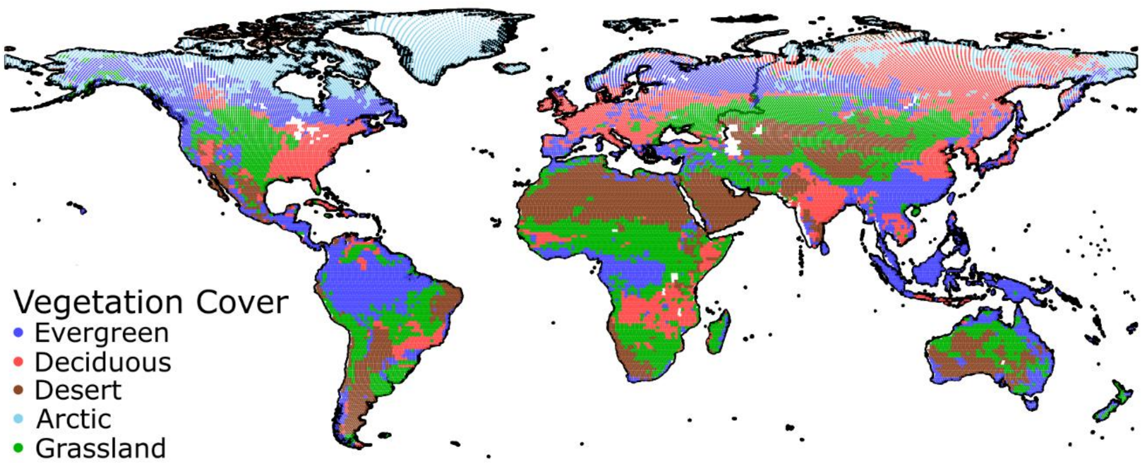


**Figure S1.** Vegetation cover simplified from Matthews' vegetation cover (1). The full and simplified vegetation categories are listed in Table S9.

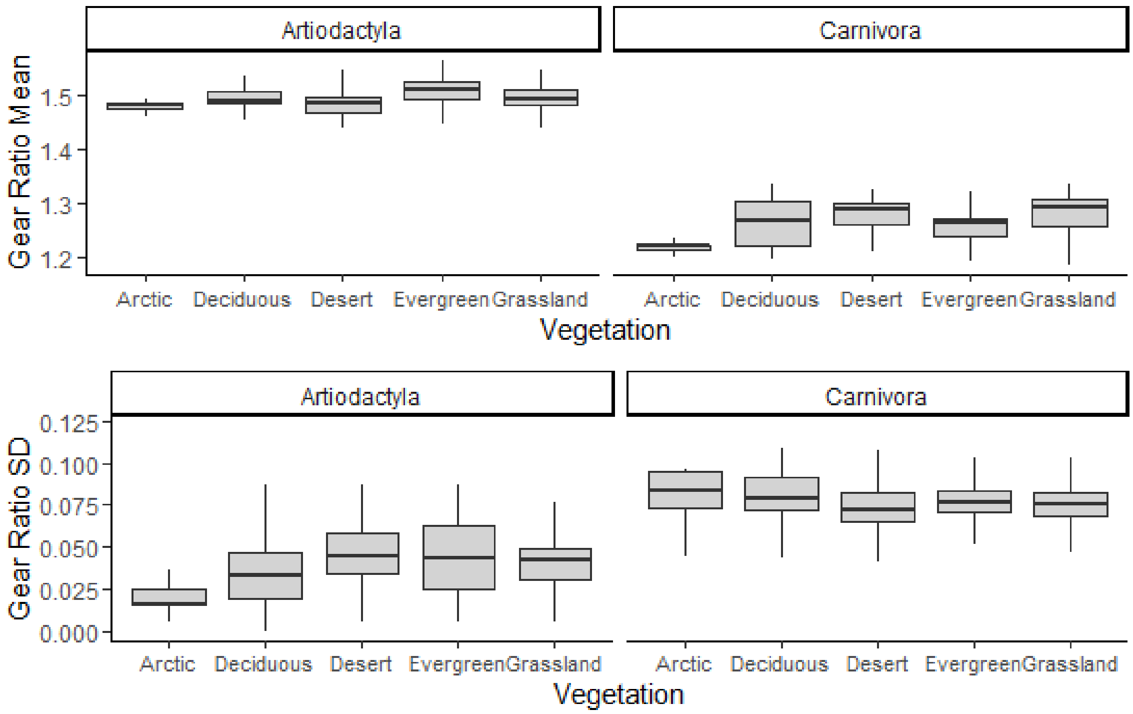


**Figure S2.** Distribution of mean and standard deviation of gear ratios in each vegetation type for Artiodactyla and Carnivora communities.

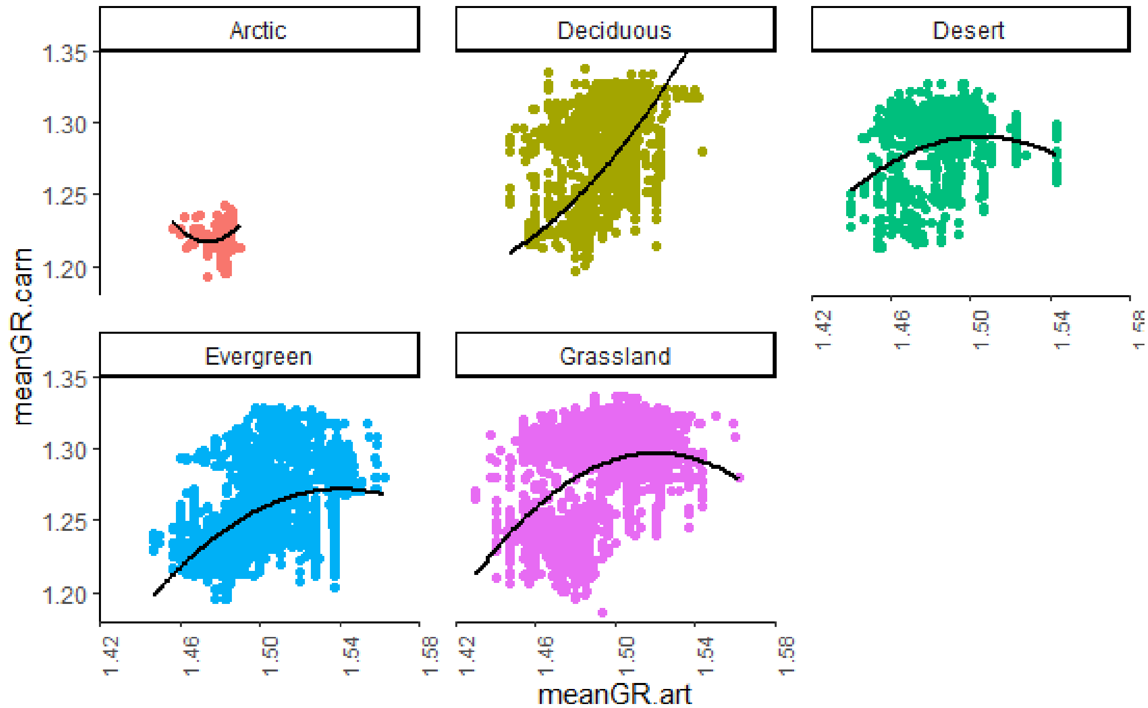


**Figure S3.** Distribution of means of gear ratios within each vegetation type for Artiodactyla and Carnivora. The second order polynomial curves are plotted for each vegetation type. Arctic (n = 374), Deciduous (n = 5215), Desert (n = 1538), Evergreen (n = 7569) and Grassland (n = 6067). Each point is mean gear ratio summarized for each community from our systematic sampling at 50 km equidistant points across the globe.

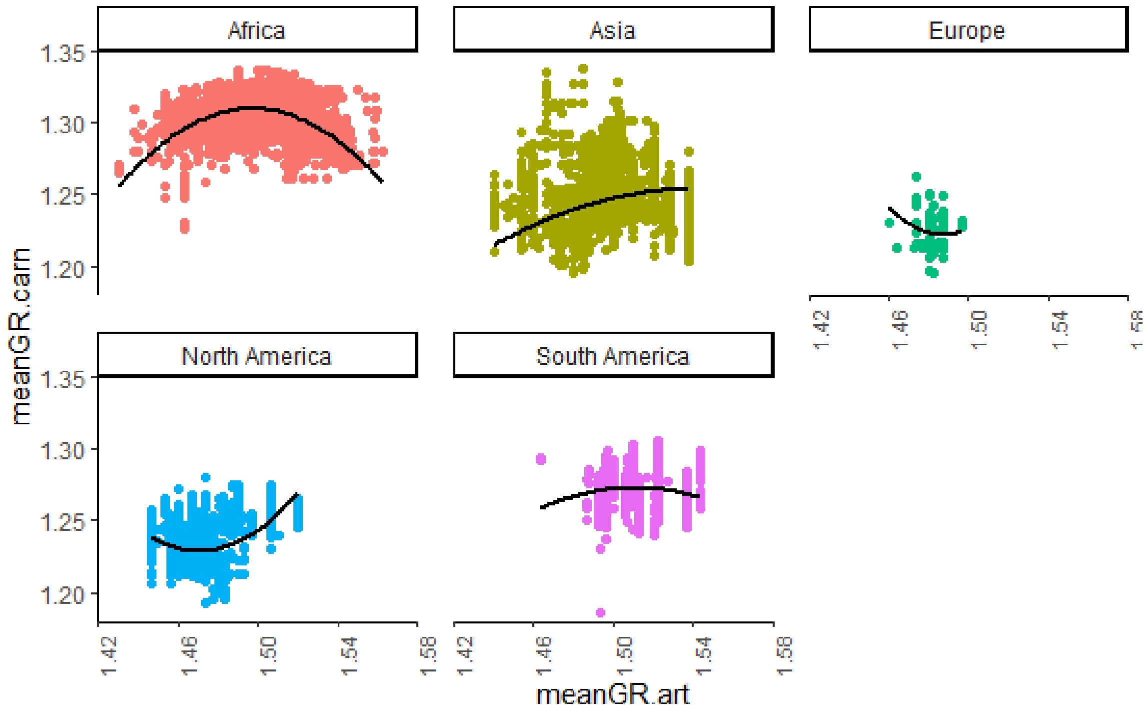


**Figure S4.** Distribution of means of gear ratios within each continent for Artiodactyla and Carnivora. The second order polynomial curves are plotted for each continent. Africa (n = 7307), Asia (n = 6271), Europe (n = 530), North America (n = 2494) and South America (n = 4454). Each point is mean gear ratio summarized for each community from our systematic sampling at 50 km equidistant points across the globe.

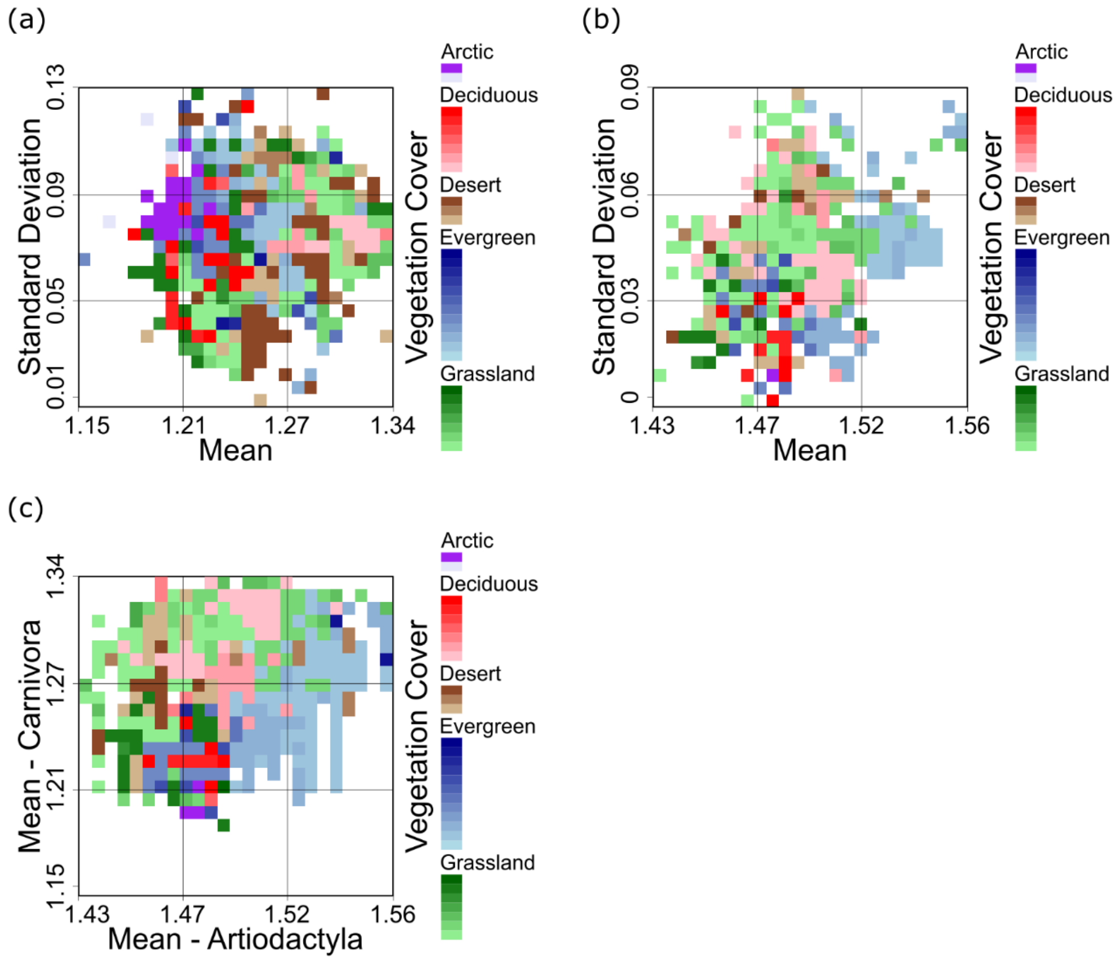


**Figure S5.** Ecometric spaces showing the most likely vegetation cover given the mean and standard deviation of gear ratios that occur within each ecometric bin. (a) carnivorans only; (b) artiodactyls only; (c) trophically integrated.

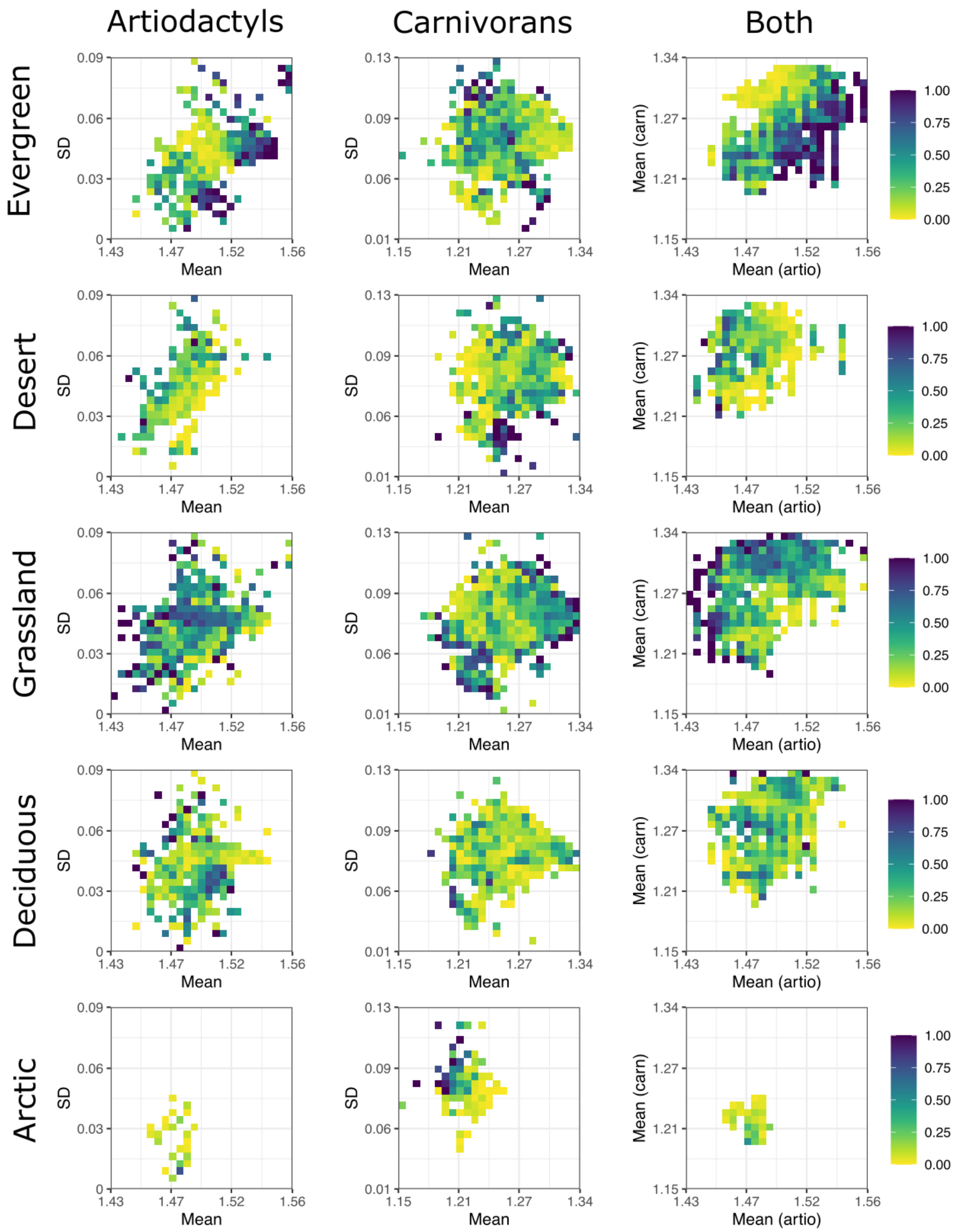


**Figure S6.** Likelihood surfaces of the ecometric trait spaces for Artiodactyla (first column), Carnivora (second column), and the integrated model (third column) for each of five simplified vegetation categories (rows). The ecometric trait spaces for the first two columns show mean on the x axis and standard deviation on the y axis. The third column of spaces shows the artiodactyl mean on the x axis and the carnivoran mean on the y axis. The color gradients represent the likelihood for each vegetation type given the mean and standard deviation of the gear ratios that occur within each ecometric trait bin.

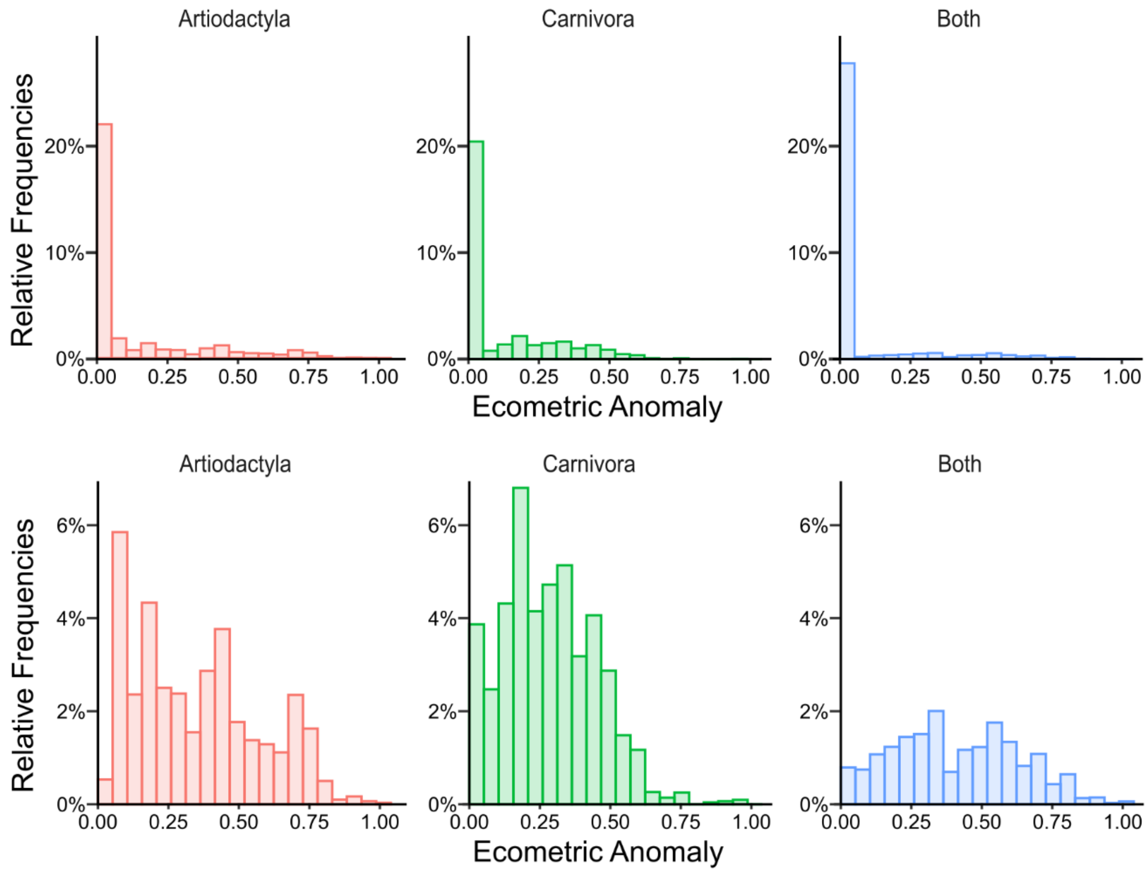


**Figure S7.** Distribution of ecometric anomalies for each of the three ecometric models (Artiodactyla only, Carnivora only and trophically integrated). The top row includes communities that had correctly classified vegetation types from the ecometric models, where the ecometric anomaly equals zero, and communities that do not have correctly classified vegetation type, where the ecometric anomaly is greater than zero. The bottom row displays only the communities that do not have correctly classified vegetation type, where the ecometric anomaly is greater than zero.

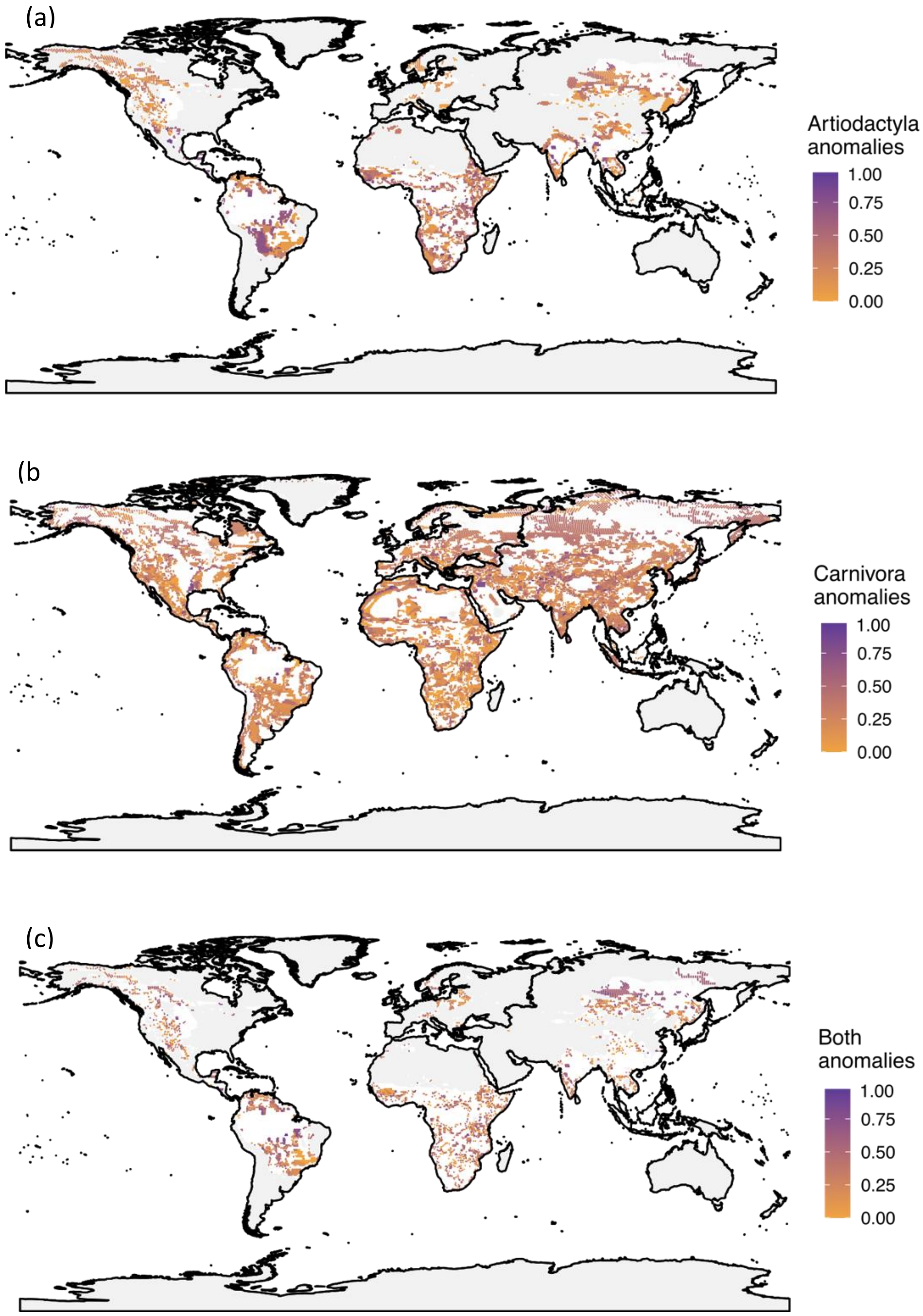


**Figure S8.** Geographic distribution of the ecometric anomalies for (a) the Artiodactyla model, (b) the Carnivora model, and (c) the trophically integrated model. Anomalies are calculated from the likelihood value of the most likely vegetation type minus the likelihood value of the observed vegetation type given observed gear ratios within ecometric trait bins. An ecometric anomaly of zero is white and indicates that the most likely vegetation type is also the observed vegetation type. There are more communities with white or lighter hues in the trophically integrated model.

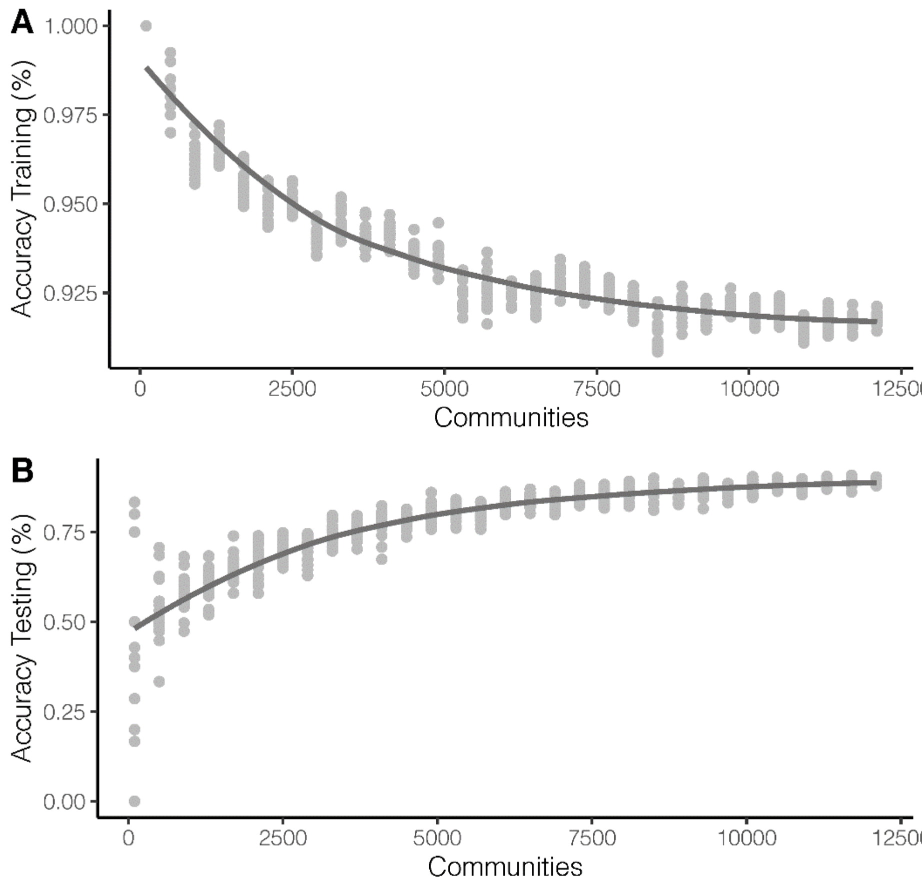


**Figure S9.** Accuracy of training data (a) and testing data (b) measured by the percent of communities that have ecometric anomalies less than 0.3. The loess curve is fitted to the data using default parameters for the loess() function in R with default parameters.

**Table S1.** Analysis of variance table evaluating the gear ratio across vegetation types for each community level metric (artiodactyl mean $R^2_{adj} = 0.16$, $p < 0.01$, artiodactyl standard deviation $R^2_{adj} = 0.04$, $p < 0.01$, carnivoran mean $R^2_{adj} = 0.14$, $p < 0.01$, and carnivoran standard deviation $R^2_{adj} = 0.07$, $p < 0.01$).

| | Df | Sum Sq | Mean Sq | F value | Pr (>F) |
|---|---|---|---|---|---|
| **Artiodactyl mean** | | | | | |
| Vegetation type | 4 | 1.64 | 0.409 | 957.75 | < 2.2e-16 |
| Residuals | 20758 | 8.87 | 0.0004 | | |
| **Artiodactyl standard deviation** | | | | | |
| Vegetation type | 4 | 0.12 | 0.0293 | 196.68 | < 2.2e-16 |
| Residuals | 20758 | 3.09 | 0.0001 | | |
| **Carnivoran mean** | | | | | |
| Vegetation type | 4 | 3.16 | 0.789 | 823.31 | < 2.2e-16 |
| Residuals | 20758 | 19.91 | 0.01 | | |
| **Carnivoran standard deviation** | | | | | |
| Vegetation type | 4 | 0.511 | 0.128 | 391.7 | < 2.2e-16 |
| Residuals | 20758 | 6.77 | 0.0003 | | |

**Table S2.** Gear ratio data for each continent. N values refer to the number of communities in the integrated model. Mean, standard deviation, minimum, maximum, and range are provided for the mean gear ratio and the standard deviation of gear ratio for both trophic levels.

| Continent | Model | Mean | Standard Deviation | Minimum | Maximum | Range |
|---|---|---|---|---|---|---|
| Africa (n = 7307) | | | | | | |
| | Mean Artiodactyla | 1.50 | 0.02 | 1.43 | 1.56 | 0.13 |
| | SD Artiodactyla | 0.04 | 0.01 | 0.00 | 0.08 | 0.08 |
| | Mean Carnivora | 1.30 | 0.02 | 1.23 | 1.34 | 0.11 |
| | SD Carnivora | 0.07 | 0.01 | 0.03 | 0.11 | 0.08 |
| Asia (n = 6271) | | | | | | |
| | Mean Artiodactyla | 1.49 | 0.02 | 1.44 | 1.54 | 0.10 |
| | SD Artiodactyla | 0.03 | 0.01 | 0.01 | 0.06 | 0.05 |
| | Mean Carnivora | 1.24 | 0.02 | 1.20 | 1.34 | 0.14 |
| | SD Carnivora | 0.08 | 0.01 | 0.02 | 0.12 | 0.10 |
| Europe (n = 530) | | | | | | |
| | Mean Artiodactyla | 1.48 | 0.00 | 1.46 | 1.50 | 0.04 |
| | SD Artiodactyla | 0.01 | 0.01 | 0.00 | 0.03 | 0.03 |
| | Mean Carnivora | 1.22 | 0.01 | 1.20 | 1.26 | 0.07 |
| | SD Carnivora | 0.06 | 0.02 | 0.03 | 0.09 | 0.06 |
| North America (n = 2494) | | | | | | |
| | Mean Artiodactyla | 1.47 | 0.02 | 1.45 | 1.52 | 0.07 |
| | SD Artiodactyla | 0.04 | 0.02 | 0.01 | 0.09 | 0.08 |
| | Mean Carnivora | 1.23 | 0.02 | 1.19 | 1.28 | 0.09 |
| | SD Carnivora | 0.07 | 0.01 | 0.03 | 0.10 | 0.07 |
| South America (n = 4454) | | | | | | |
| | Mean Artiodactyla | 1.52 | 0.01 | 1.46 | 1.54 | 0.08 |
| | SD Artiodactyla | 0.06 | 0.00 | 0.02 | 0.08 | 0.07 |
| | Mean Carnivora | 1.27 | 0.01 | 1.19 | 1.31 | 0.12 |
| | SD Carnivora | 0.08 | 0.01 | 0.07 | 0.11 | 0.04 |

**Table S3.** Linear mixed effects model evaluating the relationship between mean gear ratios of communities of artiodactyls and carnivorans with the random effect of continent. The correlation of fixed effects for this model is -0.553.

| Fixed Effects | | | | | |
|---|---|---|---|---|---|
| | numDf | denDF | Coefficient | F value | Pr (>F) |
| Intercept | 1 | 21050 | 1.13 | 7821.20 | < 0.0001 |
| Artiodactyla Gear Ratio | 1 | 21050 | 0.08 | 167.80 | < 0.0001 |
| Random Effect | | | | | |
| | Observations | Variance | Std Dev | | |
| Continent | 5 | 0.0101 | 0.0317 | | |
| Residual | 21056 | 0.00029 | 0.0169 | | |

**Table S4.** Agreement between the estimated vegetation and observed vegetation for each model (carnivoran only, n = 47,270, artiodactyl only, n = 20,766, and trophically integrated, n = 20,763) and within each vegetation type. Kappa scores were only calculated for the complete dataset of vegetation cover.

| | Carnivora | | | Artiodactyla | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|
| Vegetation | Agreement | Kappa | p value | Agreement | Kappa | p value | Agreement | Kappa | p value |
| All | 57.66% | 0.45 | 0 | 64.75% | 0.50 | 0 | 80.85% | 0.73 | 0 |
| Arctic | 56.96% | - | - | 5.61% | - | - | 22.19% | - | - |
| Deciduous | 47.35% | - | - | 62.30% | - | - | 77.66% | - | - |
| Desert | 60.62% | - | - | 26.72% | - | - | 77.24% | - | - |
| Evergreen | 62.01% | - | - | 75.33% | - | - | 87.24% | - | - |
| Grassland | 59.49% | - | - | 66.94% | - | - | 80.14% | - | - |

**Table S5.** Select paleontological sites. Site ID is an identifier from the Neotoma Database (2). Richness and trait values are calculated from species lists housed in the Neotoma Database.

| | Site Name | Site ID | Age | | Artiodactyl | | | Carnivoran | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Minimum | Maximum | Richness | Mean gear ratio | SD gear ratio | Richness | Mean gear ratio | SD gear ratio |
| 1. | Sjovold [EiNs-4] | 23638 | 0 | 4500 | 3 | 1.483 | 0.0208 | 6 | 1.232 | 0.0893 |
| 2. | Lamar | 4367 | 1 | 1695 | 4 | 1.490 | 0.0258 | 6 | 1.218 | 0.0703 |
| 3. | Bear River No. 3 | 4980 | 950 | 1500 | 3 | 1.473 | 0.0416 | 5 | 1.230 | 0.0892 |
| 4. | Fisher | 5763 | 550 | 1650 | 3 | 1.487 | 0.0416 | 11 | 1.238 | 0.0590 |
| 5. | McKinstry [21KC2] | 5893 | 1150 | 1650 | 4 | 1.480 | 0.0337 | 10 | 1.230 | 0.0897 |

**Table S6.** Modern and past vegetation types at select paleontological sites. Estimated vegetation types are reported from the trophically integrated model. When two vegetation types had high probabilities, we have provided both. The modern estimated and modern observed vegetation types are reported from the nearest modern sampling point to each paleontological site, except for Fisher and McKinstry sites because they are too far from any of our modern sampling points. Modern observed data are from our simplified version of Matthews' vegetation cover (see Table S9). The paleoenvironmental interpretation is also simplified from discussions in the literature, cited in the References.

| | Site Name | Site ID | Vegetation | | | | References |
|---|---|---|---|---|---|---|---|
| | | | Modern Estimated | Modern Observed | Paleo Estimated | Paleo Interpretation | |
| 1. | Sjovold [EiNs-4] | 23638 | grassland | grassland | deciduous/evergreen | Grasslands to parklands transition | (3–7) |
| 2. | Lamar | 4367 | evergreen | evergreen | evergreen | Mixed evergreen forest and grasslands, Forest habitats (evergreen) persisted from then to now in same relative abundance, Dense tall grass habitats reduced to sparse and arid grasslands habitats | (8, 9) |
| 3. | Bear River No. 3 | 4980 | grassland | grassland | deciduous | Grassland with increasing mosaic habitats towards modern that decreased grassland connectivity | (10–12) |
| 4. | Fisher | 5763 | NA | NA | evergreen/grassland | "Tundra forest" to boreal forest | (13–15) |
| 5. | McKinstry [21KC2] | 5893 | NA | NA | deciduous | Mixed forest (evergreens and deciduous) | (16, 17) |

**Table S7.** Fauna recorded at each site in the fossil community and in the modern community. Site ID is an identifier from the Neotoma Database (2). Point ID is the nearest sampling point from which the modern communities were extracted. O ID is the species list compiled from sampling range maps at the Point ID.

| | Site Name | Bear River No. 3 | | Lamar | | Sjovold [EiNs-4] | |
|---|---|---|---|---|---|---|---|
| | Site ID | 4980 | | 4367 | | 23638 | |
| | Point ID | 136819 | | 132163 | | 124709 | |
| | O ID | 32141 | | 29827 | | 25600 | |
| Order | Species | Time Period | | | | | |
| | | Fossil | Modern | Fossil | Modern | Fossil | Modern |
| Artiodactyla | *Alces americanus* | | | | | x | |
| | *Antilocapra americana* | x | x | x | | x | x |
| | *Bison bison* | x | | x | | | |
| | *Cervus elaphus* | | x | x | x | x | |
| | *Odocoileus hemionus* | x | x | | x | | x |
| | *Odocoileus virginianus* | | x | | x | | x |
| | *Ovis canadensis* | | | x | | | |
| Carnivora | *Canis latrans* | | x | x | x | | x |
| | *Canis lupus* | | | x | x | x | |
| | *Lontra canadensis* | x | x | | x | | x |
| | *Lynx canadensis* | | | | | x | |
| | *Lynx rufus* | x | x | | x | | |
| | *Martes pennanti* | | | | | x | |
| | *Mephitis mephitis* | x | x | x | x | | x |
| | *Mustela erminea* | | x | | x | | |
| | *Mustela frenata* | | x | | x | | x |
| | *Mustela nivalis* | | | | | | x |
| | *Neovison vison* | x | | | x | | x |
| | *Procyon lotor* | | | | x | | x |
| | *Puma concolor* | | x | | x | | |
| | *Spilogale gracilis* | | x | | | | |
| | *Taxidea taxus* | | x | x | x | x | x |
| | *Urocyon cinereoargenteus* | | x | | | | |
| | *Ursus americanus* | x | | | x | | |
| | *Ursus arctos* | | | x | x | x | |
| | *Vulpes velox* | | | | | x | |
| | *Vulpes vulpes* | | | x | | | |

**Table S8.** Sample sizes of communities associated with the systematic 50 km equidistant sampling scheme for carnivoran and artiodactyl communities within and among regions.

| | | Richness > 0 | | Richness > 2 | |
|---|---|---|---|---|---|
| Regions | All | Carnivora | Artiodactyla | Carnivora | Artiodactyla |
| Global | 54090 | 49838 | 47404 | 48682 | 25659 |
| Africa | 12046 | 11968 | 11653 | 11835 | 7355 |
| Asia | 17988 | 17351 | 16651 | 17148 | 9605 |
| Europe | 3961 | 3913 | 3722 | 3802 | 1641 |
| North America | 9699 | 9488 | 8682 | 8905 | 2504 |
| South America | 7132 | 7110 | 6694 | 6992 | 4554 |

**Table S9.** Corresponding vegetation cover categories between Matthews' vegetation cover (1) and the simplified version from Short and Lawing (18).

| Matthews' Vegetation Number | Matthews' Vegetation Name | Simplified Vegetation Number | Simplified Vegetation Name |
|---|---|---|---|
| 1 | tropical evergreen rainforest | 1 | evergreen |
| 2 | trop/subtropical evergreen seasonal broad-leaved forest | 1 | evergreen |
| 3 | subtropical evergreen rainforest | 1 | evergreen |
| 4 | temperate/subpolar evergreen rainforest | 1 | evergreen |
| 5 | temperate evergreen seasonal broadleaved forest, summer rain | 1 | evergreen |
| 6 | evergreen broadleaved sclerophyllous forest, winter rain | 1 | evergreen |
| 7 | tropical/subtropical evergreen needle-leaved forest | 1 | evergreen |
| 8 | temperate/subpolar evergreen needle-leaved forest | 1 | evergreen |
| 9 | tropical/subtropical drought-deciduous forest | 2 | deciduous |
| 10 | cold-deciduous forest, with evergreens | 2 | deciduous |
| 11 | cold-deciduous forest, without evergreens | 2 | deciduous |
| 12 | xeromorphic forest/woodland | 3 | desert |
| 13 | evergreen broadleaved sclerophyllous woodland | 1 | evergreen |
| 14 | evergreen needle-leaved woodland | 1 | evergreen |
| 15 | tropical/subtropical drought-deciduous woodland | 2 | deciduous |
| 16 | cold-deciduous woodland | 2 | deciduous |
| 17 | evergreen broadleaved shrubland/thick, evergreen dwarf-shrubland | 1 | evergreen |
| 18 | evergreen needle-leaved or microphyllous shrubland/thicket | 1 | evergreen |
| 19 | drought-deciduous shrubland/thicket | 2 | deciduous |
| 20 | cold-deciduous subalpine/subpolar shrubland/dwarf shrub | 2 | deciduous |
| 21 | xeromorphic shrubland/dwarf shrubland | 3 | desert |
| 22 | arctic/alpine tundra, mossy bog | 4 | arctic |
| 23 | tall/medium/short grassland, 10-40% woody cover | 5 | grassland |

| | | | |
|---|---|---|---|
| 24 | tall/medium/short grassland, < 10% woody cover | 5 | grassland |
| 25 | tall/medium/short grassland, shrub cover | 5 | grassland |
| 26 | tall grassland, no woody cover | 5 | grassland |
| 27 | medium grassland, no woody cover | 5 | grassland |
| 28 | meadow, short grassland, no woody cover | 5 | grassland |
| 29 | forb formations | 5 | grassland |
| 30 | desert | 3 | desert |
| 31 | ice | 4 | arctic |
| 32 | cultivation | NA | NA |

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