Ecography

ECOG-05126
Tucker, M. A., Santini, L., Carbone, C. and Mueller, T. 2020. Mammal population densities at a global scale are higher in human-modified areas. – Ecography doi: 10.1111/ecog.05126

Supplementary material

Appendix 1. Supplementary Figures and Tables

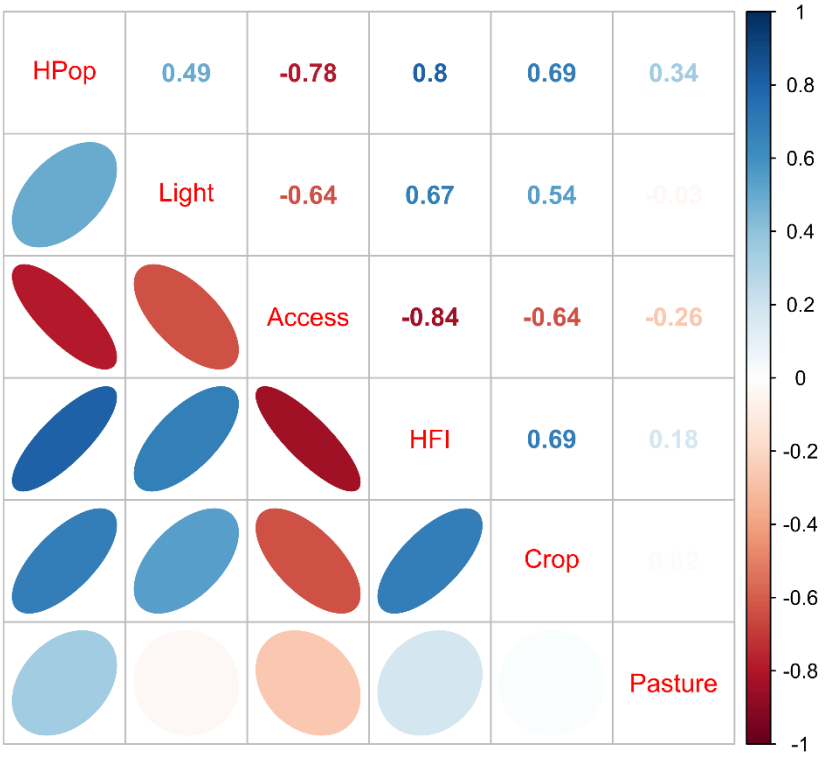

Fig. A1. Correlation plot between the anthropogenic predictive variables: Human Population Density (HPop), Night-Time Lights (Light), Accessibility (Access), Human Footprint Index (HFI), Croplands (Crop) and Pastures (Pasture).

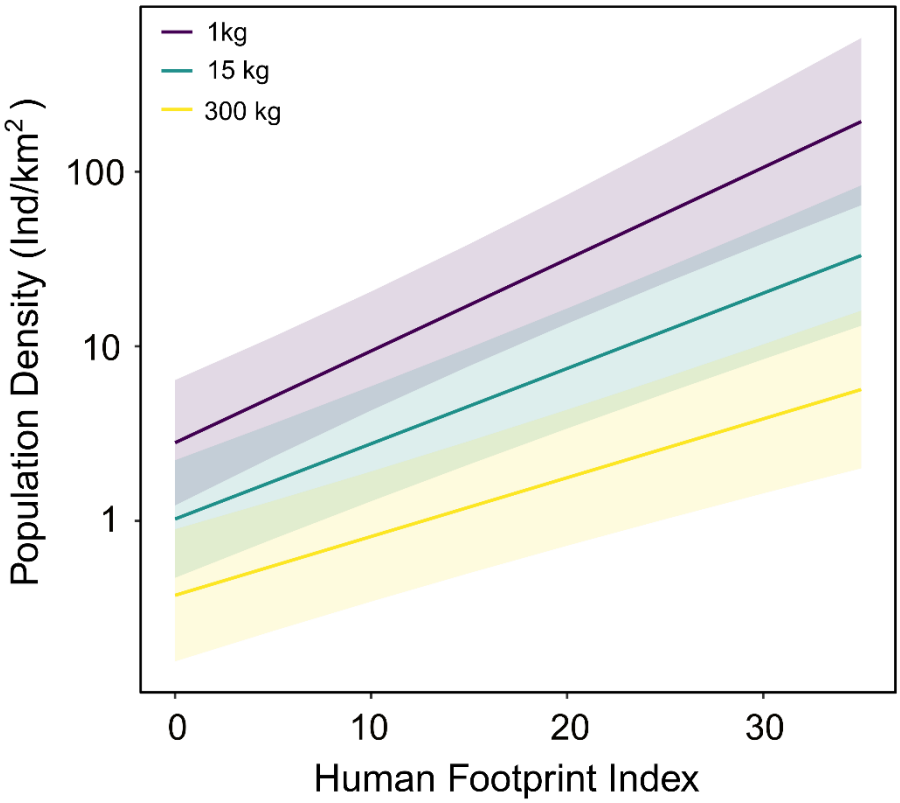

Fig. A2. Plot illustrating the significant interaction term between body mass and the Human Footprint Index (HFI) from the Density($\log_{10}$) ~ Mass + HFI + NDVI + Diet + Mass:HFI + Diet:HFI model.

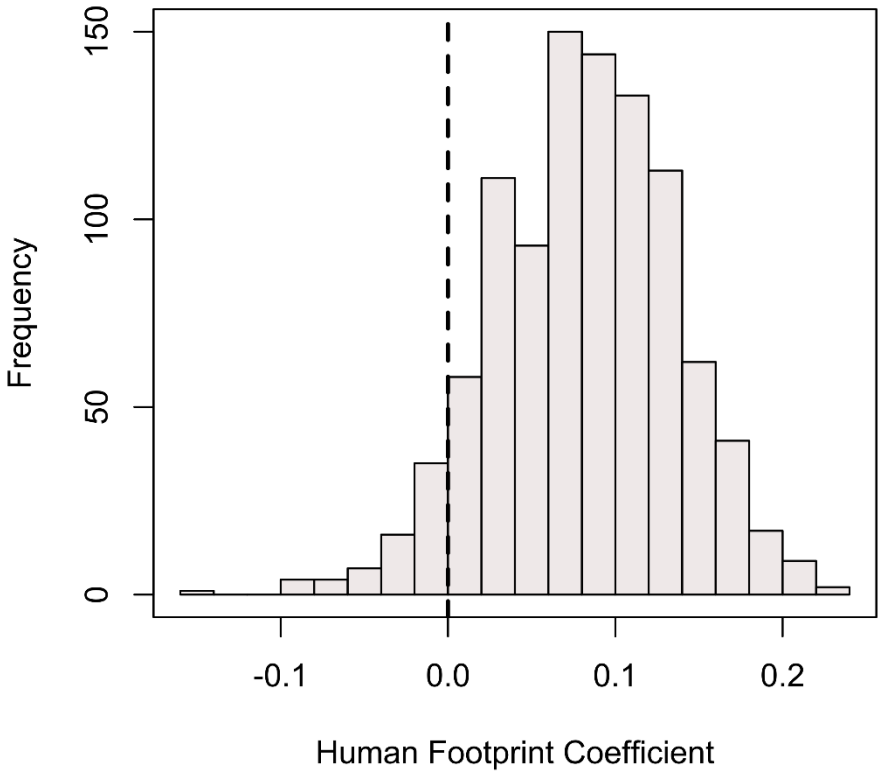

Fig. A3. Histogram of the Human Footprint Index (HFI) coefficients from 1000 regressions where an equal number of points were sampling across the range of HFI. The dashed line at 0 represents no effect, bars to left of this line represent a negative relationship between density and HFI (6.7%) and those on the right represent a positive relationship (93.3%).

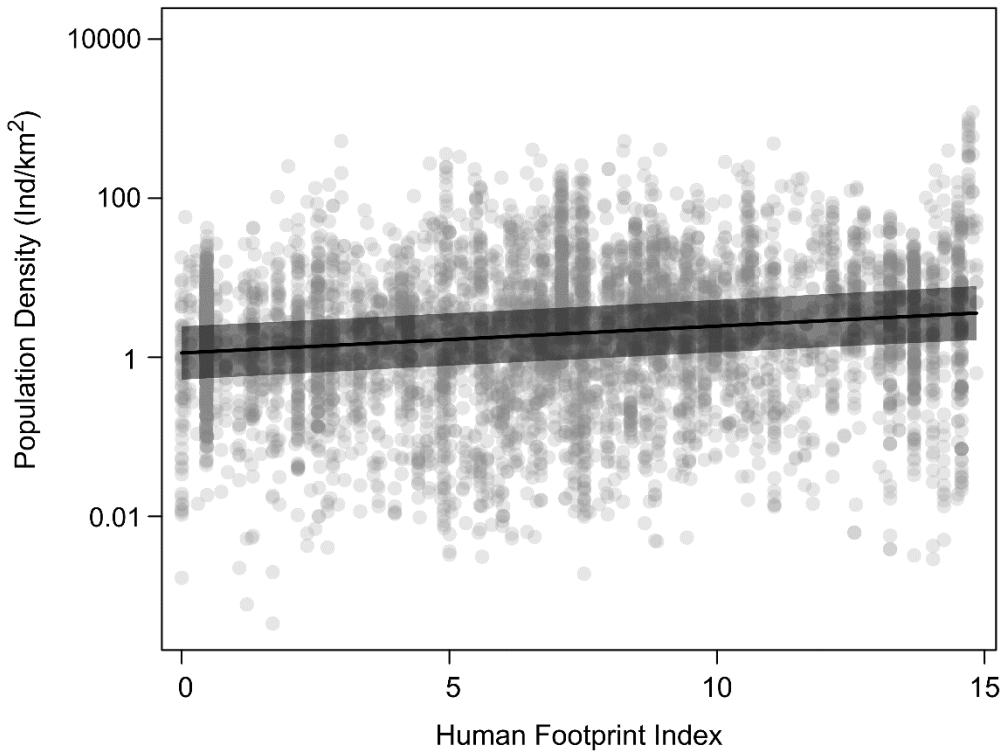

Fig. A4. Partial residual plot for the relationship between mammal population density (individuals per km^2) and the Human Footprint Index bounded between 0 and 15 (n = 5863) with 95% confidence intervals (shaded area). This is a visualisation of the regression model fit in Table A3.

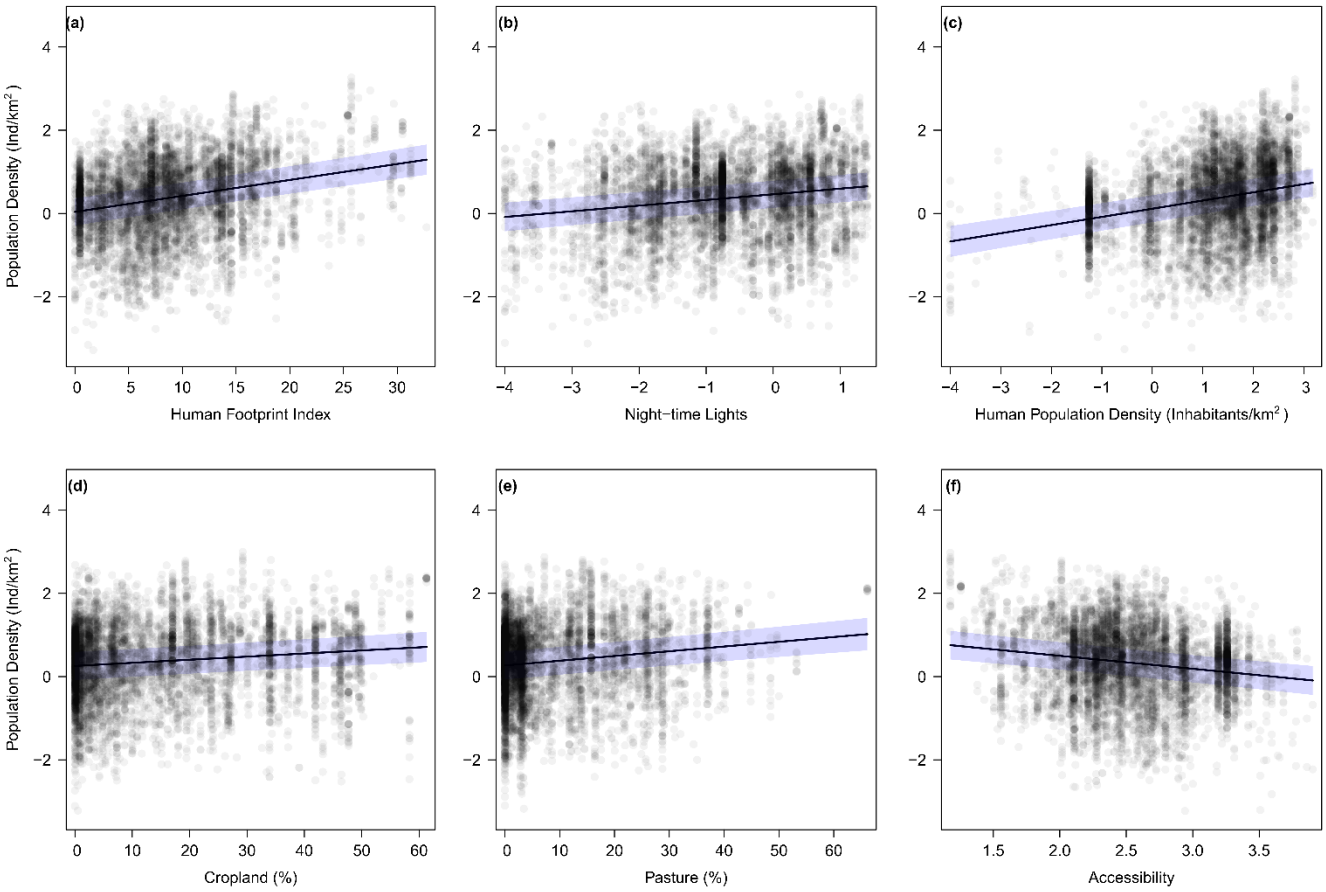

Fig. A5. Partial residual plots for the relationships between $\log_{10}$ mammal population density and the anthropogenic variables a) Human Footprint Index, b) Night-time Lights, c) Human Population Density, d) Percentage of Cropland, e) Percentage of Pasture and f) Accessibility. The blue shaded areas represent the 95% confidence intervals.

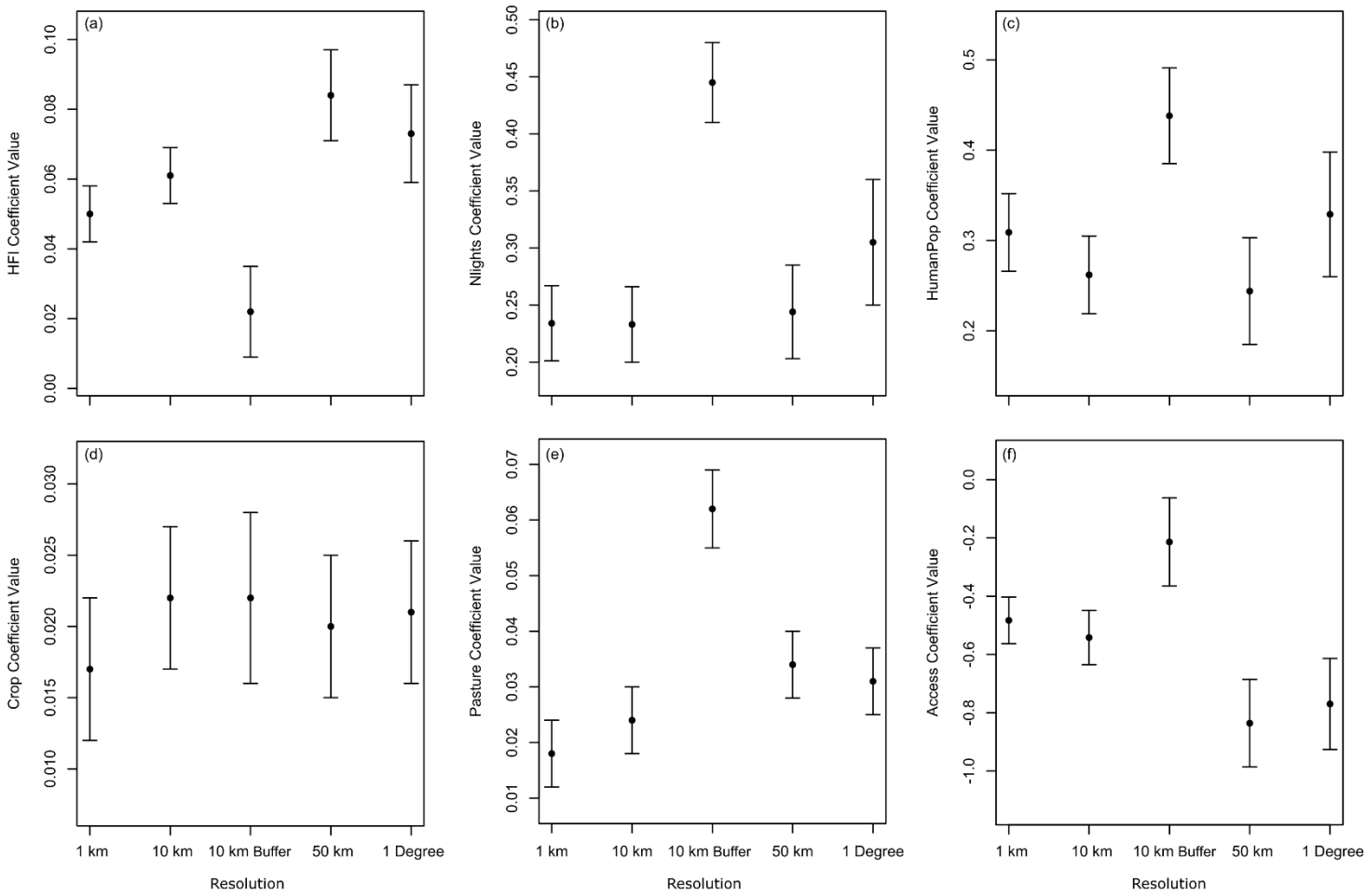

Fig. A6. Average coefficient values (± S.E.) for a) Human Footprint Index, b) Night-time Lights, c) Human Population Density, d) Percentage of Cropland, e) Percentage of Pasture and f) Accessibility. The coefficient values are from models based on 1 km, 10 km, 50 and 1-degree resolution anthropogenic data. The 10 km buffer value is from a model where the anthropogenic data was extracted using on a buffer around each longitude/latitude position based on 100 individuals.

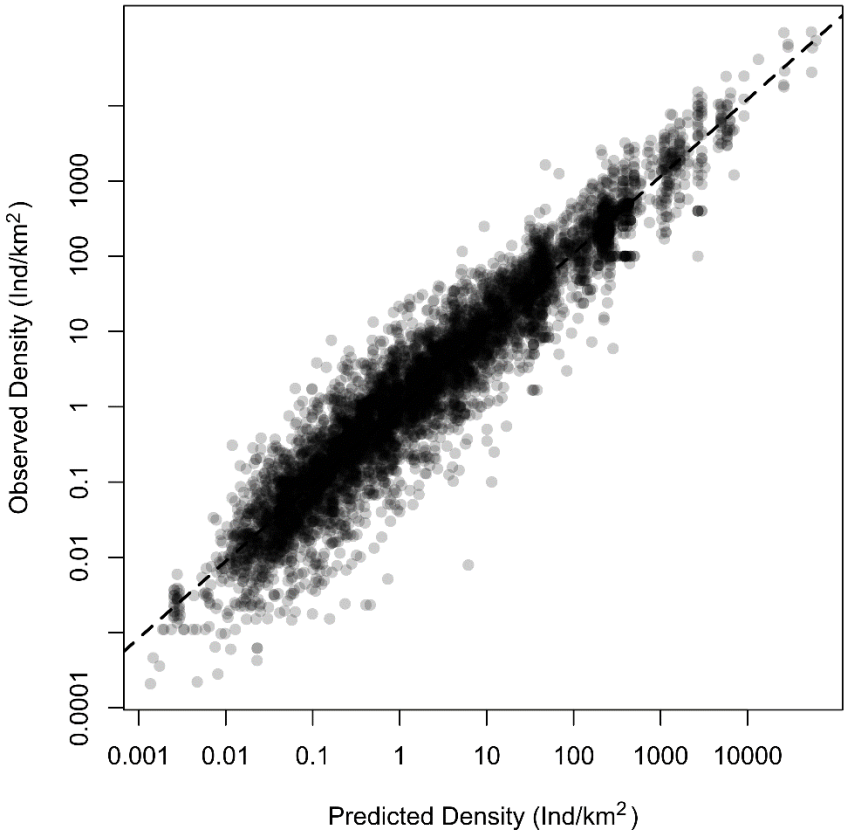

Fig. A7. Predicted vs. observed population densities for the best predictive model (lowest mean absolute error) obtained from the spatial block cross-validation. The relationship between the observed and predicted values to confirm that there is no bias in our model predictions of population density.

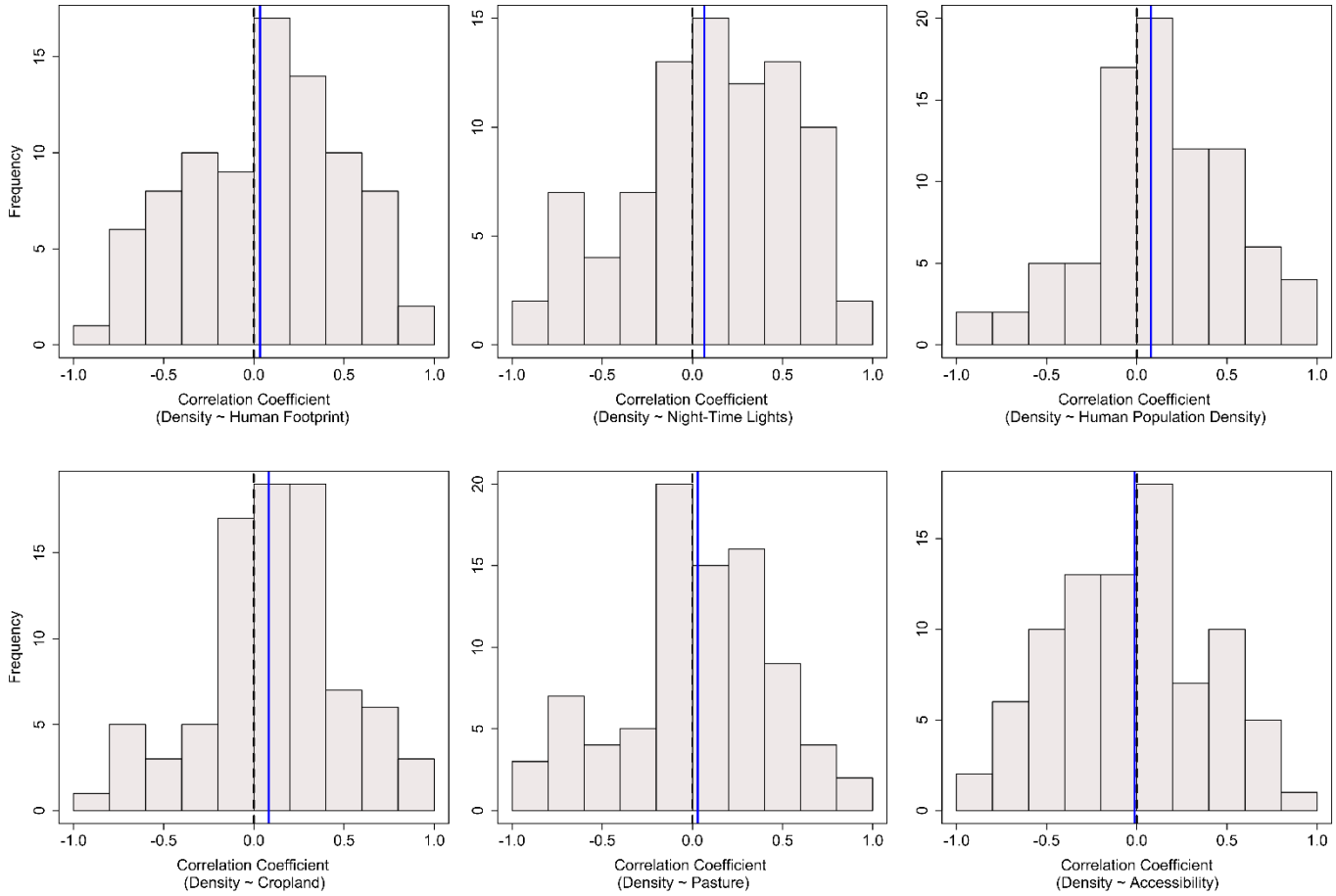

Fig. A8. Histogram of the species-level Spearman's correlation coefficients for the relationship between population density and a) the Human Footprint Index, b) night-time lights, c) human population density, d) croplands, e) pastures and f) accessibility. The black dashed line at 0 represents no effect, bars to left of this line represent a negative relationship and those on the right represent a positive relationship. The solid blue line represents the overall effect size from the meta-regression analyses (see Table A10).

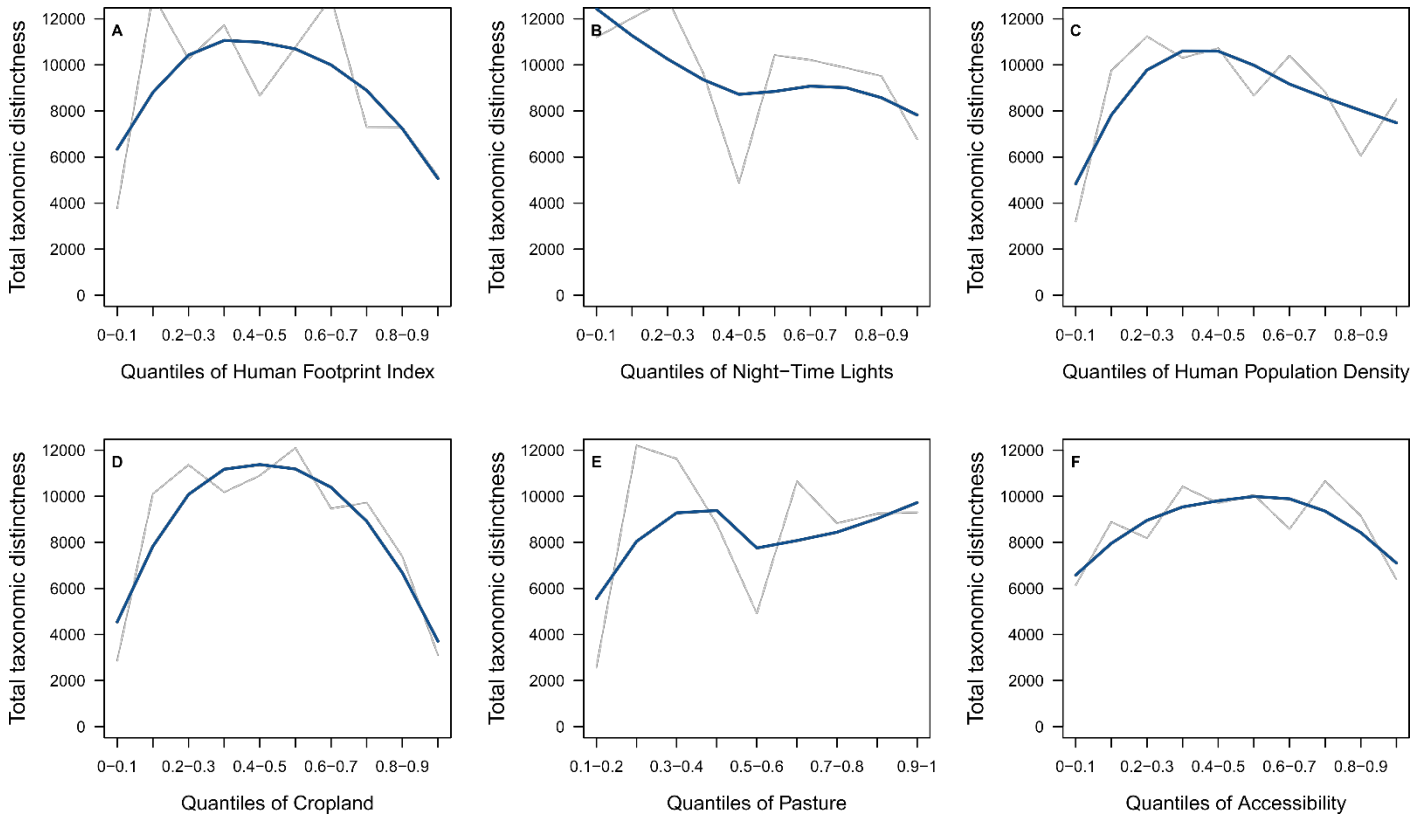

Fig. A9. Taxonomic distinctness relationships with the anthropogenic variables a) Human Footprint Index, b) night-time lights, c) human population density, d) croplands, e) pastures and f) accessibility. The grey lines represent the mean values of each quantile bin and the blue line represents the smoothed trends across the bins.

Table A1. Correlation coefficients between the various anthropogenic variables. Bold values indicate significant correlations ($p < 0.05$).

	Human Population Density	Night-Time Lights	Accessibility	Human Footprint Index	Cropland	Pasture
Human Population Density	-	**0.49**	**-0.78**	**0.8**	**0.69**	**0.34**
Night-Time Lights	**0.49**	-	**-0.64**	**0.68**	**0.54**	**-0.03**
Accessibility	**-0.78**	**-0.64**	-	**-0.84**	**-0.64**	**-0.26**
Human Footprint Index	**0.8**	**0.68**	**-0.84**	-	**0.69**	**0.18**
Cropland	**0.69**	**0.54**	**-0.64**	**0.69**	-	0.02
Pasture	**0.34**	**-0.03**	**-0.26**	**0.18**	0.02	-

Table A2. Details of R packages used in the analyses including the specific function used and its role in the analyses.

Package Name	Function	Role	Reference
lmerTest	lmer()	Used for the linear mixed effects modelling.	Kuznetsova A, Brockhoff PB, Christensen RHB (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, **82**, 1-26. doi: 10.18637/jss.v082.i13
MuMIn	r.squaredGLMM()	Calculating the marginal r2 and conditional r2 for each linear mixed effects model.	Barton, K. (2017). MuMIn: Multi-Model Inference. R package version 1.40.0. https://CRAN.R-project.org/package=MuMIn
bootpredictlme4	predict()	Calculate confidence intervals for lmer model predictions based on parametric bootstrapping.	Duursma, R. (2019). bootpredictlme4: Predict Method For lme4 With Bootstrap. R package version 0.1.
effects	Effect()	Extraction of partial residuals and plotting of model variables.	Fox, J. (2003). Effect Displays in R for Generalised Linear Models. Journal of Statistical Software, 8(15), 1-27. URL http://www.jstatsoft.org/v08/i15/.
phytools	phylosig()	Examine phylogenetic signal in the model residuals (Pagel's λ)	Revell, L. J. (2012) phytools: An R package for phylogenetic comparative biology (and other things). Methods Ecol. Evol. **3** 217-223. doi:10.1111/j.2041-210X.2011.00169.x
ape	read.tree() drop.tip()	Used for phylogenetic tree manipulation	Paradis E. & Schliep K. 2018. ape 5.0: an environment for modern phylogenetics and evolutionary analyses in R. Bioinformatics 35: 526-528.
gdalUtils	gdalwarp()	Used for spatial data manipulation including raster reprojection and resampling.	Greenberg, J.A., and Mattiuzzi, M. (2018). gdalUtils: Wrappers for the Geospatial Data Abstraction Library (GDAL) Utilities. R package version 2.0.1.14. https://CRAN.R-project.org/package=gdalUtils
raster	extract()	Used for spatial data extraction.	Hijmans, R. J. (2019). raster: Geographic Data Analysis and Modeling. R package version 2.8-19. https://CRAN.R-project.org/package=raster
metaphor	escalc() rma.mv()	Used for running mixed-effects meta-regression models.	Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. Journal of Statistical Software, 36(3), 1-48. URL: http://www.jstatsoft.org/v36/i03/
vegan	veg.dist()	Used for calculating the taxonomic distinctness of density estimates	Oksanen, J., Guillaume Blanchet, F., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E., and Wagner, H. (2019). vegan: Community Ecology Package. R package version 2.5-6. https://CRAN.R-project.org/package=vegan
corrplot	corrplot()	Used to estimate the correlation coefficients between the model variables.	Wei, T. and Simko, V. (2017). R package "corrplot": Visualization of a Correlation Matrix (Version 0.84). Available from https://github.com/taiyun/corrplot

Table A3 Model coefficients, standard errors (SE), p values, sample sizes and variance explained (marginal and conditional R^2) of linear mixed effects models predicting terrestrial mammal population density (log_{10}). Predictor variables included fixed effects for body mass (Mass), Human Footprint Index (HFI: 0 – 15 only), Normalized Difference Vegetation Index (NDVI), species richness, diet (H = herbivore and O = omnivore coefficients), and an interaction between HFI and body mass, and HFI and diet. The model also included a nested random effect accounting for the taxonomy and random effects accounting for sampling location, sampling method, continent, season and year. Bold text indicates significance $p < 0.05$.

	Estimate (SE)	**p**
Intercept	1.264 (0.342)	**<0.001**
Mass	-0.338 (0.063)	**<0.001**
Human Footprint (0 – 15)	0.072 (0.02)	**<0.001**
NDVI	0.216 (0.138)	0.116
Species Richness	0.036 (0.089)	0.687
Diet (Carnivore)	-0.277 (0.135)	**0.040**
Diet (Omnivore)	0.340 (0.108)	**0.002**
Human Footprint:Mass	-0.008 (0.004)	**0.039**
Human Footprint:Diet (Carnivore)	0.019 (0.009)	**0.038**
Human Footprint:Diet (Omnivore)	-0.040 (0.009)	**<0.001**
Species	444	
Populations	5831	
R2 Marginal	0.192	
R2 Conditional	0.835	

Table A4. Model coefficients, standard errors (SE), p values, sample sizes and variance explained (marginal and conditional R^2) of linear mixed effects models predicting terrestrial mammalian population density (log_{10}). Predictor variables included fixed effects for body mass (Mass), night-time lights, Normalized Difference Vegetation Index (NDVI), diet (C = carnivore and O = omnivore coefficients and interactions between night-time lights and body mass, and night-time lights and diet. The model also included a nested random effect accounting for the taxonomy and random effects accounting for sampling location, sampling method, continent, season and year. Bold text indicates significance with $p < 0.05$.

Human Population Density	**Estimate (SE)**	**p**
Intercept	2.015 (0.307)	**<0.001**
Mass	-0.352 (0.056)	**<0.001**
Human Pop Density	0.329 (0.069)	**<0.001**
NDVI	-0.161 (0.138)	**0.244**
Species Richness	-0.198 (0.084)	**0.018**
Diet (Carnivore)	-0.207 (0.119)	0.082
Diet (Omnivore)	0.219 (0.094)	**0.021**
Human Pop Density:Mass	-0.028 (0.014)	**0.045**
Human Pop Density:Diet (Carnivore)	0.074 (0.033)	**0.026**
Human Pop Density:Diet (Omnivore)	-0.13 (0.032)	**<0.001**
Species	460	
Populations	6614	
R^2 Marginal	0.197	
R^2 Conditional	0.840	

Table A5. Model coefficients, standard errors (SE), p values, sample sizes and variance explained (marginal and conditional R^2) of linear mixed effects models predicting terrestrial mammalian population density (log_{10}). Predictor variables included fixed effects for body mass (Mass), human population density (Human Pop Density), Normalized Difference Vegetation Index (NDVI), diet (C = carnivore and O = omnivore coefficients and interactions between human population density and body mass, and human population density and diet. The model also included a nested random effect accounting for the taxonomy and random effects accounting for sampling location, sampling method, continent, season and year. Bold text indicates significance with $p < 0.05$.

Night-Time Lights	**Estimate (SE)**	**p**
Intercept	2.394 (0.297)	**<0.001**
Mass	-0.432 (0.054)	**<0.001**
Night Lights	0.305 (0.055)	**<0.001**
NDVI	0.051 (0.125)	0.685
Species Richness	-0.064 (0.086)	0.451
Diet (Carnivore)	-0.171 (0.118)	0.146
Diet (Omnivore)	-0.071 (0.09)	0.430
Night Lights:Mass	-0.036 (0.011)	**0.001**
Night Lights: Diet (Carnivore)	0.042 (0.031)	0.183
Night Lights: Diet (Omnivore)	-0.104 (0.028)	**<0.001**
Species	468	
Populations	6724	
R^2 Marginal	0.236	
R^2 Conditional	0.848	

Table A6. Model coefficients, standard errors (SE), p values, sample sizes and variance explained (marginal and conditional R^2) of linear mixed effects models predicting terrestrial mammalian population density (log_{10}). Predictor variables included fixed effects for body mass (Mass), pasture, cropland, Normalized Difference Vegetation Index (NDVI), diet (C = carnivore and O = omnivore coefficients and interactions between pasture/cropland and body mass, and pasture/cropland and diet. The model also included a nested random effect accounting for the taxonomy and random effects accounting for sampling location, sampling method, continent, season and year. Bold text indicates significance with $p < 0.05$.

Cropland and Pasture	**Estimate (SE)**	**p**
Intercept	1.661 (0.311)	**<0.001**
Mass	-0.308 (0.055)	**<0.001**
Pasture	0.031 (0.006)	**<0.001**
Crop	0.021 (0.005)	**<0.001**
Diet (Carnivore)	-0.13 (0.118)	0.274
Diet (Omnivore)	0.195 (0.092)	**0.034**
NDVI	0.163 (0.139)	0.241
Species Richness	-0.173 (0.089)	0.052
Pasture:Mass	-0.004 (0.001)	**0.001**
Crop:Mass	-0.004 (0.001)	**0.001**
Pasture:Diet (Carnivore)	-0.001 (0.003)	0.662
Pasture:Diet (Omnivore)	-0.016 (0.004)	**<0.001**
Crop:Diet (Carnivore)	0.002 (0.002)	0.423
Crop:Diet (Omnivore)	0.003 (0.002)	0.247
Species	460	
Populations	6614	
R^2 Marginal	0.205	
R^2 Conditional	0.845	

Table A7. Model coefficients, standard errors (SE), p values, sample sizes and variance explained (marginal and conditional R^2) of linear mixed effects models predicting terrestrial mammalian population density (log_{10}). Predictor variables included fixed effects for body mass (Mass), accessibility, Normalized Difference Vegetation Index (NDVI), diet (C = carnivore and O = omnivore coefficients and interactions between accessibility and body mass, and accessibility and diet. The model also included a nested random effect accounting for the taxonomy and random effects accounting for sampling location, sampling method, continent, season and year. Bold text indicates significance with $p < 0.05$.

Accessibility	**Estimate (SE)**	**p**
Intercept	3.927 (0.485)	**<0.001**
Mass	-0.636 (0.096)	**<0.001**
Accessibility	-0.77 (0.156)	**<0.001**
NDVI	0.042 (0.128)	0.740
Species Richness	-0.009 (0.09)	0.918
Diet (Carnivore)	-0.11 (0.239)	0.646
Diet (Omnivore)	-0.659 (0.207)	**0.001**
Accessibility:Mass	0.097 (0.032)	**0.002**
Accessibility:Diet (Carnivore)	-0.026 (0.082)	0.749
Accessibility:Diet (Omnivore)	0.28 (0.072)	**<0.001**
Species	458	
Populations	6626	
R^2 Marginal	0.206	
R^2 Conditional	0.840	

Table A8. Pagel's λ for each model. Note that 0.000066 is the minimum λ value possible for this test.

Model	**Pagel's λ**	**p**
Full Models		
Human Footprint Index	0.000066	1
Night-time Lights	0.000066	1
Human Population Density	0.000066	1
Cropland/Pasture	0.000066	1
Accessibility	0.000066	1

Table A9. Results from the spatial block cross-validation. Spatial blocks were 100 x 100 km, with 8 unique blocks and a systematic sample fold. The Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Mean Absolute Error (MAE), Root Mean Squared Error (RMSE) and pseudo R^2 (squared correlation coefficient between the 'Predicted' and the 'Observed' data) represent the mean values across all 10 spatial blocks. The bold text indicates the model with the lowest MAE.

Model	**AIC**	**BIC**	**MAE**	**RMSE**	**Pseudo R^2**
Null Model					
Density ~ Mass + NDVI + Species Richness + Diet	9995.76	10088.73	0.726	0.868	0.518
Density ~ Mass + HFI + NDVI + Species Richness + Diet + Mass:HFI + Diet:HFI	9945.28	10064.81	0.683	0.818	0.551
Density ~ Mass + HFI + NDVI + Species Richness + Diet + Mass:HFI	9940.38	10046.63	0.698	0.833	0.554
Density ~ Mass + HFI + NDVI + Species Richness + Diet + Diet:HFI	**9939.77**	**10052.66**	**0.663**	**0.797**	**0.559**
Density ~ Mass + NightLights + NDVI + Species Richness + Diet + Mass:NightLights + Diet:NightLights	9941.34	10060.86	0.708	0.838	0.546
Density ~ Mass + NightLights + NDVI + Species Richness + Diet + Mass:NightLights	9942.67	10048.91	0.716	0.846	0.548
Density ~ Mass + NightLights + NDVI + Species Richness + Diet + Diet:NightLights	9937.00	10043.24	0.699	0.831	0.545
Density ~ Mass + HumanDensity + NDVI + Species Richness + Diet + Mass:HumanDensity + Diet:HumanDensity	9734.21	9853.43	0.706	0.835	0.534
Density ~ Mass + HumanDensity + NDVI + Species Richness + Diet + Mass:HumanDensity	9746.22	9852.20	0.787	0.925	0.525
Density ~ Mass + HumanDensity + NDVI + Species Richness + Diet + Diet:HumanDensity	9732.89	9845.49	0.692	0.823	0.541
Density ~ Mass + Crops + Pastures + NDVI + Species Richness + Diet + Mass:Crops + Diet:Crops + Mass:Pastures + Diet:Pastures	9832.51	9978.22	0.782	0.915	0.506
Density ~ Mass + Crops + Pastures + NDVI + Species Richness + Diet + Mass:Crops + Diet:Crops + Mass:Pastures	9802.15	9921.37	0.784	0.919	0.511
Density ~ Mass + Crops + Pastures + NDVI + Species Richness + Diet + Mass:Crops + Diet:Crops + Diet:Pastures	9832.09	9964.56	0.744	0.878	0.520
Density ~ Mass + Access + NDVI + Species Richness + Diet + Mass:Access + Diet:Access	9809.02	9928.27	0.720	0.853	0.564
Density ~ Mass + Access + NDVI + Species Richness + Diet + Mass:Access	9810.16	9916.16	0.740	0.875	0.547
Density ~ Mass + Access + NDVI + Species Richness + Diet + Diet:Access	9810.37	9923.00	0.706	0.839	0.554

Table A10. Model intercepts and p values of the mixed-effects meta-analysis models examining the relationship between mammal population density and the Human Footprint Index, accessibility, cropland, pasture, night-time lights and human population density. The models included a nested term for taxonomy. Significant Q-test values indicate a significant amount of variability in the effect sizes of the predictor variables on mammal population density. Bold text indicates significance with $p < 0.05$.

Predictor	**Intercept (SE)**	**p**	**Q-test**	**Q-test p**
Human Footprint Index	0.034 (0.063)	0.593	136.107	**<0.001**
Night-light	0.067 (0.08)	0.401	149.562	**<0.001**
Human Population density	0.079 (0.073)	0.279	130.018	**0.001**
Cropland	0.082 (0.065)	0.207	108.791	**0.036**
Pasture	0.03 (0.062)	0.625	134.388	**<0.001**
Accessibility	-0.011 (0.078)	0.887	136.996	**<0.001**

Table A11. Model intercepts and p values of the mixed-effects meta-regression models between mammal population density and the anthropogenic variables using body mass and diet as moderators. The models included a nested term of taxonomy. A significant QM-test indicates that the moderator explains a significant amount of the variability between the effect sizes. Bold text indicates significance with $p < 0.05$.

Human Footprint Index			**Estimate(SE)**	**p**	**QM-test**	**QM-test p**
	Body mass	Intercept	0.022(0.262)	0.934	0.002	0.965
		Body mass	0.003(0.057)	0.965		
	Diet	Carnivore	**0.292(0.138)**	**0.034**	4.793	0.188
		Herbivore	-0.016(0.077)	0.837		
		Omnivore	-0.028(0.137)	0.838		
Night-Time Lights						
	Body mass	Intercept	-0.016(0.268)	0.951	0.109	0.741
		Body mass	0.02(0.06)	0.741		
	Diet	Carnivore	**0.32(0.149)**	**0.032**	4.796	0.187
		Herbivore	0.013(0.095)	0.895		
		Omnivore	0.019(0.153)	0.899		
Human Population Density						
	Body mass	Intercept	0.124(0.253)	0.624	0.034	0.854
		Body mass	-0.01(0.056)	0.854		
	Diet	Carnivore	0.257(0.145)	0.076	3.212	0.36
		Herbivore	0.05(0.088)	0.57		
		Omnivore	0.022(0.146)	0.881		
Cropland						
	Body mass	Intercept	0.26(0.223)	0.243	0.703	0.402
		Body mass	-0.04(0.048)	0.402		
	Diet	Carnivore	**0.299(0.134)**	**0.026**	5.064	0.167
		Herbivore	0.061(0.082)	0.456		
		Omnivore	-0.017(0.137)	0.903		
Pasture						
	Body mass	Intercept	0.082(0.246)	0.738	0.051	0.822
		Body mass	-0.012(0.054)	0.822		
	Diet	Carnivore	0.078(0.139)	0.573	0.976	0.807
		Herbivore	0.05(0.079)	0.527		
		Omnivore	-0.08(0.141)	0.568		
Accessibility						
	Body mass	Intercept	0.001(0.262)	0.997	0.003	0.957
		Body mass	-0.003(0.058)	0.957		
	Diet	Carnivore	**-0.357(0.133)**	**0.007**	**10.47**	**0.015**
		Herbivore	0.094(0.08)	0.242		
		Omnivore	-0.009(0.136)	0.946		