
Supplementary information

**Landscape-scale benefits of protected areas
for tropical biodiversity**

In the format provided by the
authors and unedited

SUPPLEMENTARY INFORMATION:
Landscape-scale benefits of protected areas for tropical biodiversity

TABLE 1. Results from mixed-effects linear regression (two-tailed) for species richness (SR), functional richness (FR), and phylogenetic diversity (PD). Values are the model β coefficients (SE; p -value) for the exposure variables in each analysis ('PA', 'PA size', and 'Distance to PA') and associated covariates, with conditional R^2 shown. Adjustments were not made for multiple comparisons. HDI = Human Development Index (a national-level metric); PA = Protected Area; other variables are explained in the main text. All continuous covariates were standardized prior to analysis. Exposure variable coefficients with p -values <0.05 are in bold; covariate coefficients and p -values should not be interpreted in propensity score-matched analyses ¹.

Variable	Birds			Mammals		
	SR	FR	PD	SR	FR	PD
<i>All sites</i>						
R^2	0.343 ^a	0.299 ^b	0.360 ^c	0.377	0.324	0.442
Intercept	133.48 (13.26; 0)	219.05 (10.15; 0)	2.93 (0.28; 0)	9.49 (1.27; 0)	11.08 (1.56; 0)	2.14 (0.23; 0)
Forest canopy height	20.40 (2.05; 0)	36.95 (2.74; 0)	0.09 (0.03; 0.007)	0.30 (0.20; 0.126)	1.41 (0.35; 0.0001)	0.06 (0.03; 0.039)
Site accessibility	4.60 (1.65; 0.005)	5.27 (2.32; 0.024)	-0.08 (0.03; 0.002)	-0.37 (0.29; 0.202)	-0.58 (0.50; 0.242)	-0.05 (0.04; 0.230)
HDI	-7.30 (10.43; 0.506)	-20.83 (7.97; 0.035)	-0.005 (0.22; 0.983)	-0.47 (0.85; 0.607)	0.42 (1.11; 0.725)	0.07 (0.15; 0.639)
PA	25.66 (4.74; 0)	16.26 (5.99; 0.007)	0.38 (0.08; 0)	-0.21 (0.46; 0.655)	-0.47 (0.79; 0.556)	-0.05 (0.06; 0.416)
<i>Outside protected areas - 'PA size' effect</i>						
R^2	0.381 ^b	0.476 ^a	0.428 ^c	0.448 ^d	0.463 ^d	0.540 ^c
Intercept	110.96 (18.57; 0)	209.46 (28.40; 0)	3.09 (0.33; 0)	8.35 (1.58; 0)	4.98 (2.07; 0.017)	1.80 (0.22; 0)
Forest canopy height	19.36 (2.80; 0)	24.17 (2.61; 0)	-0.05 (0.04; 0.189)	0.59 (0.38; 0.124)	0.81 (0.64; 0.208)	0.09 (0.04; 0.036)
Site accessibility	-4.78 (3.23; 0.140)	-11.71 (3.61; 0.001)	-0.33 (0.05; 0)	-0.47 (0.43; 0.273)	-2.51 (0.68; 0.002)	-0.09 (0.04; 0.051)
HDI	-6.07 (14.52; 0.689)	-7.15 (22.30; 0.758)	0.27 (0.26; 0.33)	-0.09 (1.04; 0.932)	2.46 (1.33; 0.138)	0.17 (0.14; 0.290)
Distance to PA	-48.07 (8.58; 0)	-23.59 (7.89; 0.003)	-0.30 (0.10; 0.002)	-0.63 (0.43; 0.142)	-1.81 (0.72; 0.012)	-0.07 (0.05; 0.154)

PA size (binary)	6.89 (6.31; 0.275)	19.77 (6.44; 0.002)	0.31 (0.09; 0.0005)	2.13 (0.64; <0.001)	9.95 (1.09; 0)	0.43 (0.07; 0)
<i>Outside protected areas - 'Distance to PA' effect</i>						
R ²	0.463 ^b	0.351 ^a	0.411 ^c	0.346 ^d	0.300 ^d	0.303 ^c
Intercept	113.76 (22.33; 0)	215.36 (14.75; 0)	2.85 (0.22; 0)	9.10 (1.38; 0)	12.23 (1.30; 0)	2.23 (0.10; 0)
Forest canopy height	21.34 (2.56; 0)	34.91 (2.76; 0)	0.20 (0.03; 0)	0.62 (0.33; 0.060)	3.25 (0.52; 0)	0.19 (0.04; 0)
Site accessibility	-1.27 (3.13; 0.684)	-5.12 (3.20; 0.109)	-0.18 (0.04; 0)	-0.79 (0.48; 0.099)	-0.27 (0.76; 0.727)	-0.09 (0.06; 0.147)
HDI	-4.02 (18.05; 0.830)	-25.34 (11.74; 0.068)	0.02 (0.18; 0.924)	-0.19 (0.92; 0.848)	0.47 (1.17; 0.708)	0.13 (0.09; 0.171)
PA size	3.51 (2.89; 0.226)	-3.15 (3.51; 0.369)	0.14 (0.04; 0.0001)	0.73 (0.64; 0.250)	0.92 (0.94; 0.328)	0.15 (0.08; 0.046)
Distance to PA (binary)	12.92 (5.76; 0.025)	6.96 (6.84; 0.309)	-0.04 (0.08; 0.654)	1.22 (0.69; 0.078)	1.84 (1.16; 0.111)	0.16 (0.09; 0.076)

^a Six data points removed to improve normality of model residuals

^b Four data points removed to improve normality of model residuals

^c Five data points removed to improve normality of model residuals

^d Three data points removed to improve normality of model residuals

TABLE 2. Locations of the mammal study areas showing mean (SD) latitude, longitude, elevation, topographic position index (TPI), and site accessibility, along with the percentage of camera stations inside protected areas (PAs).

Region	Study area	Number of camera stations	Latitude	Longitude	Elevation (m)	TPI	Accessibility (log ₁₀ amps)	Inside PA (%)
Borneo	Bako	11	1.7217 (0.0057)	110.46 (0.0178)	39.6 (48.1)	-0.39 (0.23)	-3.55 (0.31)	100
Borneo	Baleh	36	1.5623 (0.0342)	114.0011 (0.2535)	242.2 (178)	-0.32 (0.89)	-0.03 (0.44)	0
Borneo	Danum_Malua	39	5.0213 (0.0642)	117.7342 (0.0729)	416.8 (118.4)	-0.08 (0.46)	-0.41 (0.34)	100
Borneo	DerekKrianNP	1	1.3926 (0)	110.181 (0)	79 (0)	-0.8 (0)	0.54 (0)	0
Borneo	GunungGadingNP	26	1.7032 (0.0095)	109.8395 (0.0044)	42.4 (43.1)	0.14 (1.38)	-0.44 (0.32)	50
Borneo	GunungLesungNP	4	1.2622 (0.0018)	111.1678 (0.0011)	60.5 (19)	0.47 (0.44)	-0.02 (0.45)	0
Borneo	GunungPueh	23	1.7153 (0.0016)	109.6804 (0.0108)	423.7 (347.7)	-0.08 (1.34)	-1.08 (0.09)	0
Borneo	KapitFMU	119	1.831 (0.0372)	112.8979 (0.0212)	154.2 (35.5)	-0.16 (0.94)	-0.4 (0.54)	0
Borneo	KubahNP	58	1.6018 (0.0086)	110.1858 (0.0077)	99.5 (41)	0.4 (1.14)	0.28 (0.46)	20.7
Borneo	Lambir2017	52	4.1965 (0.012)	114.0181 (0.0181)	196.2 (25.3)	-0.16 (0.48)	0.29 (0.63)	75
Borneo	LoaganBunutNP	20	3.7628 (0.0235)	114.2433 (0.0135)	141.6 (27.6)	-0.14 (0.13)	-0.56 (0.43)	80
Borneo	Luasong	142	4.7758 (0.1645)	117.2249 (0.1485)	457.5 (249.4)	-0.16 (0.59)	-0.43 (0.51)	50
Borneo	Pelaugus	34	2.1594 (0.0339)	113.0607 (0.0367)	81.9 (9.7)	-0.04 (0.9)	-0.76 (0.28)	8.8
Borneo	Penrisen	54	1.1238 (0.0089)	110.2209 (0.0065)	859 (324)	1.45 (2.77)	-0.15 (0.27)	0
Borneo	SamaJayaNR	3	1.5222 (0.0008)	110.388 (0.0017)	5 (0)	-0.12 (0)	0.99 (0)	0
Borneo	Santubong	22	1.7497 (0.0218)	110.3261 (0.0076)	141.6 (127.5)	0.07 (1.55)	-3.23 (1.05)	0
Borneo	SimilajauNP	8	3.3697 (0.032)	113.1671 (0.0191)	14.5 (5.9)	-0.05 (0.15)	0.31 (0.68)	62.5
Borneo	SungaiMeluangNP	8	3.3199 (0.0204)	113.8262 (0.0116)	520.8 (14.1)	-0.09 (0.2)	-0.66 (0.43)	62.5
Borneo	UluBaram	19	3.5052 (0.2988)	115.2966 (0.1663)	1068.8 (719.7)	-0.21 (0.76)	-0.43 (0.48)	0
Borneo	UluSebayauNP	16	1.3911 (0.0132)	111.0325 (0.0278)	22.1 (11.4)	-0.19 (0.04)	-0.36 (0.09)	68.8
Borneo	Wilmar	10	3.4739 (0.0277)	113.8106 (0.0296)	253 (45.1)	0.34 (0.64)	-0.36 (0.63)	0
China	Xishuangbanna_BLS	13	21.5556 (0.0417)	100.3084 (0.0618)	1402.3 (207.6)	-0.27 (1.44)	0.93 (0.33)	0
China	Xishuangbanna_LSL	10	21.9053 (0.0035)	101.2917 (0.004)	1103.5 (284.4)	8.53 (0.59)	3.52 (0.58)	0
China	Xishuangbanna_LSL	2	21.9081 (0.0041)	101.29 (0.002)	1284.5 (280.7)	0.76 (0.02)	1.4 (1.1)	0
China	Xishuangbanna_MG	13	22.0837 (0.0126)	100.3207 (0.0282)	1341.2 (48.9)	2.25 (5.47)	3.39 (0.02)	0
China	Xishuangbanna_ML	24	21.6807 (0.0526)	101.4786 (0.0388)	1495.8 (204.5)	-0.27 (0.75)	0.68 (0.08)	79.2

China	Xishuangbanna_MS	5	21.5231 (0.0158)	100.5025 (0.0284)	1317.2 (195.5)	-0.42 (0.76)	0.65 (0.14)	0
China	Xishuangbanna_NBH	19	22.2433 (0.0206)	100.6607 (0.0244)	1052.1 (210.3)	0.02 (1.46)	0.98 (0.23)	100
China	Xishuangbanna_NBH	22	22.2421 (0.0207)	100.6622 (0.0244)	1054 (196.8)	3.06 (12.62)	3.47 (0.17)	100
Malaya	Pasoh_TEAM_2017	22	3.0449 (0.0573)	102.3185 (0.0237)	274.2 (155.9)	0.02 (1.1)	0.45 (0.11)	27.3
Malaya	Ulu_Muda_FN_2015	56	6.1013 (0.0266)	101.0018 (0.0366)	267.9 (127.6)	-0.14 (0.76)	0.51 (0.23)	57.1
Singapore	Singapore_CCNR	18	1.3592 (0.0115)	103.8006 (0.0093)	1.6 (0.5)	-0.09 (0.07)	1.65 (0.05)	94.4
Singapore	Singapore_PU	9	1.4118 (0.0027)	103.9821 (0.006)	0.9 (0.3)	0.16 (0.21)	0.81 (0.1)	0
Singapore	Singapore_SS	2	1.269 (0.0136)	103.811 (0.0057)	1.5 (0.7)	-0.19 (0.21)	1.38 (0.41)	0
Sumatra	BBS_frag1	1	-5.3357 (0)	104.0988 (0)	93 (0)	-0.47 (0)	-1.38 (0)	0
Sumatra	BBS_frag10	1	-5.4217 (0)	104.2554 (0)	265 (0)	0.06 (0)	-1.49 (0)	0
Sumatra	BBS_frag2	1	-5.2174 (0)	104.0208 (0)	148 (0)	0.56 (0)	-0.8 (0)	100
Sumatra	BBS_frag3	1	-5.2911 (0)	104.0637 (0)	109 (0)	0.12 (0)	-0.81 (0)	0
Sumatra	BBS_frag4	1	-5.2505 (0)	104.038 (0)	162 (0)	0.01 (0)	-1.22 (0)	0
Sumatra	BBS_frag5	1	-5.3879 (0)	104.188 (0)	129 (0)	-0.4 (0)	-1.54 (0)	100
Sumatra	BBS_frag6	1	-5.3964 (0)	104.1904 (0)	111 (0)	-0.08 (0)	-1.56 (0)	100
Sumatra	BBS_frag7	1	-5.365 (0)	104.1578 (0)	119 (0)	-0.48 (0)	-1.4 (0)	100
Sumatra	BBS_frag8	1	-5.4274 (0)	104.2232 (0)	152 (0)	-0.62 (0)	-1.12 (0)	100
Sumatra	BBS_frag9	1	-5.4021 (0)	104.2187 (0)	205 (0)	-0.21 (0)	-1.53 (0)	100
Sumatra	BBS_main	65	-5.2606 (0.0984)	104.1197 (0.0814)	296.4 (160.9)	0.01 (0.56)	-1.31 (0.21)	93.9
Sumatra	Kerinci_frag1	1	-1.5147 (0)	101.4245 (0)	343 (0)	0.17 (0)	-0.86 (0)	100
Sumatra	Kerinci_frag10	3	-1.5773 (0.0005)	101.4827 (0.0025)	492.3 (9.8)	-0.25 (0.03)	-0.78 (0.09)	0
Sumatra	Kerinci_frag13	2	-1.4916 (0.0009)	101.5466 (0.0007)	303 (1.4)	0.27 (1.06)	-0.8 (0.02)	0
Sumatra	Kerinci_frag2	1	-1.5885 (0)	101.2944 (0)	609 (0)	1.21 (0)	-0.55 (0)	0
Sumatra	Kerinci_frag3	1	-1.5363 (0)	101.2749 (0)	527 (0)	-0.42 (0)	0.5 (0)	0
Sumatra	Kerinci_frag4	4	-1.4705 (0.0009)	101.5281 (0.0017)	305 (0)	2.39 (0)	-0.78 (0)	0
Sumatra	Kerinci_frag5	1	-1.4498 (0)	101.5527 (0)	278 (0)	-0.26 (0)	-0.37 (0)	0
Sumatra	Kerinci_frag6	2	-1.4332 (0.0008)	101.589 (0.0004)	215.5 (13.4)	0.05 (0.8)	-0.55 (0.13)	0
Sumatra	Kerinci_frag7	2	-1.5682 (0.0059)	101.4617 (0.0011)	480.5 (24.7)	-0.21 (0.02)	-0.84 (0)	0
Sumatra	Kerinci_frag8	1	-1.617 (0)	101.4905 (0)	606 (0)	0.15 (0)	-0.79 (0)	0
Sumatra	Kerinci_main	45	-1.5607 (0.0922)	101.3971 (0.0807)	589.1 (162.2)	-0.02 (0.61)	-0.72 (0.25)	42.2
Sumatra	Leuser_frag1	1	3.6741 (0)	98.0882 (0)	152 (0)	-0.16 (0)	-0.24 (0)	0
Sumatra	Leuser_frag2	1	3.6778 (0)	98.082 (0)	150 (0)	-0.61 (0)	-0.78 (0)	0

Sumatra	Leuser_frag3	1	3.7071 (0)	98.0702 (0)	177 (0)	-0.46 (0)	-0.59 (0)	0
Sumatra	Leuser_frag4	1	3.8109 (0)	98.1145 (0)	73 (0)	-0.25 (0)	-0.18 (0)	100
Sumatra	Leuser_frag5	1	3.7181 (0)	98.0646 (0)	242 (0)	-0.47 (0)	-0.23 (0)	100
Sumatra	Leuser_frag6	1	3.7958 (0)	98.1024 (0)	69 (0)	-0.26 (0)	0.34 (0)	100
Sumatra	Leuser_frag7	1	3.9721 (0)	98.0886 (0)	52 (0)	-0.27 (0)	0.65 (0)	0
Sumatra	Leuser_frag8	1	3.7985 (0)	98.1071 (0)	69 (0)	-0.26 (0)	0.34 (0)	100
Sumatra	Leuser_main	54	3.7391 (0.1248)	98.0563 (0.0331)	250.5 (168.6)	-0.1 (0.91)	-0.4 (0.22)	100
Thailand	KhaoChong2018	64	7.5289 (0.0356)	99.8043 (0.0194)	425.9 (282.3)	0.11 (1)	1.11 (0.89)	95.3
Thailand	KhaoYai2019	55	14.4392 (0.0113)	101.3669 (0.0162)	768.6 (30.7)	-0.13 (0.26)	1.62 (0.5)	100
Vietnam	KonPlong2019-20	171	14.7625 (0.119)	108.3337 (0.0977)	1123 (254.9)	0.07 (0.92)	0.52 (0.56)	0
Vietnam	KonPlong2019-20	239	14.7547 (0.1173)	108.3302 (0.0954)	1119.9 (252.8)	1.7 (7.52)	3.21 (0.45)	0

TABLE 3. Propensity score statistical matching results. UTM = Universal Transverse Mercator; TPI = Topographic Position Index; HDI = Human Development Index (a national-level metric); PA = Protected Area; other variables are explained in the main text.

Variable	All data		Matched data		Std. pair distance	Dataset	Sample sizes	
	Std. mean difference	Variance ratio	Std. mean difference	Variance ratio			Control	Treated
PA analysis - Bird PD; eBird sampling locations								
distance	1.3404	1.8747	0.0006	0.9941	0.0118	All	856	217
UTM east	0.174	2.3687	-0.0644	0.9259	0.6508	Matched (ESS)	86.21	217
UTM north	0.24	0.8985	0.1107	0.8203	0.9553	Matched	856	217
forest canopy height	1.3155	1.3406	-0.0382	0.8661	0.5068	Unmatched	0	0
accessibility	-0.5148	1.9362	0.0727	0.8985	0.7515	Discarded	0	0
HDI	-0.2191	0.6372	-0.0374	1.4058	1.1981			
PA analysis - Mammal PD; camera trap locations								
distance	0.6563	1.4537	0.0003	0.9967	0.0053	All	786	579
UTM east	-0.4645	2.2859	0.0045	1.7327	0.5725	Matched (ESS)	198.44	579
UTM north	-0.0524	1.101	-0.0891	0.8479	0.8682	Matched	786	579
forest canopy height	0.2196	1.1772	0.1148	0.7918	1.0929	Unmatched	0	0
accessibility	0.1145	1.5101	-0.0067	0.9848	0.9078	Discarded	0	0
HDI	0.0424	0.7889	-0.0862	0.5936	0.9513			
PA size analysis - Bird PD; eBird sampling locations outside PAs								
distance	1.1041	1.8668	0.0049	0.9969	0.0343	All	608	248
UTM north	0.8572	0.5248	-0.0560	0.7363	1.0005	Matched (ESS)	64.97	248
UTM east	-0.1188	0.6362	0.0275	1.1783	1.4019	Matched	608	248
forest canopy height	-0.0413	1.3386	-0.0750	0.9104	0.8605	Unmatched	0	0
accessibility	0.0501	0.7053	0.0454	1.1935	1.1969	Discarded	0	0
HDI	-1.0982	1.2205	-0.0817	1.0596	0.4440			
distance to PA	0.0507	0.4844	0.1761	1.2212	0.7860			

PA size analysis - Mammal PD; camera trap stations outside PAs

distance	1.1599	2.9684	0.0021	0.8037	0.0676	All	496	285
UTM north	-0.5722	1.0004	-0.2270	1.4320	0.7855	Matched (ESS)	6.96	285
UTM east	0.1357	2.6622	-0.2015	2.6069	0.9581	Matched	496	285
forest canopy height	0.1511	0.3149	0.8535	0.5085	1.7782	Unmatched	0	0
accessibility	-0.3381	0.5383	-0.5718	0.6915	1.3098	Discarded	0	0
HDI	0.3512	0.3877	-0.3448	0.3729	1.2948			
distance to PA	0.5297	1.4804	-0.2208	1.2351	0.6965			

Distance to PA analysis - Bird PD; eBird sampling locations outside PAs

distance	0.9149	3.3408	0.0017	1.0048	0.0116	All	717	139
UTM north	-0.4048	1.0913	-0.0661	1.1044	0.9823	Matched (ESS)	83.36	139
UTM east	0.3723	3.1785	0.0404	1.2558	0.5281	Matched	717	139
forest canopy height	0.9548	2.3957	-0.0204	0.9021	0.2187	Unmatched	0	0
accessibility	-0.4621	1.3824	0.0077	0.9270	0.7669	Discarded	0	0
HDI	0.3383	0.9049	0.1236	0.9727	0.8936			
PA size	0.0296	1.8828	-0.0176	1.5531	0.6777			

Distance to PA analysis - Mammal PD; camera trap stations outside PAs

distance	1.1937	1.102	0.0327	1.1313	0.0661	All	566	215
UTM north	-0.8762	0.2894	-0.1455	0.6400	1.5364	Matched (ESS)	84.37	215
UTM east	0.0016	1.9656	0.1006	1.4719	0.8919	Matched	566	215
forest canopy height	-0.0874	0.794	0.1494	0.6416	1.0584	Unmatched	0	0
accessibility	0.1534	0.6481	-0.0314	0.6133	1.2240	Discarded	0	0
HDI	0.6804	0.3788	-0.0299	0.5190	1.0727			
PA size	-0.5922	0.6116	0.0689	1.1770	0.9779			

TABLE 4. Results from mixed-effects linear regression (two-tailed) for species richness (SR), functional richness (FR), and phylogenetic diversity (PD) of birds and mammals as a function of protected area size (binary) across different size thresholds. Adjustments were not made for multiple comparisons. Values are the model β coefficients (p -value).

'Large' protected area size threshold (km ²)	Birds			Mammals		
	SR	FR	PD	SR	FR	PD
400	2.552	21.133	0.502	0.559	5.672	0.202
	(0.680)	(0.002)	(<0.001)	(0.381)	(<0.001)	(0.018)
500	7.895	20.103	0.381	2.257	9.518	0.438
	(0.211)	(0.002)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
600	3.682	9.969	0.337	2.350	10.403	0.409
	(0.546)	(0.132)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
1000	10.741	1.865	0.146	2.060	9.612	0.302
	(0.051)	(0.811)	(0.312)	(0.001)	(<0.001)	(<0.001)

EXTENDED DATA LITERATURE CITED

- 1 Stuart, E. A., King, G., Imai, K. & Ho, D. MatchIt: nonparametric preprocessing for parametric causal inference. *Journal of statistical software* (2011).