

Supplementary Material

Conservation Challenges for Brazilian Primates and the Role of Protected Areas in a Changing Climate

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Table S1. List of endangered primate species of Brazil, threat status according to national (MMA, 2018) and international (IUCN, 2022) assessment, and the biome where it occurs.

Family	Taxons	MMA	IUCN	Biome
Atelidae	<i>Alouatta belzebul</i> (Linnaeus, 1766)	VU	VU	Amazon/Atlantic Forest
	<i>Alouatta discolor</i> (Spix, 1823)	VU	VU	Amazon
	<i>Alouatta guariba clamitans</i> (Cabrera, 1940)	VU	LC	Atlantic Forest
	<i>Alouatta guariba guariba</i> (Humboldt, 1812)	CR	CR	Atlantic Forest
	<i>Alouatta ululata</i> (Elliot, 1912)	EN	EN	Cerrado/Caatinga
	<i>Ateles belzebuth</i> (É. Geoffroy, 1806)	VU	EN	Amazon
	<i>Ateles chamek</i> (Humboldt, 1812)	VU	EN	Amazon
	<i>Ateles marginatus</i> (É. Geoffroy, 1809)	EN	EN	Amazon
	<i>Brachyteles arachnoides</i> (É. Geoffroy, 1806)	EN	CR	Atlantic Forest
	<i>Brachyteles hypoxanthus</i> (Khul, 1820)	CR	CR	Atlantic Forest
	<i>Lagothrix lagothricha cana</i> (É. Geoffroy in Humboldt, 1812)	EN	EN	Amazon
	<i>Lagothrix lagothricha lagothricha</i> (Humboldt, 1812)	EN	EN	Amazon
	<i>Lagothrix lagothricha poeppigii</i> (Schinz, 1844)	VU	EN	Amazon
	<i>Callithrix aurita</i> (É. Geoffroy in Humboldt, 1812)	EN	EN	Atlantic Forest
Callitrichidae	<i>Callithrix flaviceps</i> (Thomas, 1903)	EN	CR	Atlantic Forest
	<i>Leontopithecus caissara</i> (Lorini & Persson, 1990)	EN	CR	Atlantic Forest
	<i>Leontopithecus chrysomelas</i> (Kuhl, 1820)	EN	EN	Atlantic Forest
	<i>Leontopithecus chrysopygus</i> (Mikan, 1823)	EN	EN	Atlantic Forest
	<i>Leontopithecus rosalia</i> (Linnaeus, 1766)	EN	EN	Atlantic Forest
	<i>Mico rondoni</i> (Ferrari, Sena, Schneider & Silva Jr., 2010)	VU	VU	Amazon
	<i>Saguinus bicolor</i> (Spix, 1823)	CR	CR	Amazon
	<i>Saguinus niger</i> (É. Geoffroy, 1803)	VU	VU	Amazon
	<i>Cebus kaapori</i> (Queiroz, 1992)	CR	CR	Amazon
	<i>Saimiri vanzolinii</i> (Ayres, 1985)	VU	VU	Amazon
Cebidae	<i>Sapajus cay</i> (Illiger, 1815)	VU	LC	Cerrado/Pantanal/Chaco
	<i>Sapajus flavius</i> (Schreber, 1774)	EN	EN	Atlantic Forest/Caatinga
	<i>Sapajus robustus</i> (Kuhl, 1820)	EN	EN	Atlantic Forest
	<i>Sapajus xanthosternos</i> (Wied-Neuwied, 1826)	EN	CR	Atlantic Forest/Caatinga
	<i>Cacajao hosomi</i> (Boubli, Silva, Amado, Hrbk, Pontual & Farias, 2008)	EN	VU	Amazon
Pitheciidae	<i>Callicebus barbarabrownae</i> (HersHKovitz, 1990)	CR	CR	Caatinga
	<i>Callicebus coimbrai</i> (Kobayashi & Langguth, 1999)	EN	EN	Atlantic Forest

<i>Callicebus melanochir</i> (Wied-Neuwied, 1820)	VU	VU	Atlantic Forest
<i>Callicebus personatus</i> (É. Geoffroy, 1812)	VU	VU	Atlantic Forest
<i>Chiropotes satanas</i> (Hoffmannsegg, 1807)	CR	CR	Amazon
<i>Chiropotes utahickae</i> (Herskovitz, 1985)	VU	EN	Amazon

Table S2. Bioclimatic variables used to construct species distribution models.

Variables	Description	Units
BIO1	Annual mean temperature	°C
BIO2	Mean diurnal range	°C
BIO3	Isothermality	°C
BIO4	Temperature Seasonality	%
BIO5	Max temperature of the warmest month	°C
BIO6	in temperature of the coldest month	°C
BIO7	Temperature annual range	°C
BIO8	Mean temperature of the wettest quarter	°C
BIO9	Mean temperature of the driest quarter	°C
BIO10	Mean temperature of warmest quarter	°C
BIO11	Mean temperature of coldest quarter	°C
BIO12	Annual precipitation	mm
BIO13	Precipitation of wettest month	mm
BIO14	Precipitation of driest month	mm
BIO15	Precipitation seasonality	
BIO16	Precipitation of wettest quarter	mm
BIO17	Precipitation of driest quarter	mm
BIO18	Precipitation of warmest quarter	mm
BIO19	Precipitation of coldest quarter	mm

Table S3. Principal component coefficients that were selected from the Principal Component Analysis (PCA) performed on the environmental data.

Principal Components	Explained Variance for each Principal Component	Cumulative Variance Explained
1	0.57	0.57
2	0.54	0.75
3	0.09	0.84
4	0.05	0.90
5	0.06	0.94
6	0.03	0.97

Table S4. Number of unique occurrences used to construct species distribution models, and Jaccard, and AUC performance metric.

Taxons	Unique Occurrences	Jaccard	AUC
<i>Alouatta belzebul</i>	128	0.96	0.99
<i>Alouatta discolor</i>	52	0.89	0.95
<i>Alouatta guariba clamitans</i>	488	0.94	0.99
<i>Alouatta guariba guariba</i>	63	0.82	0.95
<i>Alouatta ululata</i>	23	0.88	0.95
<i>Ateles belzebuth</i>	113	0.9	0.95
<i>Ateles chamek</i>	252	0.85	0.97
<i>Ateles marginatus</i>	56	0.71	0.83
<i>Brachyteles arachnoides</i>	70	0.94	0.99
<i>Brachyteles hypoxanthus</i>	90	0.72	0.83
<i>Lagothrix lagothricha</i>	71	0.81	0.94
<i>Lagothrix lagothricha cana</i>	53	0.83	0.97
<i>Lagothrix lagothricha poeppigii</i>	101	0.7	0.81
<i>Callithrix aurita</i>	117	0.93	0.99
<i>Callithrix flaviceps</i>	33	0.88	0.94
<i>Leontopithecus caissara</i>	7	1	1
<i>Leontopithecus chrysomelas</i>	49	0.82	0.88
<i>Leontopithecus chrysopygus</i>	30	0.71	0.8
<i>Leontopithecus rosalia</i>	24	0.83	0.92
<i>Mico rondoni</i>	16	0.59	0.56
<i>Saguinus bicolor</i>	10	1	0.96
<i>Saguinus niger</i>	30	0.77	0.9
<i>Cebus kaapori</i>	42	0.93	0.98
<i>Saimiri vanzolinii</i>	5	1	1
<i>Sapajus cay</i>	136	0.74	0.91
<i>Sapajus flavius</i>	19	0.71	0.69
<i>Sapajus robustus</i>	69	0.8	0.9
<i>Sapajus xanthosternos</i>	132	0.83	0.96
<i>Cacajao hosomi</i>	24	0.68	0.72
<i>Callicebus barbarabrownae</i>	62	0.87	0.97
<i>Callicebus coimbrai</i>	29	0.82	0.93
<i>Callicebus melanochir</i>	59	0.91	0.97
<i>Callicebus personatus</i>	71	0.65	0.64
<i>Chiropotes satanas</i>	54	0.89	0.97
<i>Chiropotes utahickae</i>	31	0.75	0.86

Table S5. Values of climatically suitable areas of primate taxa threatened with extinction in Brazil for the baseline scenario and losses and gains in the optimistic and pessimistic future scenarios. Negative and positive area percentage values mean, respectively, reduction and enlargement of climatically suitable areas for the future scenario.

Taxons	Baseline Km ²	2041-2060	2041-2060	2041-2060	2041-2060	2061-2080	2061-2080	2061-2080	2061-2080
		SSP245	SSP245	SSP585	SSP585	SSP245	SSP245	SSP585	SSP585
		Km ²	%	Km ²	%	Km ²	%	Km ²	%
<i>Alouatta belzebul</i>	527973.6	10113.78	-98.08	171.42	-99.96	8142.45	-98.46	0	-100.00
<i>Alouatta discolor</i>	363838.95	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Alouatta guariba clamitans</i>	197561.55	44654.91	-77.40	37712.4	-80.91	53225.91	-73.06	25970.13	-86.85
<i>Alouatta guariba guariba</i>	80824.53	60939.81	-24.60	55197.24	-31.71	34969.68	-56.73	14742.12	-81.76
<i>Alouatta ululata</i>	87852.75	65225.31	-25.76	67539.48	-23.12	55111.53	-37.27	21598.92	-75.41
<i>Ateles belzebuth</i>	220446.12	207932.46	-5.68	187790.61	-14.81	0	-100.00	0	-100.00
<i>Ateles chamek</i>	1573807.02	1038033.81	-34.04	801817.05	-49.05	631768.41	-59.86	389466.24	-75.25
<i>Ateles marginatus</i>	410808.03	358782.06	-12.66	242130.75	-41.06	2657.01	-99.35	0	-100.00
<i>Brachyteles arachnoides</i>	46626.24	22884.57	-50.92	15942.06	-65.81	11399.43	-75.55	6085.41	-86.95
<i>Brachyteles hypoxanthus</i>	103880.52	64711.05	-37.71	64453.92	-37.95	59654.16	-42.57	48683.28	-53.14
<i>Lagothrix lagothricha</i>	116737.02	75510.51	-35.32	14142.15	-87.89	0	-100.00	0	-100.00
<i>Lagothrix lagothricha cana</i>	1158370.65	130364.91	-88.75	2057.04	-99.82	0	-100.00	0	-100.00
<i>Lagothrix lagothricha poeppigii</i>	170562.9	169362.96	-0.70	86395.68	-49.35	6856.8	-95.98	22798.86	-86.63
<i>Callithrix aurita</i>	107480.34	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Callithrix flaviceps</i>	18599.07	2485.59	-86.64	1628.49	-91.24	3856.95	-79.26	342.84	-98.16
<i>Leontopithecus caissara</i>	514.26	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Leontopithecus chrysomelas</i>	23055.99	22370.31	-2.97	23655.96	2.60	0	-100.00	0	-100.00
<i>Leontopithecus chrysopygus</i>	13113.63	3514.11	-73.20	2142.75	-83.66	2571.3	-80.39	0	-100.00
<i>Leontopithecus rosalia</i>	8313.87	2485.59	-70.10	1885.62	-77.32	7799.61	-6.19	7971.03	-4.12
<i>Mico rondoni</i>	58454.22	11656.56	-80.06	771.39	-98.68	40112.28	-31.38	28798.56	-50.73
<i>Saguinus bicolor</i>	12342.24	0	-100.00	0	-100.00	0	-100.00	0	-100.00

<i>Saguinus niger</i>	154449.42	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Cebus kaapori</i>	97795.11	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Saimiri vanzolinii</i>	4714.05	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Sapajus cay</i>	319441.17	139707.3	-56.27	92738.22	-70.97	49711.8	-84.44	9170.97	-97.13
<i>Sapajus flavius</i>	2914.14	514.26	-82.35	85.71	-97.06	342.84	-88.24	85.71	-97.06
<i>Sapajus robustus</i>	71824.98	43369.26	-39.62	38226.66	-46.78	27255.78	-62.05	9342.39	-86.99
<i>Sapajus xanthosternos</i>	227045.79	95309.52	-58.02	79453.17	-65.01	72767.79	-67.95	56740.02	-75.01
<i>Cacajao hosomi</i>	29312.82	0	-100.00	0	-100.00	0	-100.00	0	-100.00
<i>Callicebus barbarabrownae</i>	74481.99	7971.03	-89.30	3856.95	-94.82	3256.98	-95.63	85.71	-99.88
<i>Callicebus coimbrai</i>	8571	5913.99	-31.00	5913.99	-31.00	5828.28	-32.00	5056.89	-41.00
<i>Callicebus melanochir</i>	49883.22	29227.11	-41.41	30598.47	-38.66	34712.55	-30.41	36598.17	-26.63
<i>Callicebus personatus</i>	68482.29	55111.53	-19.52	51768.84	-24.41	38226.66	-44.18	29055.69	-57.57
<i>Chiropotes satanas</i>	160534.83	104480.49	-34.92	76196.19	-52.54	24255.93	-84.89	599.97	-99.63
<i>Chiropotes utahickae</i>	160106.28	2571.3	-98.39	85.71	-99.95	0	-100.00	0	-100.00

Table S6. Number of Protected Areas, by management category, significantly effective for the conservation of endangered primate species richness in Brazil, in the baseline, optimistic (SSP245) and pessimistic (SSP585) future scenarios in 2041-2060 and 2061-2080.

Category	Baseline	2041-2060 SSP245	2041-2060 SSP585	2061-2080 SSP245	2061-2080 SSP585
Strictly Protected Areas	27	18	18	21	10
Sustainable use areas	21	20	12	14	12
Indigenous lands	41	49	27	21	26

Table S7. Results of the influence of different scenarios on the potential of PAs to retain suitable areas for maintaining the richness of threatened primates (effective or non-effective). We used Logistic regression models to predict it (GLM, binomial distribution) and utilized the baseline scenario as a reference category.

SPAs					
Scenario	Estimate	Std. Error	z value	Pr(> z)	
(Intercept)	-2.1247	0.2036	-10.435	<2e-16	***
2041-2060 SSP245	-0.3862	0.3136	-1.231	0.2182	
2041-2060 SSP585	-0.4445	0.3182	-1.397	0.1625	
2061-2080 SSP245	-0.2775	0.3056	-0.908	0.3638	
2061-2080 SSP585	-0.9663	0.3694	-2.616	0.0089	**
SPAs + SUAs					
Scenario	Estimate	Std. Error	z value	Pr(> z)	
(Intercept)	-2.2291	0.1519	-14.674	< 2e-16	***
2041-2060 SSP245	-0.2276	0.2256	-1.009	0.31309	
2041-2060 SSP585	-0.5096	0.242	-2.106	0.03523	*
2061-2080 SSP245	-0.3446	0.232	-1.485	0.13748	
2061-2080 SSP585	-0.7902	0.262	-3.016	0.00256	**
SPAs + SUAs + IL					
Scenario	Estimate	Std. Error	z value	Pr(> z)	
(Intercept)	-2.3556	0.1103	-21.357	< 2e-16	***
2041-2060 SSP245	0.0121	0.1556	0.078	0.937992	
2041-2060 SSP585	-0.4725	0.1744	-2.709	0.006748	**
2061-2080 SSP245	-0.5097	0.1762	-2.893	0.003817	**
2061-2080 SSP585	-0.6503	0.1832	-3.549	0.000387	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table S8. Classification of taxa according to the degree of conservation goal achieved by protected areas of Brazil in the baseline conditions, optimistic (SSP245), and pessimistic (SSP585) future scenarios for the periods 2041-2060 and 2061-2080. SPAs: Strictly Protected Areas, SUAs: Sustainable Use Areas; and IL: Indigenous Lands. P: protected; PP: partially protected; G: gap; NP: not protected.

Taxons	Baseline				2041-2060 SSP245			2041-2060 SSP585			2061-2080 SSP245			2061-2080 SSP285		
	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	SPAs	
		SUAs	SUAs	IL		SUAs	SUAs	IL	SUAs	SUAs	IL	SUAs	SUAs	IL	SUAs	SUAs
<i>Alouatta belzebul</i>	PP	P	P	NP	G	PP	NP	NP	NP	NP	NP	PP	NP	NP	NP	
<i>Alouatta discolor</i>	P	P	P	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
<i>Alouatta guariba clamitans</i>	G	PP	PP	G	PP	PP	G	PP	PP	G	PP	PP	G	PP	PP	
<i>Alouatta guariba guariba</i>	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	
<i>Alouatta ululata</i>	G	PP	PP	G	PP	PP	G	PP	PP	G	PP	PP	NP	PP	PP	
<i>Ateles belzebuth</i>	P	P	P	P	P	P	PP	P	P	NP	NP	NP	NP	NP	NP	
<i>Ateles chamek</i>	P	P	P	PP	P	P	PP	P	P	PP	P	P	G	P	P	
<i>Ateles marginatus</i>	P	P	P	P	P	P	P	P	P	NP	NP	G	NP	NP	NP	
<i>Brachyteles arachnoides</i>	G	PP	PP	PP	PP	PP	G	PP	PP	PP	PP	PP	PP	PP	PP	
<i>Brachyteles hypoxanthus</i>	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	
<i>Lagothrix lagothricha</i>	G	PP	P	G	PP	PP	G	PP	PP	NP	NP	NP	NP	NP	NP	
<i>Lagothrix lagothricha cana</i>	P	P	P	PP	PP	P	PP	PP	P	NP	NP	NP	NP	NP	NP	
<i>Lagothrix poeppigii</i>	G	PP	P	G	PP	P	G	G	P	PP	PP	PP	NP	NP	P	
<i>Callithrix aurita</i>	G	PP	PP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
<i>Callithrix flaviceps</i>	NP	G	G	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
<i>Leontopithecus caissara</i>	PP	P	P	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
<i>Leontopithecus chrysomelas</i>	G	G	PP	G	G	PP	G	G	PP	NP	NP	NP	NP	NP	NP	

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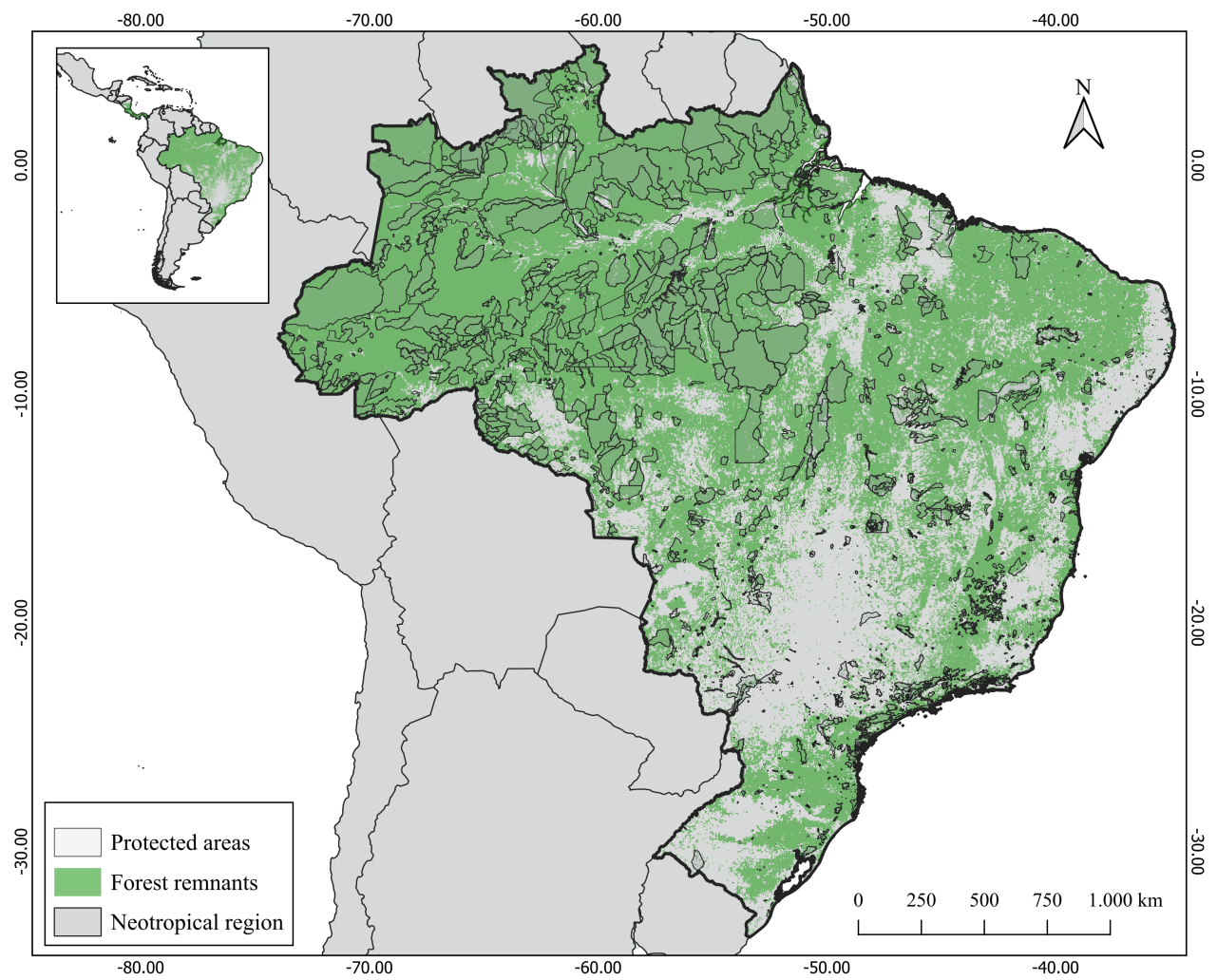


Figure S1. Location of the study area and network of protected areas. The map was generated using Qgis – version 3.3.24 (<https://www.qgis.org>).

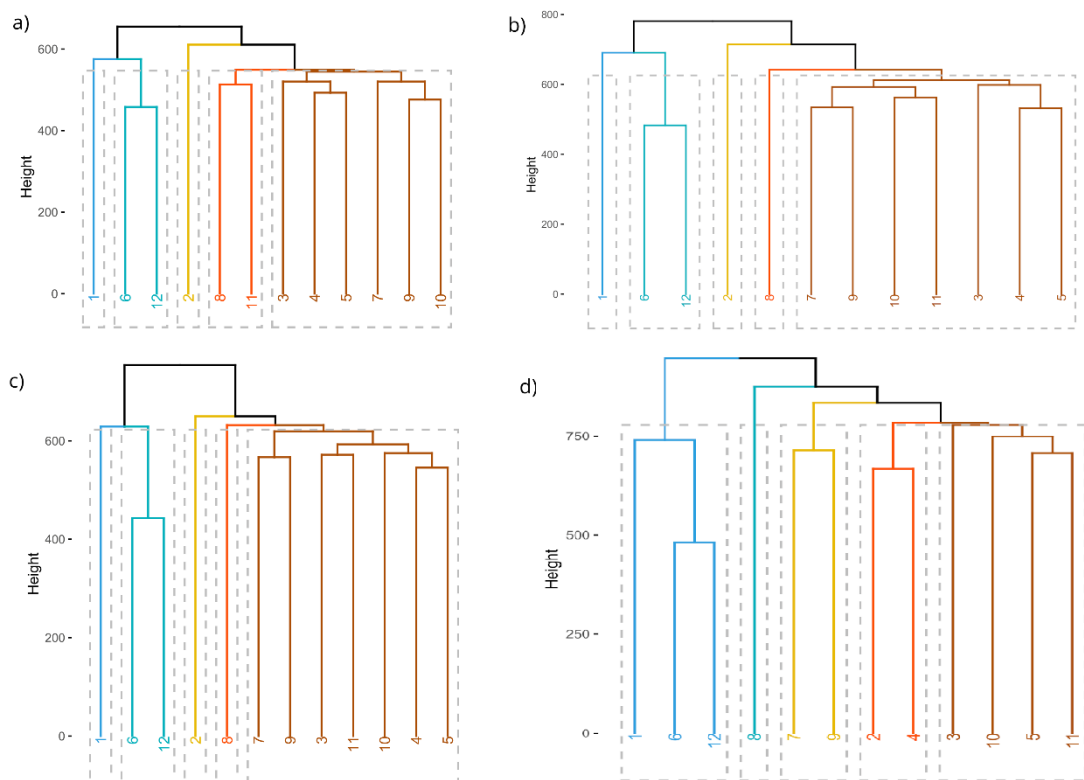
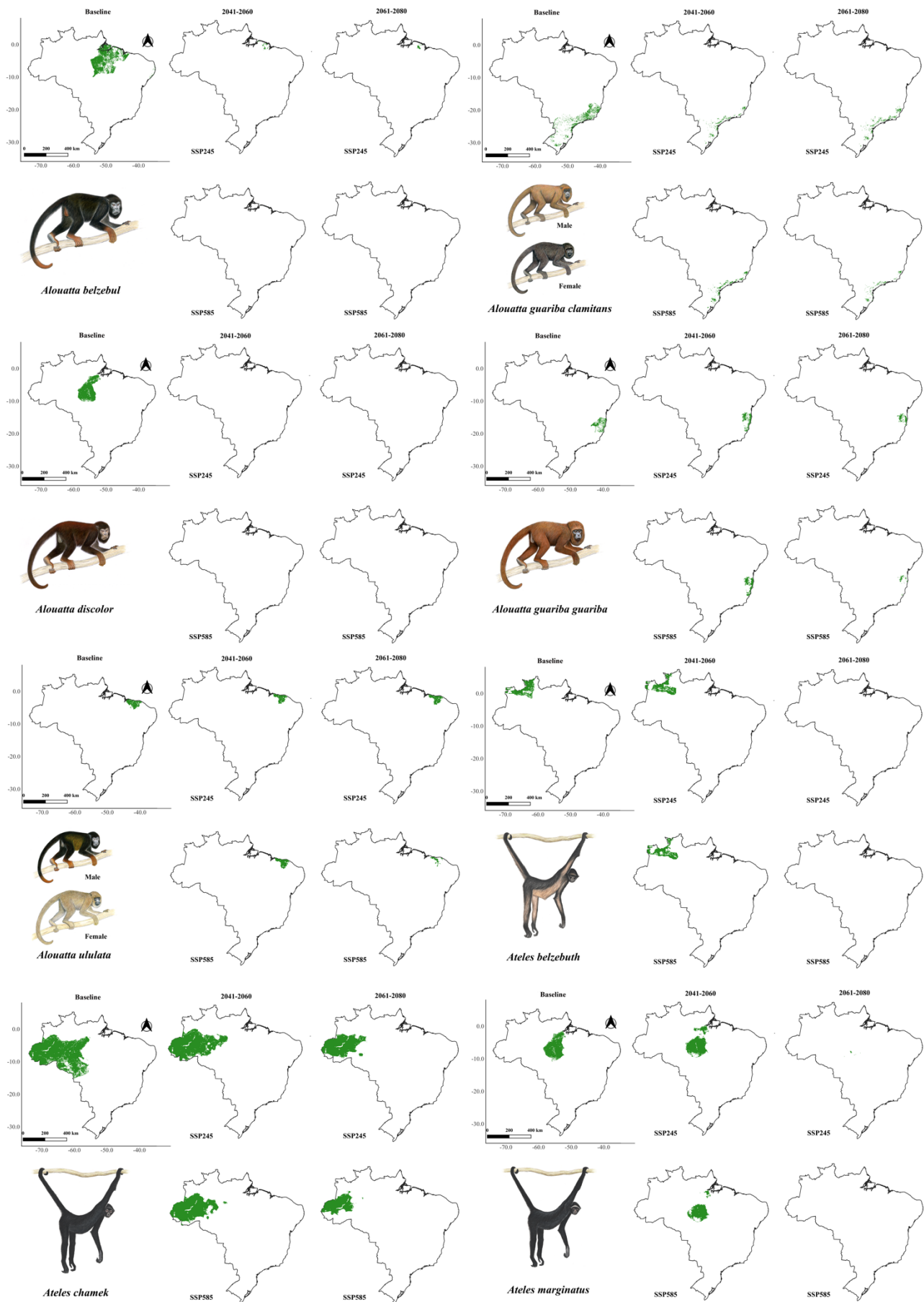
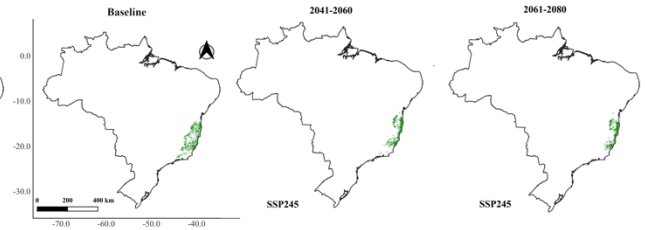


Figura S2: Cluster analysis of GCMs. a) SSP245 (2041-2060); b) SSP585 (2041-2060); c) SSP245 (2061-2080); d) SSP585 (2061-2080).





Brachyteles arachnoides



Brachyteles hypoxanthus



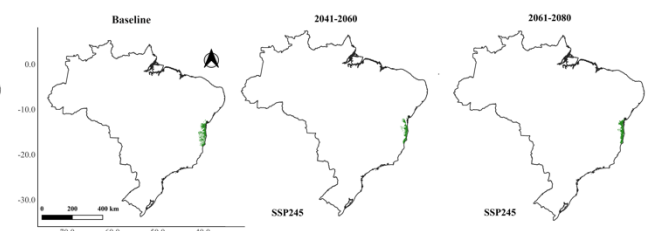
Cacajao hosomi



Callicebus barbarabrownae



Callicebus coimbrai



Callicebus melanochir



Callicebus personatus

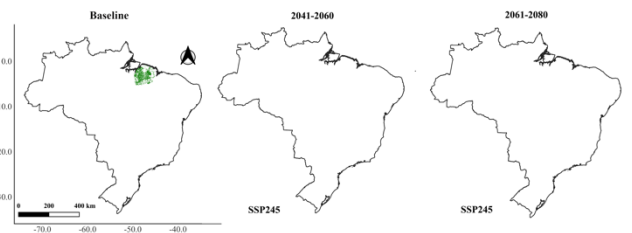


Callithrix aurita





Callithrix flaviceps



Cebus kaapori



Chiropotes satanas



Chiropotes utahickae



Lagothrix lagothricha cana



Lagothrix lagothricha lagothricha



Lagothrix lagothricha poeppigii



Leontopithecus caissara



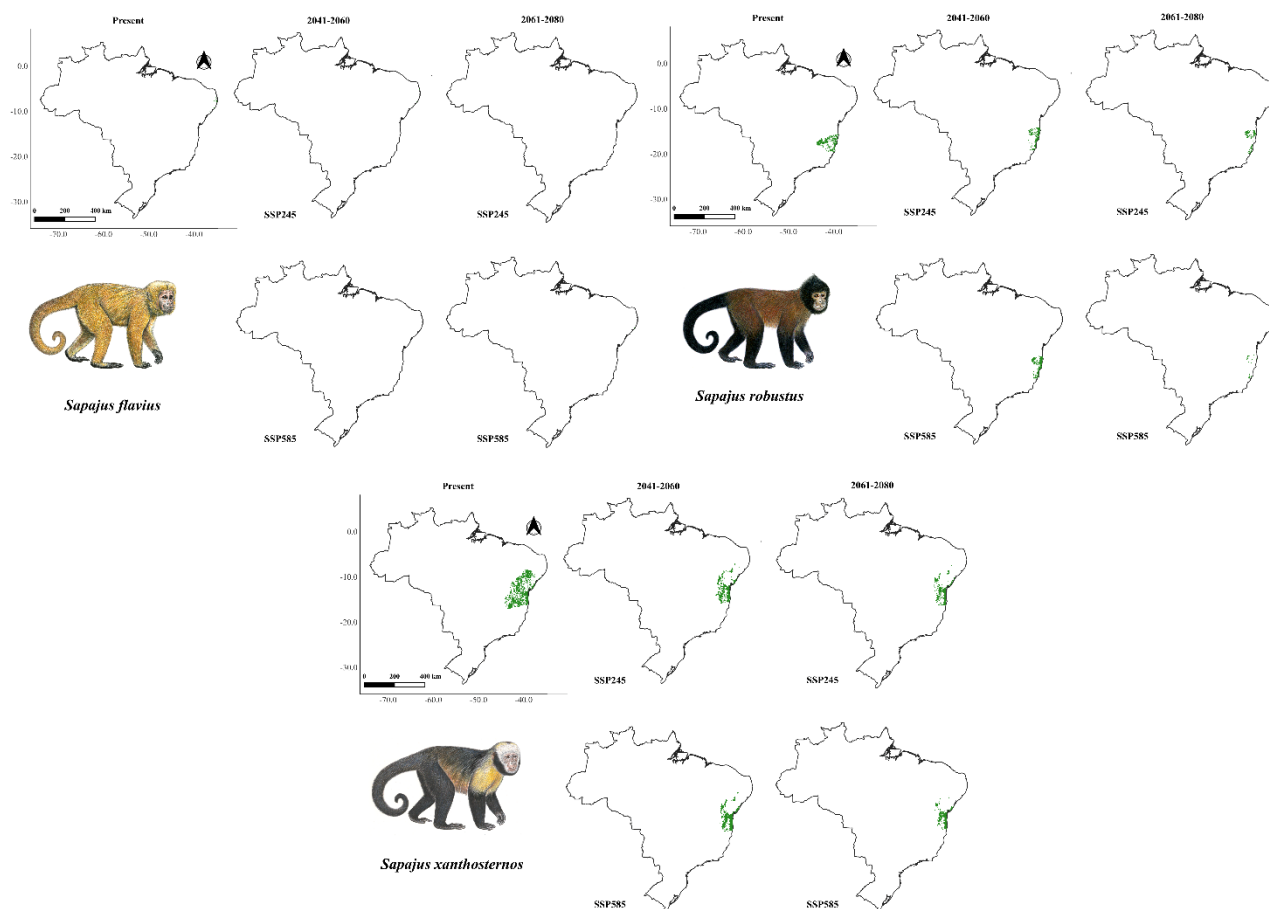


Figure S3. Suitability models (climate + vegetation cover) of Brazil's 35 primate taxa threatened with extinction. Black lines delimit the study area, while the green area delimits each taxon's potential distribution. Illustrations copyright 2013 Stephen D. Nash / IUCN SSC.

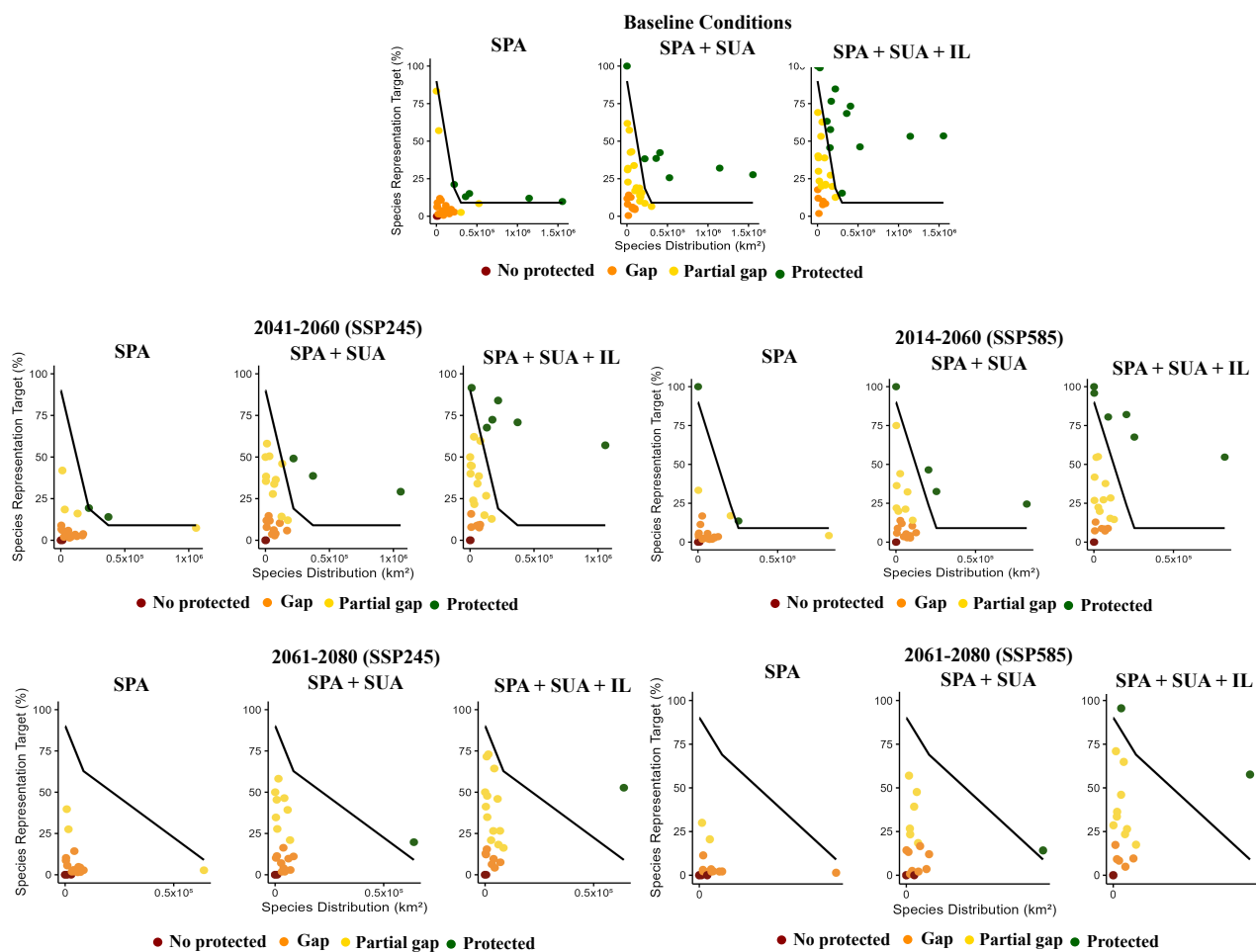


Figure S4. Relationship between distribution area and the percentage of the target reached of endangered primate taxa. Each point represents a taxon. Black lines represent the target representation for different distribution areas of the taxa.