

The Cost of Postponing Biodiversity Conservation:

Supplementary Materials

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Biodiversity Place Prioritization

The minimization and maximization problems were coded in the GAMS modelling language version 21.4¹ and solved using a branch-and-bound algorithm². Computations were performed on a Dell Precision 530 Workstation with dual 1.8GHz Xeon processors and 1GB of RAM running SuSE Linux 9.0 at the Mechanical Engineering High Performance Computing Lab at the University of Texas at Austin (<http://hpc.me.utexas.edu/>). The relative tolerance for the branch-and-bound was 1.0×10^{-5} .

Minimization problem

Sets:

$i \in I$ species

$j \in J$ sites

Data:

a_{ij} 1 if species i is present in cell j . 0 otherwise. $a_{ij} \in \{0,1\}$.

t_i target for species i . $t_i \in [0,1,2,\dots,|\mathcal{J}|]$.

Decision variables:

x_j 1 if site j is selected. 0 otherwise. $x \in \{0,1\}^{|\mathcal{J}|}$.

Formulation:

$$\min_x \sum_{j \in \mathcal{J}} x_j \quad (1.1)$$

$$\sum_{j \in \mathcal{J}} a_{ij} x_j \geq t_i, \quad i \in I \quad (1.2)$$

$$x_j \in \{0,1\}, \quad j \in \mathcal{J} \quad (1.3)$$

The objective function (1.1) minimizes the total number of sites selected. Constraint (1.2) ensures that each species is represented at or above its target level in the set of selected sites. Constraint (1.3) states that each site must be selected or not selected.

Maximization problem

Sets:

$i \in I$ species

$j \in \mathcal{J}$ sites

Data:

a_{ij} 1 if species i is present in cell j . 0 otherwise. $a_{ij} \in \{0,1\}$.

t_i target for species i . $t_i \in [0,1,2,\dots,|\mathcal{J}|]$.

b budget. $b \in [0,1,2,\dots,|\mathcal{J}|]$.

Decision variables:

x_j 1 if site j is selected. 0 otherwise. $x \in \{0,1\}^{|\mathcal{J}|}$.

y_i 1 if species i is represented in the set of selected sites. 0 otherwise. $y \in \{0,1\}^{|\mathcal{I}|}$.

Formulation:

$$\max_y \sum_{i \in \mathcal{I}} y_i \quad (2.1)$$

$$\sum_{j \in \mathcal{J}} a_{ij} x_j \geq y_i t_i, \quad i \in \mathcal{I} \quad (2.2)$$

$$\sum_{j \in \mathcal{J}} x_j \leq b \quad (2.3)$$

$$x_j \in \{0,1\}, \quad j \in \mathcal{J} \quad (2.4)$$

$$y_i \in \{0,1\}, \quad i \in \mathcal{I} \quad (2.5)$$

The objective function (2.1) maximizes the total number of species represented in the set of selected sites. Constraint (2.2) ensures that each species represented in the set of selected sites satisfies its target. The budgetary constraint (2.3) stipulates that no more than b sites are selected. Constraint (2.4) states that each site must be selected or not selected. Constraint (2.5) states that each species must be represented or not represented in the set of selected sites.

Table 1. The number of sites occupied by each endemic mammal (1970-2000).

Species	1970	1976	1993	2000	Percent change in the number of sites occupied by the species (1970-2000)
<i>Artibeus hirsutus</i>	10713	10319	10041	10107	-5.65668
<i>Chaetodipus arenarius</i>	2820	2598	2611	2597	-7.9078
<i>Chaetodipus artus</i>	2197	2110	2080	2061	-6.19026
<i>Chaetodipus dalquesti</i>	8	8	8	8	0
<i>Chaetodipus pernix</i>	1985	1835	1704	1728	-12.9471
<i>Cratogeomys fumosus</i>	214	209	199	190	-11.215
<i>Cratogeomys gymnurus</i>	3479	3267	3148	3159	-9.19805
<i>Cratogeomys neglectus</i>	260	260	251	236	-9.23077
<i>Cratogeomys tylorhinus</i>	7084	6495	5953	6273	-11.4483
<i>Cratogeomys zinseri</i>	272	176	157	152	-44.1176
<i>Cryptotis magna</i>	708	704	701	705	-0.42373
<i>Cryptotis mexicana</i>	3045	2967	2930	2969	-2.49589
<i>Cynomys</i>	3009	3163	3075	3109	3.323363

mexicanus					
Dasyprocta mexicana	3475	2879	2359	2311	-33.4964
Dipodomys gravipes	1184	1015	1040	1016	-14.1892
Dipodomys nelsoni	8405	8304	8217	8184	-2.62939
Dipodomys phillipsii	8336	7837	7365	7595	-8.88916
Habromys chinanteco	1674	1496	1495	1469	-12.2461
Habromys lepturus	427	430	426	430	0.702576
Habromys simulatus	168	136	124	134	-20.2381
Hodomys alleni	8097	7891	7743	5235	-35.3464
Liomys spectabilis	649	586	568	547	-15.7165
Marmosa canescens	16425	15971	14990	15257	-7.11111
Megadontomys cryophilus	625	616	608	612	-2.08
Megadontomys thomasi	10580	10436	10105	10131	-4.24386
Megasorex gigas	5099	4843	4734	4739	-7.06021
Microtus oaxacencis	395	376	376	379	-4.05063

Microtus quasiater	5587	5038	4675	4880	-12.6544
Microtus umbrosus	52	53	52	53	1.923077
Musonycteris harrisoni	5609	4990	4730	4770	-14.9581
Myotis peninsularis	260	254	255	253	-2.69231
Myotis vivesi	264	165	133	137	-48.1061
Neotoma angustapalata	270	260	253	244	-9.62963
Neotoma goldmani	13148	12856	12675	12613	-4.06906
Neotoma palatina	909	833	814	809	-11.0011
Neotoma phenax	2390	2178	1965	2136	-10.6276
Neotomodon alstoni	1753	1441	1314	1311	-25.2139
Orthogeomys cuniculus	48	11	7	5	-89.5833
Osgoodomys banderanus	12835	12450	12033	7522	-41.3946
Pappogeomys alcorni	4	4	4	4	0
Pappogeomys bulleri	5897	5603	5431	3282	-44.3446
Peromyscus aztecus	19065	18333	17723	17861	-6.31524

Peromyscus bullatus	363	260	178	116	-68.0441
Peromyscus eva	913	899	892	887	-2.84775
Peromyscus fervus	5171	5142	4864	5058	-2.18526
Peromyscus megalops	4381	3845	3467	3454	-21.1596
Peromyscus mekisturus	1936	1754	1754	1752	-9.50413
Peromyscus melanotis	3937	3881	4978	3831	-2.69241
Peromyscus merriami	45	34	28	30	-33.3333
Peromyscus ochraventer	8775	8223	7983	8005	-8.77493
Peromyscus perfulvus	893	860	828	818	-8.39866
Peromyscus polius	4052	4017	4005	3931	-2.98618
Peromyscus simulus	1435	1642	1530	1518	5.783972
Peromyscus spicilegus	8766	8964	8923	8861	1.083733
Peromyscus winkelmanni	108	108	108	106	-1.85185
Peromyscus yucatanicus	3207	3171	3133	3119	-2.744

Peromyscus zarhynchus	402	378	370	371	-7.71144
Plecotus mexicanus	18783	18596	17706	17620	-6.19177
Reithrodontomys burti	1699	1503	1391	1366	-19.5998
Reithrodontomys chrysopsis	2419	2252	2030	2188	-9.5494
Reithrodontomys hirsutus	575	559	550	543	-5.56522
Rheomys mexicanus	1504	1405	1386	1367	-9.10904
Rhogeessa aeneus	1821	1807	1805	1785	-1.97694
Rhogeessa alleni	5619	5272	4985	5135	-8.61363
Rhogeessa gracilis	8445	7972	7730	7790	-7.75607
Rhogeessa mira	1	1	1	1	0
Romerolagus diazi	1692	1509	1332	1473	-12.9433
Sciurus alleni	1532	1526	1442	1478	-3.5248
Sciurus colliaei	4496	4530	4350	4363	-2.95819
Sciurus oculatus	3680	3674	3201	3536	-3.91304
Sigmodon alleni	4514	4394	4286	4274	-5.31679
Sigmodon leucotis	8737	8217	7941	8045	-7.92034
Sigmodon	8416	7818	7369	7569	-10.0642

mascotensis					
Sorex macrodon	78	29	34	51	-34.6154
Sorex milleri	851	828	820	810	-4.81786
Sorex sclateri	22	8	1	5	-77.2727
Sorex veraepacis	3066	3024	3000	3005	-1.98956
Spermophilus adocetus	2394	2318	2272	2285	-4.55305
Spermophilus annulatus	1108	1070	1034	1018	-8.12274
Spermophilus madrensis	5006	4947	4957	4902	-2.07751
Spermophilus perotensis	1533	1330	1077	981	-36.0078
Spilogale pygmaea	5161	5066	4915	4874	-5.56094
Sylvilagus cunicularius	9332	9066	8745	8930	-4.30776
Sylvilagus insonus	30	26	27	23	-23.3333
Tamias bulleri	10234	10042	9947	9728	-4.9443
Xenomys nelsoni	420	387	382	375	-10.7143

Table 2. The number of sites in decreed natural protected areas of Mexico (1970-2000). Scale: $0.05^\circ \times 0.05^\circ$.³

	Number of Sites in Decreed Natural Protected Areas
1970	227
1976	1440
1993	1440
2000	4809

When the natural protected areas were included in the conservation plan, the plan did not incorporate natural protected areas decreed after the year of the plan. For example, the conservation plan based on the species' 1970 ranges did not include natural protected areas decreed after 1970.

Spatial Model of the Species' Ranges.

Each species' range was modeled as an inhomogeneous Poisson point process with intensity function $\lambda(x,y) = \exp(a + bx)$, where x represents longitude. We estimated the values of a and b via maximum likelihood using the ppm function in the spatstat library⁴. We evaluated goodness of fit through analysis of deviance of the spatial residuals of the model⁵ using the anova.ppm function in spatstat. A p -value less than 0.05 indicates a good fit of the model to the data⁶. The data below are for the 78 species that occupied fewer sites in 2000 than in 1970.

Table 3. Goodness of fit of Poisson process model of the species' ranges*

Species	p-value			
	1970	1976	1993	2000

<i>Artibeus hirsutus</i>	1.48E-44	1.12E-76	1.36E-78	9.22E-79
<i>Chaetodipus arenarius</i>	7.41E-69	1.68E-87	4.10E-82	1.17E-84
<i>Chaetodipus artus</i>	0.000133	7.49E-05	8.48E-05	4.35E-05
<i>Chaetodipus pernix</i>	2.33E-15	4.84E-15	1.28E-12	3.93E-15
<i>Cratogeomys fumosus</i>	0.273192	0.807157	0.372386	0.779297
<i>Cratogeomys gymnurus</i>	0.000302	0.002287	0.000478	0.004423
<i>Cratogeomys neglectus</i>	0.518452	0.518452	0.451898	0.400348
<i>Cratogeomys tylorhinus</i>	3.33E-10	7.17E-05	0.313931	0.000101
<i>Cratogeomys zinseri</i>	0.01373	0.001283	1.61E-09	3.06E-14
<i>Cryptotis magna</i>	0.602992	0.142481	0.144488	0.176969
<i>Cryptotis mexicana</i>	1.93E-137	1.37E-32	6.69E-31	1.24E-34
<i>Dasyprocta mexicana</i>	0.000103	6.12E-09	3.14E-23	3.00E-36
<i>Dipodomys gravipes*</i>	2.74E-10	4.19E-08	1.79E-06	6.57E-06
<i>Dipodomys nelsoni</i>	1.65E-168	1.58E-163	1.45E-162	2.10E-165
<i>Dipodomys phillipsii</i>	7.63E-12	0.002009	0.345127	0.000296
<i>Habromys chinanteco</i>	1.09E-07	1.04E-07	0.000158	1.54E-05
<i>Habromys simulatus</i>	1.58E-14	0.000355	3.36E-05	2.02E-09
<i>Hodomys alleni</i>	3.72E-11	8.51E-25	5.72E-18	9.92E-08
<i>Liomys spectabilis</i>	0.488957	0.717032	0.621159	0.531713
<i>Marmosa canescens</i>	1.14E-13	1.90E-19	1.76E-34	3.22E-30
<i>Megadontomys</i>	0.308404	0.423394	0.441713	0.439915

cryophilus				
Megadontomys thomasi	4.16E-17	1.17E-18	3.10E-27	1.52E-14
Megasorex gigas	2.95E-45	1.38E-44	1.56E-47	1.94E-43
Microtus oaxacencis	0.235841	0.740882	0.864401	0.74618
Microtus quasiater	0.127795	0.033003	0.001742	3.50E-05
Musonycteris harrisoni	9.46E-67	2.68E-63	9.51E-60	1.09E-57
Myotis peninsularis	0.636439	0.528775	0.547771	0.553226
Myotis vivesi*	1.36E-70	0.1455	0.504694	0.4209
Neotoma angustapalata	9.58E-34	9.49E-33	1.69E-29	1.05E-28
Neotoma goldmani	7.36E-178	6.28E-169	2.08E-159	1.74E-162
Neotoma palatina	4.71E-60	2.01E-34	2.75E-66	1.75E-74
Neotoma phenax	6.12E-05	0.891754	0.066936	0.934548
Neotomodon alstoni	1.12E-237	2.04E-167	1.98E-142	2.97E-145
Orthogeomys cuniculus*	0.466933	0.72761	8.95E-01	0.436
Osgoodomys banderanus	6.03E-15	6.06E-05	4.96E-06	1.26E-132
Pappogeomys bulleri	2.74E-17	2.25E-37	1.30E-47	1.26E-132
Peromyscus aztecus	5.78E-246	1.03E-208	1.43E-235	2.48E-201
Peromyscus bullatus*	2.73E-16	0.20375	0.861327	1.08E-06
Peromyscus eva	0.755953	0.628547	0.391554	0.683239
Peromyscus furvus	1.46E-22	4.66E-22	3.01E-19	8.63E-23

<i>Peromyscus megalops</i>	1.13E-07	0.049588	0.159468	0.090874
<i>Peromyscus mekisturus</i>	2.95E-19	1.79E-34	3.05E-36	7.26E-36
<i>Peromyscus melanotis</i>	7.63E-54	3.89E-60	0.724529	1.06E-63
<i>Peromyscus merriami</i>	0.568157	0.210592	0.134287	0.066941
<i>Peromyscus ochraventer</i>	5.06E-48	1.86E-43	5.01E-53	6.39E-52
<i>Peromyscus perfulvus</i>	0.023685	0.011052	0.001547	0.021789
<i>Peromyscus polius</i>	7.82E-23	1.67E-22	9.15E-23	1.35E-23
<i>Peromyscus winkelmanni</i>	0.158435	0.158435	0.158435	0.087
<i>Peromyscus yucatanicus</i>	1.31E-11	6.67E-13	7.32E-12	6.45E-12
<i>Peromyscus zarhynchus</i>	0.087055	0.006708	0.009653	0.014065
<i>Plecotus mexicanus</i>	0	0	0	0
<i>Reithrodontomys burti</i>	7.16E-62	1.43E-46	4.82E-45	5.09E-41
<i>Reithrodontomys chrysopsis</i>	0.066393	0.59263	0.000954	0.109451
<i>Reithrodontomys hirsutus</i>	0.014836	0.002771	0.001671	0.003104
<i>Rheomys mexicanus</i>	0.061151	0.161625	0.145137	0.034029
<i>Rhogeessa aeneus</i>	3.08E-07	1.64E-08	5.65E-08	8.49E-09
<i>Rhogeessa alleni</i>	1.21E-06	0.638427	0.161395	0.621154
<i>Rhogeessa gracilis</i>	1.90E-16	7.17E-12	7.98E-08	5.17E-10
<i>Romerolagus diazi</i>	1.07E-05	0.0553	0.921723	0.13688
<i>Sciurus alleni</i>	0.001544	0.000108	2.97E-05	5.40E-05
<i>Sciurus colliaei</i>	1.37E-07	0.011591	0.049528	0.004393

Sciurus oculatus	2.78E-48	9.63E-18	4.39E-11	7.23E-17
Sigmodon alleni	3.15E-48	1.14E-46	1.39E-43	4.18E-45
Sigmodon leucotis	1.32E-20	3.77E-17	2.39E-17	1.59E-15
Sigmodon mascotensis	0.003281	0.176767	0.193133	0.080947
Sorex macrodon	0.018574	0.165661	0.247579	0.126068
Sorex milleri	0.027888	0.026241	0.014622	0.045113
Sorex sclateri	0.872085	0.113412	**	0.545646
Sorex veraepacis	2.71E-43	1.06E-46	4.35E-45	1.97E-46
Spermophilus adocetus	0.116486	0.345675	0.235912	0.113473
Spermophilus annulatus	0.001155	0.000409	0.000408	0.001667
Spermophilus madrensis	1.44E-13	9.05E-15	8.38E-15	1.22E-15
Spermophilus perotensis	0.303272	2.95E-06	3.91E-13	1.78E-09
Spilogale pygmaea	2.82E-11	3.43E-08	2.87E-08	2.63E-09
Sylvilagus cunicularius	6.79E-06	1.78E-05	4.04E-10	1.48E-09
Sylvilagus insonus*	0.072014	0.329206	6.01E-02	0.508
Tamias bulleri	1.35E-24	1.73E-27	2.76E-29	9.89E-28
Xenomys nelsoni	5.48E-16	7.64E-17	2.21E-17	1.46E-15

* The boundary domain of each species' range was the convex hull of the set of sites occupied by the species. For species marked * the default quadrature scheme in spatstat failed with the convex hull as the boundary domain. For these species, we used the bounding rectangle of the species' range⁷ as the boundary domain.

**We excluded the 1993 range of *Sorex sclateri* from the analysis because the modeled distribution consisted of only one site.

The intensity function λ of a Poisson process represents the average number of sites occupied by the species per unit area. For each species, we calculated the average intensity $\bar{\lambda} = \exp(a + b\bar{x})$. The data below are for the 78 species that occupied fewer sites in 2000 than in 1970.

Table 4. Average intensity of the Poisson process model of the species' ranges*

Species	1970	1976	1993	2000
<i>Artibeus hirsutus</i>	149.2364	144.9114	141.1642	142.0845
<i>Chaetodipus arenarius</i>	221.4565	207.598	209.7793	211.0188
<i>Chaetodipus artus</i>	128.0502	123.2204	121.2976	120.8147
<i>Chaetodipus pernix</i>	160.1112	148.316	140.8759	139.9844
<i>Cratogeomys fumosus</i>	49.22944	50.02775	57.92175	48.29342
<i>Cratogeomys gymnurus</i>	209.8194	197.3752	189.8563	191.4689
<i>Cratogeomys neglectus</i>	170.2454	170.2454	168.5423	161.158
<i>Cratogeomys tylosinus</i>	237.108	217.985	199.332	210.9674
<i>Cratogeomys zinseri</i>	72.97833	52.11229	61.3617	62.91053
<i>Cryptotis magna</i>	266.0248	261.7242	260.5104	262.0022
<i>Cryptotis mexicana</i>	145.8596	177.0058	172.9762	175.6933
<i>Dasyprocta mexicana</i>	129.2289	107.6268	90.8133	91.42957
<i>Dipodomys gravipes</i>	27.373	2.34E+01	2.39E+01	23.329

Dipodomys nelsoni	211.3616	208.7961	207.0008	206.9488
Dipodomys phillipsii	210.5892	198.2463	187.1799	192.2564
Habromys chinanteco	118.9009	123.8911	105.4436	103.5649
Habromys simulatus	93.25128	62.91875	58.74901	67.7735
Hodomys alleni	133.8427	134.6043	130.7852	88.92688
Liomys spectabilis	74.7032	71.6679	68.10292	66.16969
Marmosa canescens	113.8795	108.5582	102.2019	103.9904
Megadontomys cryophilus	221.2128	218.8462	215.813	217.8472
Megadontomys thomasi	127.9002	127.1915	122.4917	127.1194
Megasorex gigas	187.201	178.8164	173.8615	174.4375
Microtus oaxacencis	157.4801	153.9868	152.0946	150.6711
Microtus quasiater	138.0674	127.1492	118.0521	123.336
Musonycteris harrisoni	173.4635	156.1595	148.0547	149.6395
Myotis peninsularis	295.5905	288.4823	289.6633	288.1136
Myotis vivesi	15.362	29.52228	23.6840377	24.413
Neotoma angustapalata	160.1104	154.2351	146.6997	141.5457
Neotoma goldmani	202.3892	198.4249	195.5573	194.394
Neotoma palatina	61.34576	47.89622	59.1654	60.98505
Neotoma phenax	212.4211	192.1887	173.4752	188.4084
Neotomodon alstoni	98.03804	76.49923	68.5404	69.02895
Orthogeomys cuniculus	219.333	245.7961	186.772553	212.3229

Osgoodomys banderanus	203.9434	193.9338	191.7999	95.43805
Pappogeomys bulleri	146.0294	140.0449	136.1414	95.43805
Peromyscus aztecus	150.7626	150.3322	147.0044	147.2456
Peromyscus bullatus	73.7201	124.1947	94.1946959	28.04806
Peromyscus eva	151.0417	148.376	148.4009	146.3634
Peromyscus furvus	172.1107	170.8273	161.579	168.1887
Peromyscus megalops	135.1326	118.7061	107.9717	108.1714
Peromyscus mekisturus	153.2086	143.9766	142.2158	141.9896
Peromyscus melanotis	237.2488	235.6269	289.0569	232.8667
Peromyscus merriami	199.231	127.4864	122.3268	120.1528
Peromyscus ochraeater	187.1564	176.5341	171.2079	171.6305
Peromyscus perfulvus	179.4763	177.0071	175.242	169.2107
Peromyscus polius	242.2168	239.8284	239.1511	235.0789
Peromyscus winkelmanni	317.1085	317.1085	317.1085	312.0044
Peromyscus yucatanicus	293.6147	293.3095	291.3574	288.8002
Peromyscus zarhynchus	314.9757	298.4572	285.7988	286.5196
Plecotus mexicanus	139.4093	140.4936	136.7253	136.909
Reithrodontomys burti	75.89168	66.15148	62.09942	60.61079
Reithrodontomys chrysopsis	226.7655	211.8943	190.7486	206.5864

Reithrodontomys hirsutus	270.8437	263.0165	262.7221	256.9951
Rheomys mexicanus	163.4913	153.0107	153.3919	151.5403
Rhogeessa aeneus	210.6221	208.9451	209.0398	206.6119
Rhogeessa alleni	186.311	172.9754	163.697	168.5548
Rhogeessa gracilis	143.8363	136.9254	131.852	132.9426
Romerolagus diazi	170.7945	151.914	133.9046	150.1677
Sciurus alleni	214.1303	214.924	204.811	208.7419
Sciurus colliaei	178.88	171.5209	164.9865	165.4969
Sciurus oculatus	180.9992	177.7676	154.5715	171.3002
Sigmodon alleni	180.2067	176.3515	173.6554	173.3402
Sigmodon leucotis	233.7236	222.5987	217.5043	217.1753
Sigmodon mascotensis	166.6038	155.3002	146.3446	150.3522
Sorex macrodon	233.453	53.65391	89.53077	117.2761
Sorex milleri	66.65481	65.1396	64.33319	63.7767
Sorex sclateri	15.60542	3.713017	**	11.95855
Sorex veraepacis	153.254	151.3202	150.276	150.5751
Spermophilus adocetus	268.2759	272.1125	268.1462	270.8964
Spermophilus annulatus	185.3621	183.6395	178.303	175.0386
Spermophilus madrensis	260.9758	258.0414	258.5669	255.7978
Spermophilus perotensis	173.102	152.6531	125.2586	115.7246

Spilogale pygmaea	97.97704	96.07371	93.29955	92.41298
Sylvilagus cunicularius	254.5826	244.4378	236.7012	243.348
Sylvilagus insonus	43.679	39.22673	38.4404349	35.5827
Tamias bulleri	160.6763	157.8302	156.4522	152.9784
Xenomys nelsoni	93.69156	92.20107	92.7971	87.25287

**We excluded the 1993 range of *Sorex sclateri* from the analysis because the modeled distribution consisted of only one site.

Figure 2 of the manuscript shows the mean of the average intensities for the 78 species that occupied fewer sites in 2000 than in 1970. Figure 2 indicates that the mean intensity decreased from 1970 to 2000. The biological interpretation is that most species occupied fewer sites per unit area in 2000 than in 1970. Thus, for most species, the number and density of occupied sites was lower in 2000 than in 1976.

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