

**Supplementary information**

**for**

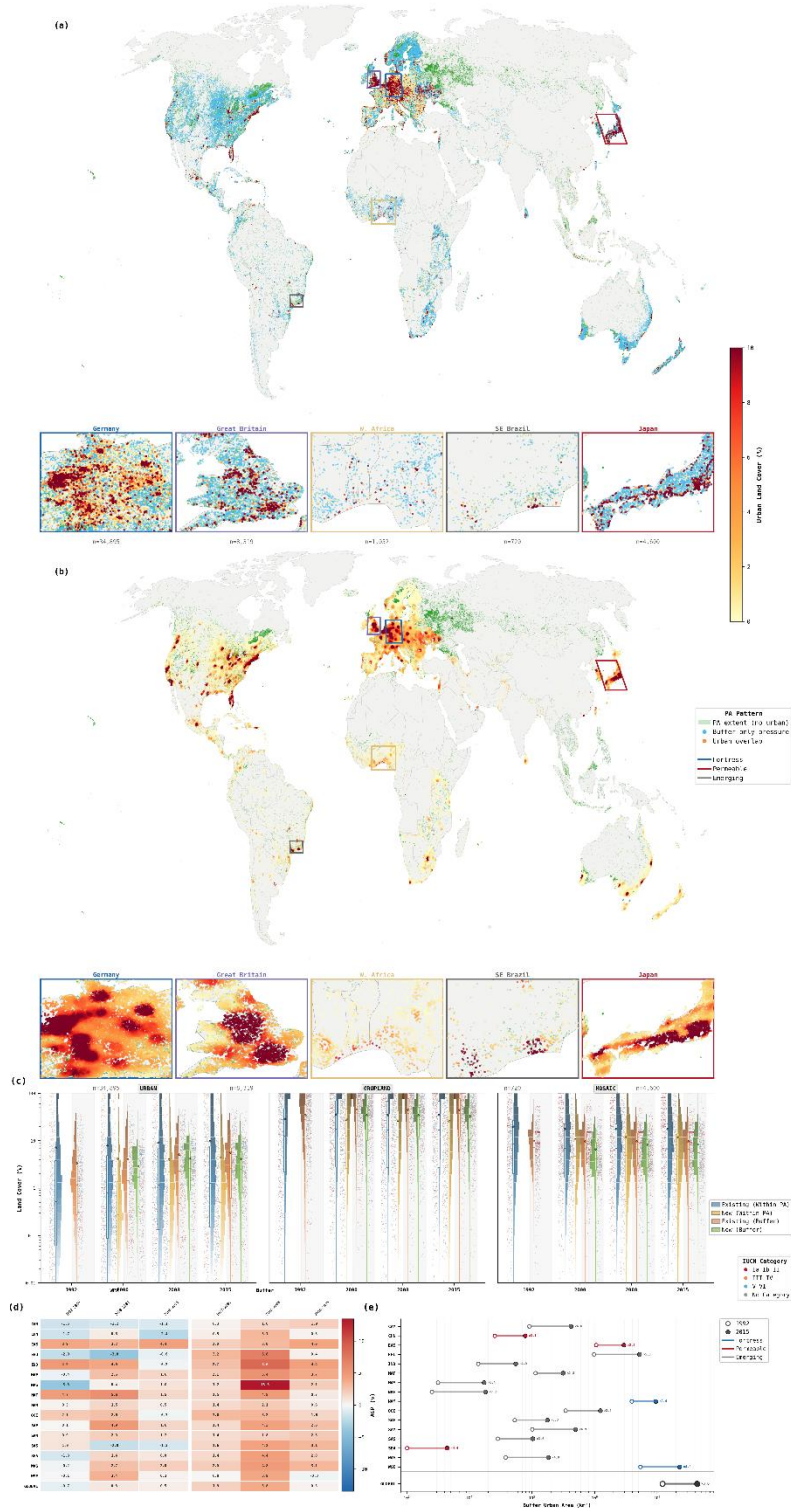
**Accelerating urbanization drives physical isolation of global protected area networks**

Rakibul Ahasan<sup>1, a, #</sup>, Burak Güneralp<sup>1</sup>

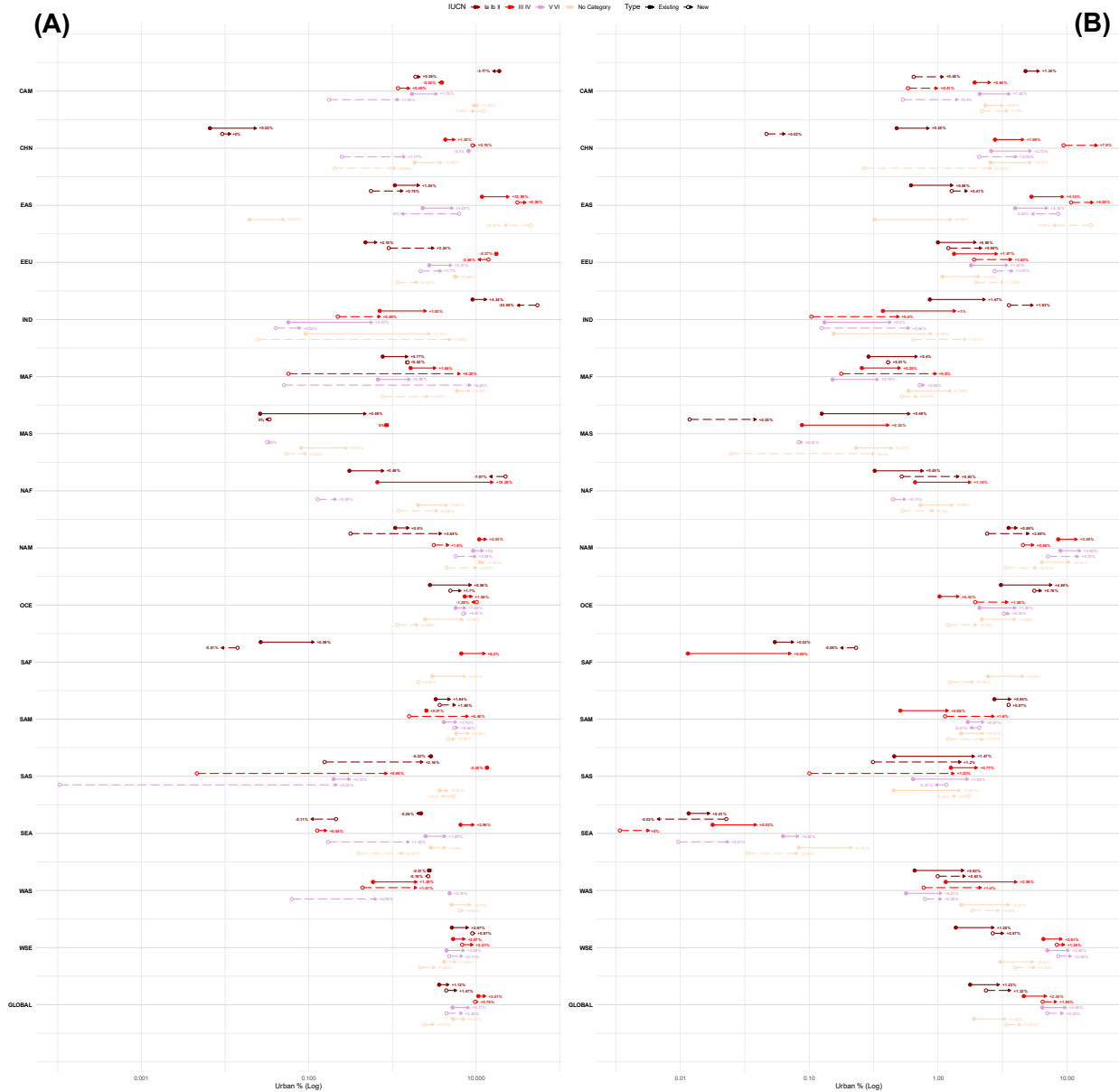
<sup>1</sup> Department of Geography, Texas A&M University, College Station, TX 77843.

<sup>a</sup> Current address: Environmental Systems Research Institute (Esri), Redlands, CA 92373.

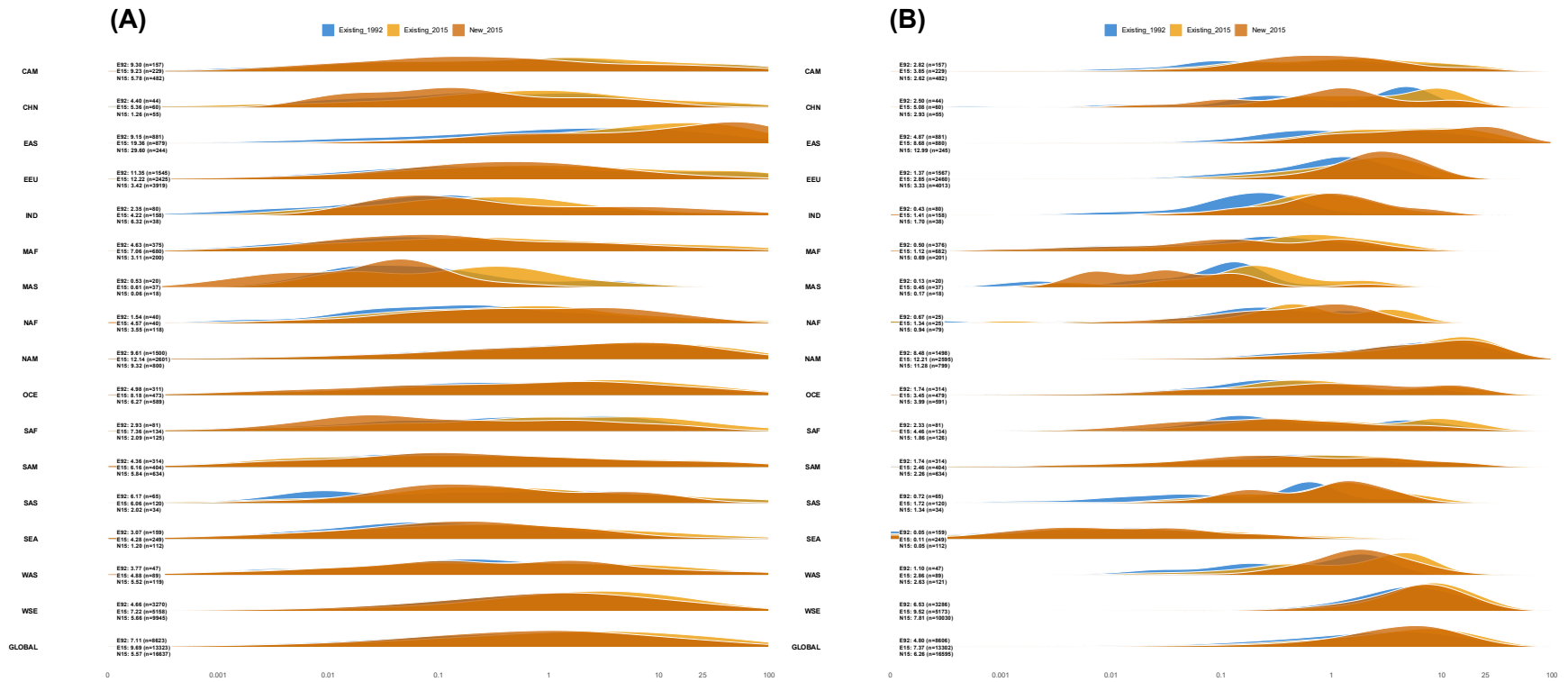
<sup>#</sup> Corresponding author: Rakibul Ahasan ([rahasan@tamu.edu](mailto:rahasan@tamu.edu))



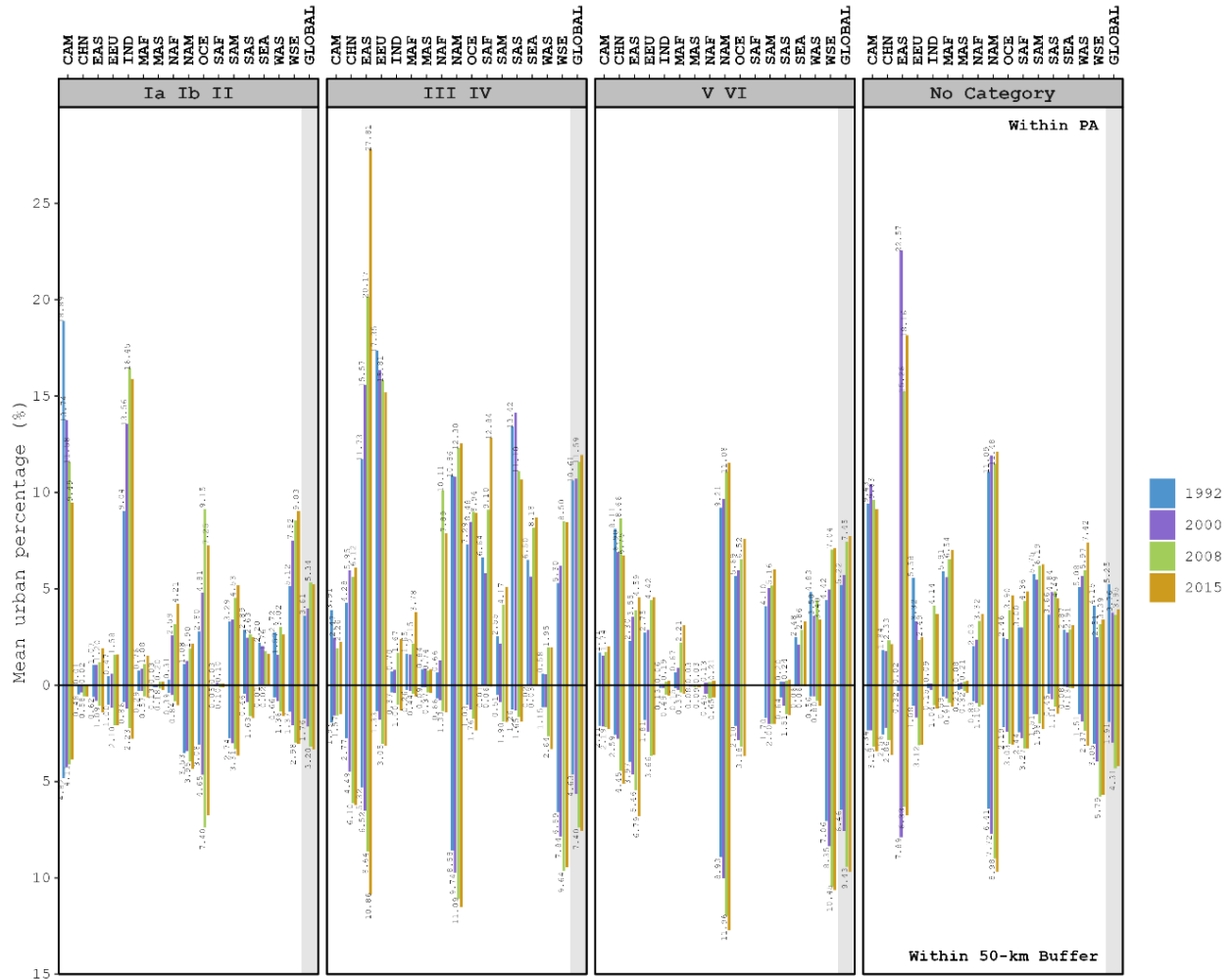
**Figure S1. Composite overview of urban encroachment on the global protected area network, 1992–2015:** (a) percentage of urban land cover within PA boundaries (2015), (b) percentage of urban land cover within the 50-km buffer zone (2015), (c) distribution of urban, cropland, and mosaic land cover (% , log scale) by designation cohort and zone, with gradient-colored frequency bars, boxplots, and IUCN-coded jittered points, (d) annual Growth Percentage of urban land cover by IPBES region and period for within-PA and buffer zones, and (e) total buffer urban area in 1992 and 2015 by region, with growth factors.



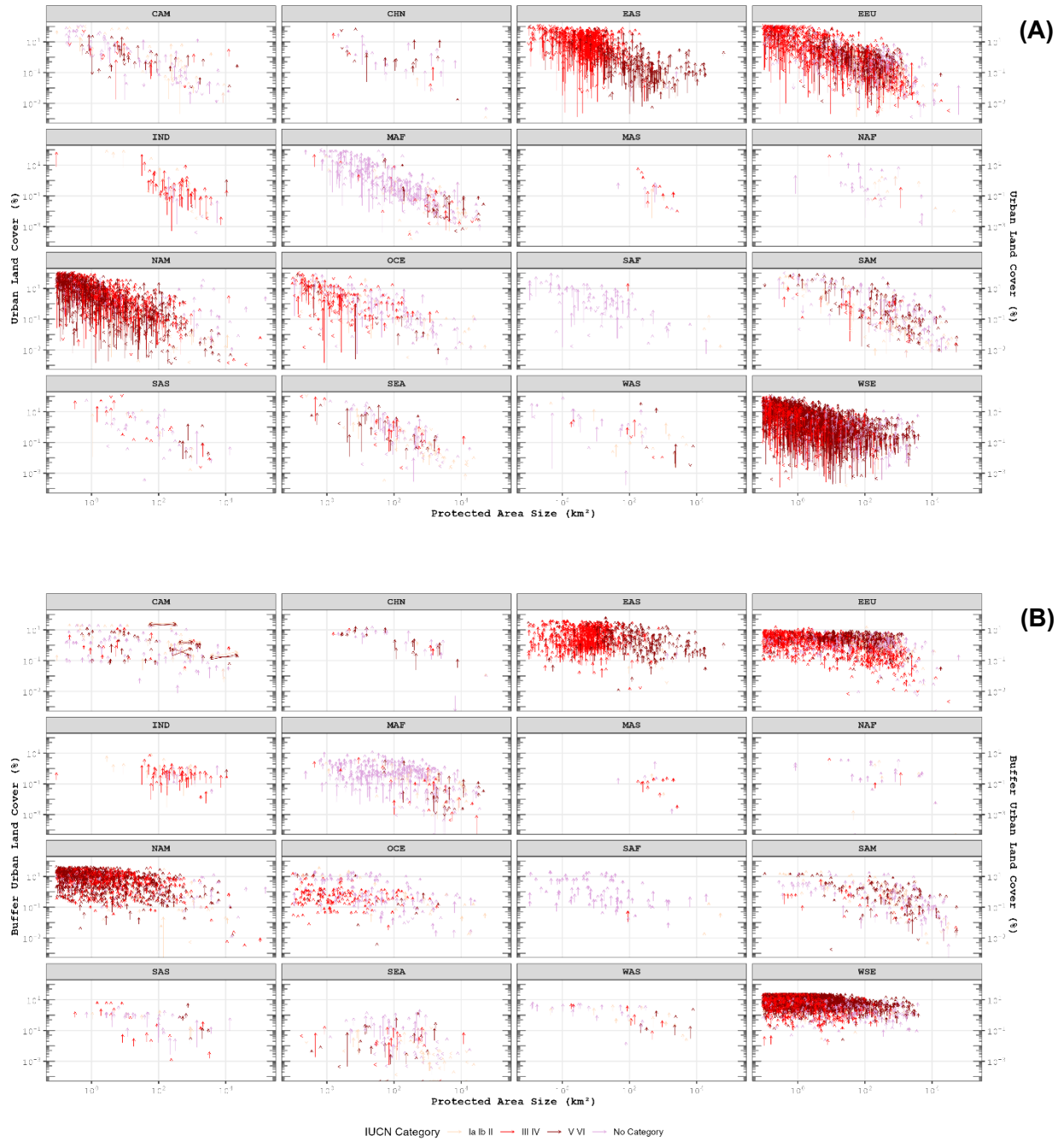
**Figure S2. Urbanization trajectories (A) within protected areas and (B) surrounding buffer zones in 16 regions and globally.** The plot illustrates mean urban land cover change (%) from 1992 to 2015 within protected areas and 50-km buffer zones, stratified by IUCN category. Each line traces the shift in mean urban density, with the tail representing the 1992 baseline and the head representing the 2015 state. The solid lines with a solid start point indicate the changes in *existing* PAs and the dashed lines with a hollow start point indicate changes within *new* PAs. The arrow indicates the direction of change between 1992 and 2015.



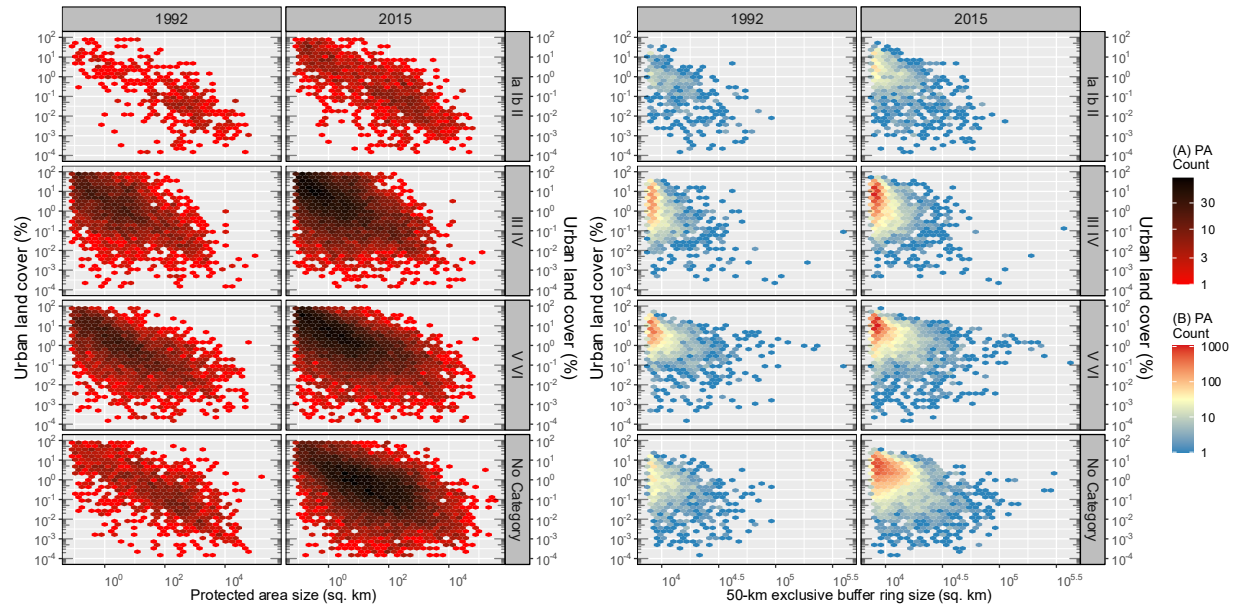
**Figure S3. Differential urbanization pressure on existing versus new protected areas:** existing PAs in 1992 (shown in Blue), new PAs in 2015 (shown in Orange), and existing PAs in 2015 (shown in Gold). Temporal density plots illustrates the percentage of urban land cover (A) within PAs and (B) within 50-km buffer around *existing* protected areas (designated pre-1992, blue). Data are aggregated by region and year (1992, 2000, 2008, 2015).



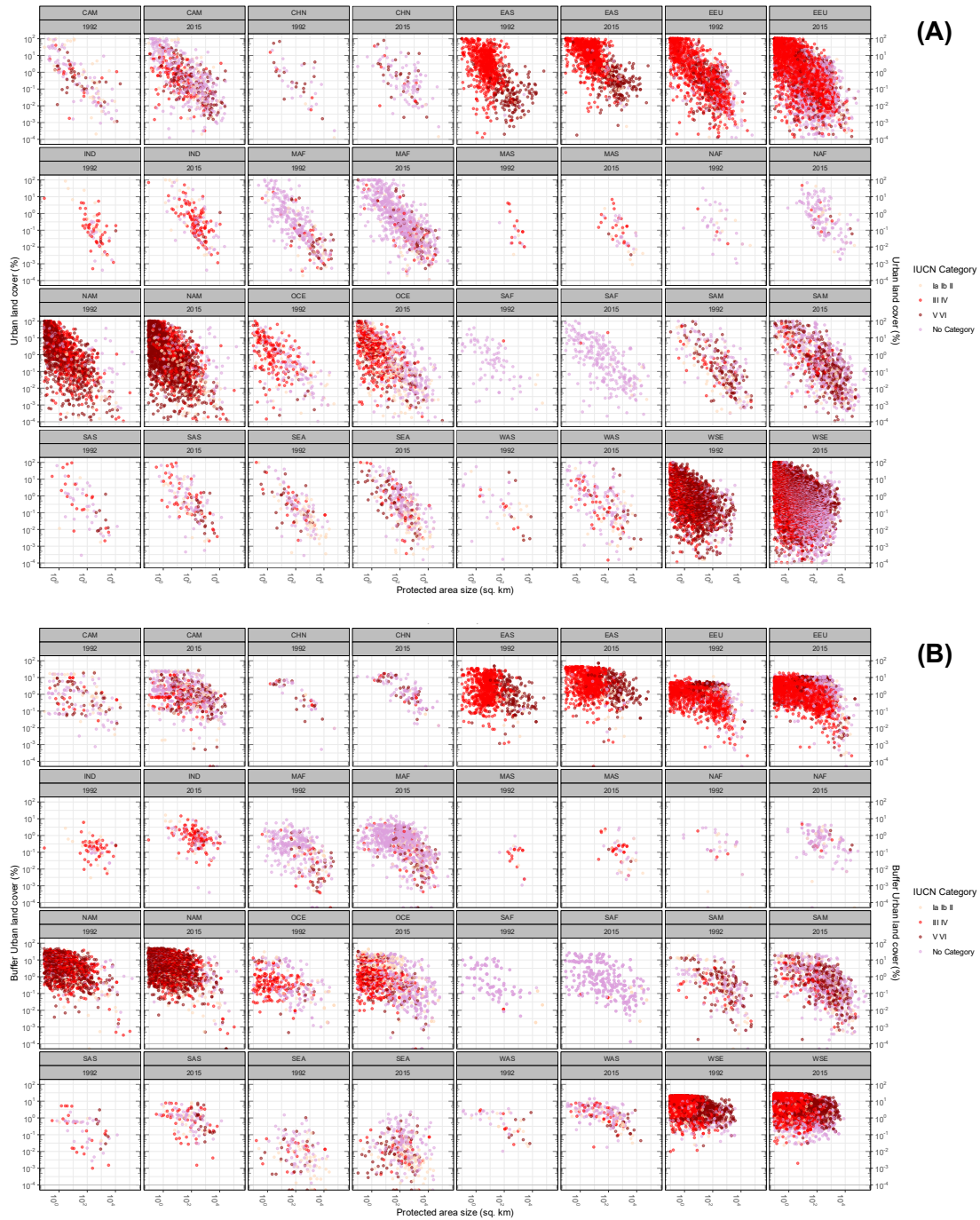
**Figure S4. Spatiotemporal trends in mean urban land cover stratified by IUCN management category.** The grouped bars illustrate the mean urban land cover percentage from 1992 to 2015 for (Top) within protected area boundaries (positive y-axis) and (Bottom) within the 50-km exclusive buffer zone (negative y-axis). The data are faceted by IUCN category: Strict Nature Reserves and National Parks (Ia, Ib, II); Natural Monuments and Habitat Management Areas (III, IV); Protected Landscapes and Seascapes (Sustainable Use, V, VI); and Reserves with No Category (No Category).



**Figure S5. Divergent trajectories of protected area isolation (1992–2015).** The plot displays spatiotemporal evolution of mean urban land cover (%): (A) within protected area boundaries and (B) within the 50-km buffer zone. Each arrow represents the trajectory of urban land changes for specific PAs from 1992 (tail) to 2015 (head).



**Figure S6. The size-dependent vulnerability of protected areas to urbanization, stratified by IUCN management category.** The relationship between protected area size (km<sup>2</sup>, log-transformed) and the percentage of urban land cover (% , log-transformed) is shown for (A) within protected area boundaries and (B) within the 50-km exclusive buffer zone. The data are stratified by IUCN category. The color gradient represents the density of protected areas within each hexagonal bin (count).



**Figure S7. The size-dependent vulnerability of protected areas to urbanization.** The relationship between protected area size ( $\text{km}^2$ , log-transformed) and urban land cover percentage (% , log-transformed) for: **(A)** within protected area boundaries and **(B)** within the 50-km buffer zone. Each point represents an individual protected area.

**Table S1.** Mean urban land cover percentage within protected areas (PAs) and within 50-km buffer around the PAs, stratified by IUCN Category

Region	IUCN Category	Mean urban land cover (%)							
		Within Protected Area				Within 50-km buffer			
		1992	2000	2008	2015	1992	2000	2008	2015
CAM	Ia Ib II	18.890	13.742	11.577	9.493	1.720	1.745	1.611	1.715
	III IV	3.906	2.475	1.920	2.257	0.532	0.602	0.718	0.911
	V VI	1.706	1.543	1.740	2.006	1.259	1.330	1.200	1.396
	No category	9.431	10.438	9.627	9.159	1.046	1.163	1.702	2.008
CHN	Ia Ib II	0.007	0.007	0.016	0.020	0.196	0.145	0.207	0.193
	III IV	4.276	5.952	5.629	6.122	3.490	3.846	6.162	6.546
	V VI	8.114	6.899	8.660	6.747	2.628	2.750	4.206	4.179
	No category	1.840	1.777	2.331	2.133	2.977	3.236	3.534	3.694
EAS	Ia Ib II	1.068	1.075	1.198	1.906	0.638	0.771	1.177	1.775
	III IV	11.731	15.568	20.168	27.809	2.807	3.336	4.383	5.854
	V VI	2.299	3.553	3.890	4.585	3.585	3.947	4.604	5.894
	No category	0.020	22.574	15.257	18.162	0.470	2.751	2.352	3.696
EEU	Ia Ib II	0.475	0.589	1.583	1.599	0.818	0.876	1.650	1.638
	III IV	17.345	16.339	15.809	15.203	1.000	1.267	2.052	2.149
	V VI	2.750	2.865	4.424	4.566	1.204	1.495	1.909	1.949
	No category	5.576	3.315	2.354	2.491	0.690	1.082	2.262	2.272
IND	Ia Ib II	9.044	13.558	16.453	15.888	0.387	0.536	0.821	1.083
	III IV	0.703	0.792	1.673	2.400	0.272	0.321	0.630	0.855
	V VI	0.057	0.061	0.189	0.246	0.108	0.096	0.304	0.425
	No category	0.091	0.090	4.139	3.708	0.163	0.202	0.566	0.778
MAF	Ia Ib II	0.764	0.848	1.077	1.533	0.160	0.190	0.284	0.376
	III IV	1.647	1.591	2.154	3.779	0.163	0.196	0.298	0.385
	V VI	5.910	5.601	6.543	7.013	0.267	0.317	0.481	0.620
	No category	0.669	0.898	2.210	3.112	0.147	0.175	0.255	0.317
MAS	Ia Ib II	0.026	0.033	0.202	0.205	0.102	0.107	0.268	0.313
	III IV	0.839	0.847	0.741	0.835	0.073	0.086	0.281	0.348
	V VI	-	0.032	0.032	0.032	0.005	0.017	0.023	0.039
	No category	0.081	0.124	0.206	0.212	0.073	0.079	0.180	0.208
NAF	Ia Ib II	0.306	2.590	3.176	4.211	0.359	0.503	0.762	0.963
	III IV	0.660	1.283	10.114	7.887	0.527	0.612	1.046	1.085
	V VI	-	0.127	0.160	0.214	-	0.408	0.612	0.709
	No category	2.029	2.373	3.324	3.694	0.665	0.623	0.879	0.946
NAM	Ia Ib II	1.077	1.261	1.904	2.141	0.588	0.652	0.728	0.791
	III IV	10.863	10.799	12.298	12.556	4.143	4.562	4.327	3.230
	V VI	9.205	9.654	11.079	11.564	2.712	3.087	3.883	4.287
	No category	11.086	11.914	11.478	12.114	5.705	6.601	7.492	7.422
OCE	Ia Ib II	2.804	4.809	9.155	7.250	0.621	0.784	1.219	1.271
	III IV	7.293	8.483	9.014	8.942	0.558	0.719	0.821	0.929
	V VI	5.688	5.985	6.524	7.602	0.587	0.970	1.051	1.223
	No category	2.457	2.380	3.901	4.646	0.628	0.689	0.887	1.043
SAF	Ia Ib II	0.027	0.116	0.096	0.080	0.101	0.127	0.174	0.240
	III IV	6.644	5.809	9.105	12.840	0.291	0.364	0.390	0.671
	V VI	-	-	-	-	0.063	0.090	0.092	0.564

Region	IUCN Category	Mean urban land cover (%)							
		Within Protected Area				Within 50-km buffer			
		1992	2000	2008	2015	1992	2000	2008	2015
	No category	2.997	2.994	4.364	4.867	0.650	0.717	0.965	1.177
SAM	Ia Ib II	3.285	3.389	4.534	5.195	0.930	1.035	1.243	1.527
	III IV	2.548	2.161	4.165	5.114	0.433	0.541	0.910	1.047
	V VI	4.103	5.040	5.162	5.998	0.945	1.100	1.094	1.139
	No category	5.754	5.474	6.190	6.264	0.800	0.861	1.036	1.297
SAS	Ia Ib II	2.887	2.466	2.629	2.491	0.711	0.796	1.089	1.197
	III IV	13.418	14.136	11.096	10.664	0.361	0.424	0.589	0.802
	V VI	0.198	0.184	0.241	0.293	0.416	0.385	0.634	0.799
	No category	3.663	4.839	4.863	4.493	0.681	0.809	1.096	1.411
SEA	Ia Ib II	2.198	2.041	1.758	1.613	0.015	0.022	0.019	0.019
	III IV	6.501	5.649	8.180	8.688	0.022	0.024	0.040	0.045
	V VI	2.482	2.092	2.859	3.304	0.069	0.060	0.068	0.068
	No category	2.871	2.730	2.907	3.125	0.088	0.098	0.143	0.170
WAS	Ia Ib II	2.719	1.575	3.024	2.636	0.603	0.747	1.106	1.409
	III IV	0.584	0.564	1.949	1.961	1.448	1.749	2.581	3.020
	V VI	4.826	3.584	4.398	3.400	0.543	0.535	1.061	1.246
	No category	5.079	5.675	5.970	7.417	1.519	1.714	2.416	3.010
WSE	Ia Ib II	5.120	7.521	8.542	9.027	0.623	0.789	1.019	0.942
	III IV	5.303	6.184	8.500	8.458	3.548	4.396	6.172	6.108
	V VI	4.147	2.514	3.177	3.392	2.188	1.938	3.099	3.037
	No category	4.424	4.962	7.042	7.113	5.082	6.395	8.673	8.887
Global	Ia Ib II	3.168	3.476	4.183	4.080	0.536	0.614	0.836	0.966
	III IV	5.891	6.165	7.657	8.470	1.229	1.440	1.963	2.124
	V VI	3.960	3.316	3.939	4.064	1.105	1.158	1.520	1.723
	No category	3.629	5.160	5.385	5.794	1.337	1.700	2.152	2.396

**Table S2.** Total urban land area within the protected areas

Region	IUCN Category	Total urban land area (km <sup>2</sup> )			
		1992	2000	2008	2015
CAM	Ia Ib II	114.39	176.71	197.84	220.43
	III IV	138.57	229.36	289.27	455.22
	V VI	56.34	450.12	514.23	548.74
	No category	154.45	295.16	594.69	766.36
CHN	Ia Ib II	0.13	0.72	0.84	1.05
	III IV	0.81	2.11	3.11	5.59
	V VI	126.16	146.18	367.80	400.28
	No category	61.69	79.39	278.68	418.40
EAS	Ia Ib II	14.60	21.50	24.05	40.87
	III IV	666.72	854.09	1113.69	1524.25
	V VI	1,224.81	1,516.44	1,943.17	3,069.95
	No category	1.29	2.65	25.79	53.33
EEU	Ia Ib II	51.98	146.26	326.22	346.73
	III IV	422.47	606.32	974.59	1,053.63
	V VI	198.93	397.26	912.54	1,012.66
	No category	297.45	725.83	2,597.20	3,139.71
IND	Ia Ib II	39.89	47.45	69.21	93.43
	III IV	89.73	103.87	183.47	252.82
	V VI	9.95	13.25	53.86	121.09
	No category	4.51	6.80	99.41	192.37
MAF	Ia Ib II	24.70	35.27	50.95	119.78
	III IV	14.97	20.34	27.28	37.63
	V VI	67.92	93.62	130.78	171.37
	No category	350.60	515.50	1,204.34	1,852.14
MAS	Ia Ib II	0.52	9.12	12.06	13.13
	III IV	27.99	31.78	38.75	44.94
	V VI	-	0.20	0.20	0.20
	No category	1.70	8.81	19.21	27.99
NAF	Ia Ib II	32.51	57.78	77.13	109.76
	III IV	0.51	1.31	4.42	18.31
	V VI	-	48.38	49.29	53.27
	No category	63.38	561.12	736.64	1,341.16
NAM	Ia Ib II	5.47	7.69	11.49	16.44
	III IV	227.49	359.39	455.82	644.55
	V VI	100.32	157.17	235.76	288.34
	No category	3,705.98	4,604.62	5,950.52	7,315.21
OCE	Ia Ib II	29.18	67.95	87.36	103.68
	III IV	43.22	64.07	73.78	97.30
	V VI	1.21	3.45	6.75	23.84
	No category	61.79	209.26	640.21	1,034.59
SAF	Ia Ib II	17.74	48.64	49.19	49.36
	III IV	5.93	6.07	11.96	18.63
	V VI	-	-	-	-
	No category	20.97	152.99	376.91	702.60
SAM	Ia Ib II	105.59	142.57	166.20	189.69

Region	IUCN Category	Total urban land area (km <sup>2</sup> )			
		1992	2000	2008	2015
	III IV	41.36	54.46	68.88	79.58
	V VI	328.00	595.18	1,038.92	1,305.28
	No category	976.91	1,929.28	3,204.45	4,044.53
	Ia Ib II	4.62	6.68	13.92	19.46
SAS	III IV	18.67	20.52	31.60	47.85
	V VI	28.24	31.19	39.68	52.62
	No category	21.85	28.65	60.93	104.54
	Ia Ib II	35.16	39.81	53.43	61.17
SEA	III IV	26.59	23.45	52.84	94.17
	V VI	32.02	38.72	49.18	85.87
	No category	49.82	85.99	199.88	340.85
	Ia Ib II	21.02	24.77	46.06	51.21
WAS	III IV	1.12	4.51	7.61	12.08
	V VI	112.49	131.84	166.70	215.08
	No category	33.72	124.91	168.29	258.43
	Ia Ib II	4.06	7.43	16.13	23.31
WSE	III IV	40.54	87.93	243.13	288.23
	V VI	386.62	788.83	1,878.60	2,114.49
	No category	364.07	875.82	2,247.91	2,536.89
	Ia Ib II	501.56	840.34	1,202.09	1,459.48
Global	III IV	1,766.70	2,469.56	3,580.20	4,674.76
	V VI	2,673.00	4,411.83	7,387.47	9,463.08
	No category	6,170.18	10,206.79	18,405.04	24,129.11
	All Category	11,111.44	17,928.51	30,574.80	39,726.43

**Table S3.** Total urban land area within 50-km buffer around protected areas

Region	IUCN Category	Total urban land area (km <sup>2</sup> )			
		1992	2000	2008	2015
CAM	Ia Ib II	26,396.08	34,564.16	45,740.49	58,872.28
	III IV	7,506.41	12,374.41	25,735.30	41,934.41
	V VI	29,760.26	43,676.41	72,618.19	113,566.65
	No category	27,467.67	59,411.48	149,280.30	205,955.75
CHN	Ia Ib II	259.01	319.39	479.75	593.29
	III IV	5,428.24	7,272.47	11,652.06	12,468.83
	V VI	6,143.71	8,656.94	14,162.93	15,916.74
	No category	13,638.45	19,055.90	37,776.80	48,757.73
EAS	Ia Ib II	7,465.34	10,864.30	17,360.81	27,441.48
	III IV	704,326.53	977,536.65	1,535,454.42	2,116,323.78
	V VI	342,882.52	413,210.11	549,144.28	755,905.07
	No category	643.40	5,876.84	12,191.17	27,434.24
EEU	Ia Ib II	36,865.67	61,064.29	169,294.54	179,612.05
	III IV	759,458.36	1,312,313.19	2,307,804.24	2,521,714.26
	V VI	116,099.39	204,723.38	394,500.77	437,043.34
	No category	70,806.57	230,496.88	1,745,649.80	2,097,114.97
IND	Ia Ib II	2,855.40	4,275.88	7,295.30	9,794.58
	III IV	9,289.35	11,453.56	22,845.02	32,376.24
	V VI	78.70	120.45	459.39	747.72
	No category	1,637.54	2,151.30	7,115.52	12,095.05
MAF	Ia Ib II	4,310.75	5,629.30	9,358.89	13,025.20
	III IV	3,508.81	4,510.24	7,140.53	9,991.57
	V VI	2,418.03	3,240.55	5,550.57	7,185.57
	No category	103,427.53	126,552.26	211,476.10	285,709.78
MAS	Ia Ib II	823.04	1,598.66	4,075.42	5,283.30
	III IV	1,570.37	1,877.36	6,019.53	8,045.61
	V VI	2.44	75.88	110.51	290.34
	No category	767.39	1,021.32	2,606.50	3,597.17
NAF	Ia Ib II	410.59	702.99	1,206.10	1,516.61
	III IV	184.51	218.38	379.36	727.79
	V VI	-	388.88	487.96	731.16
	No category	1,920.64	4,237.43	8,522.54	15,125.04
NAM	Ia Ib II	102,936.89	145,664.26	217,310.87	268,235.67
	III IV	728,054.88	898,644.74	1,102,451.21	1,225,504.86
	V VI	2,863,669.91	3,987,277.06	6,193,140.05	7,563,620.49
	No category	240,941.45	294,338.74	353,763.46	419,495.05
OCE	Ia Ib II	86,949.58	141,252.66	294,473.86	365,629.71
	III IV	174,983.53	278,648.67	395,694.33	526,453.91
	V VI	19,787.15	49,424.71	85,597.96	144,767.98
	No category	61,172.03	92,225.86	147,761.25	196,130.08
SAF	Ia Ib II	334.54	501.99	737.69	950.94
	III IV	240.76	331.94	357.63	1,092.38
	V VI	20.95	30.01	30.45	472.50
	No category	52,491.50	79,987.05	125,065.44	173,057.35
SAM	Ia Ib II	30,045.11	42,598.53	65,375.25	87,218.58

Region	IUCN Category	Total urban land area (km <sup>2</sup> )			
		1992	2000	2008	2015
	III IV	5,856.16	10,640.16	28,660.21	47,159.95
	V VI	34,954.47	60,760.69	99,525.59	125,027.80
	No category	30,146.46	63,535.10	129,979.77	235,488.93
	Ia Ib II	8,213.06	10,572.88	20,727.35	48,410.63
SAS	III IV	4,012.07	5,266.70	8,690.83	12,328.21
	V VI	2,090.76	2,859.55	5,345.26	7,195.06
	No category	14,147.29	17,295.44	25,955.90	35,127.40
	Ia Ib II	115.98	189.21	200.42	245.19
SEA	III IV	78.69	102.58	184.20	308.34
	V VI	262.86	313.90	415.64	644.59
	No category	556.32	887.05	1,934.60	3,222.88
	Ia Ib II	3,833.04	5,813.51	11,075.75	15,467.58
WAS	III IV	17,597.79	24,276.09	39,781.45	58,702.26
	V VI	2,281.59	2,911.02	6,610.45	9,113.90
	No category	14,222.15	27,055.11	62,612.51	98,909.38
	Ia Ib II	56,607.72	108,573.81	224,013.22	316,023.76
WSE	III IV	2,736,684.61	4,848,074.17	8,747,450.21	9,753,880.59
	V VI	2,345,943.83	3,771,861.93	6,292,641.95	6,909,781.83
	No category	249,464.48	2,137,641.13	5,452,736.88	5,839,708.66
	Ia Ib II	368,421.80	574,185.80	1,088,725.74	1,398,320.86
Global	III IV	5,158,781.07	8,393,541.32	14,240,300.53	16,369,013.00
	V VI	5,766,396.57	8,549,531.48	13,720,341.95	16,092,010.74
	No category	883,450.88	3,161,768.87	8,474,428.53	9,696,929.47
	All Category	12,177,050.31	20,679,027.47	37,523,796.75	43,556,274.07

**Table S4.** Year-wise breakdown of the number of protected areas in each region and the number of protected areas above the threshold considered in this study.

Region	1992		2000		2008		2015		Total	
	Total	Above 0.09 km <sup>2</sup>	Total	Above 0.09k m <sup>2</sup>	Total	Above 0.09 km <sup>2</sup>	Total	Above 0.09 km <sup>2</sup>	Total	Above 0.09 km <sup>2</sup>
CAM	918	860	1,472	1,337	2,443	2,253	3,087	2,804	3,140	2,852
CHN	128	115	170	151	219	200	240	221	252	233
EAS	916	883	1,003	955	1,160	1,091	1,200	1,127	1,201	1,127
EEU	16,636	11,797	23,048	16,977	36,730	25,014	40,877	27,462	41,661	28,084
IND	124	124	133	133	146	146	150	150	150	150
MAF	5,086	5,016	5,208	5,136	5,607	5,533	5,758	5,682	5,790	5,713
MAS	157	157	196	196	216	216	249	249	249	249
NAF	197	196	249	243	347	340	619	611	620	612
NAM	22,936	17,630	27,192	21,153	34,326	26,234	39,871	30,948	39,905	30,979
OCE	9,614	7,247	11,958	9,178	15,249	11,818	17,707	14,037	17,852	14,167
SAF	1,002	989	1,328	1,313	1,514	1,490	1,699	1,675	1,727	1,703
SAM	1,217	1,211	1,918	1,902	3,232	3,107	4,424	4,165	4,709	4,394
SAS	557	552	599	592	720	708	1,013	983	1,015	985
SEA	1,431	1,380	1,687	1,631	1,896	1,832	1,990	1,926	2,005	1,941
WAS	404	360	526	475	708	641	857	776	884	803
WSE	25,106	17,408	48,134	34,682	72,518	48,219	85,327	54,179	88,662	55,837
<b>Global</b>	95,315	71,824	137,195	104,586	194,718	139,077	224,881	158,080	229,763	160,992