Developing a framework to improve global estimates of conservation area coverage

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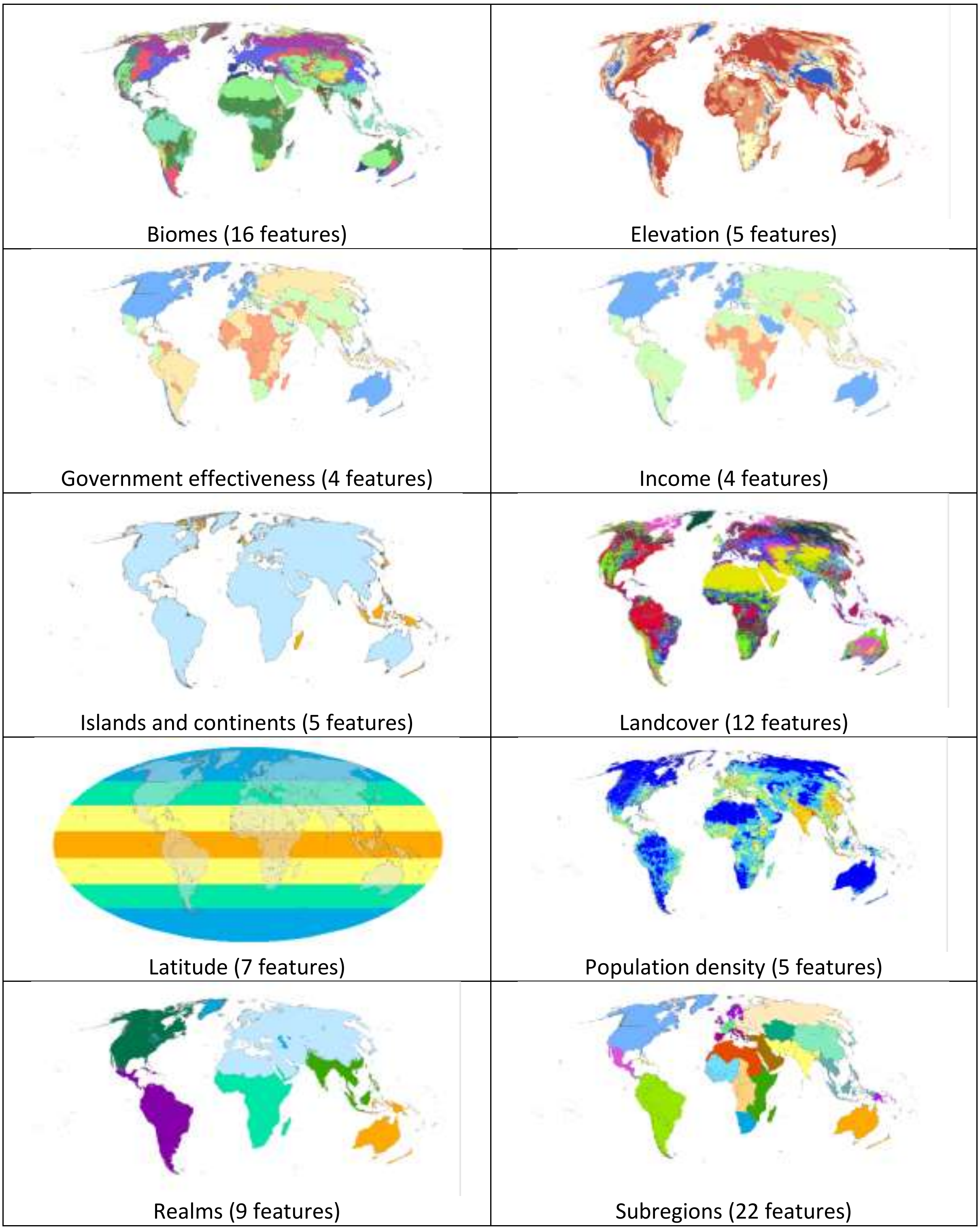
SUPPLEMENTARY TABLE 1 Initial list of factors which were discussed in our expert workshop as potential drivers of conservation area establishment and drivers of biodiversity patterns for possible inclusion in spatial prioritisation. The experts at the workshop had more than 180 years of combined experience and had published 124 relevant articles on developing global biodiversity metrics and research on conservation areas network.

African, Caribbean and Pacific Group of States	Latitude
Age of PA network	Legal system type
Carbon payments	Major habitat types
Climate vulnerability indices	PA investment
Completeness of WDPA country records	PA management effectiveness
Continents	PA management record
Corruption	PA visitor numbers
Degraded and pristine areas	Political groupings (e.g. ex-Soviet, ex-colonial)
Ecoregions	Political stability
Endemism	Rates of forest loss
Freshwater	Rates of habitat conversion
Islands	Religious groupings
Land tenure	Sacred sites
Landcover trends	Size of country
Language groups	Within country variability



SUPPLEMENTARY FIG. 1 Maps of the ten factors used in the analysis to identify a representative sample of countries demonstrating drivers of conservation area extent and drivers of global biodiversity patterns. Details of the features that make up each factor are given in Supplementary Table 4.

SUPPLEMENTARY TABLE 2 Factors that drive global biodiversity patterns and conservation area extent which were included in our spatial prioritisation analysis

Factor	Drivers of conservation area extent	Drivers of global biodiversity patterns
Biomes	Conservation area extent is higher in biomes with less land suitable for agriculture, such as deserts, and rock and ice (Hoekstra et al., 2005).	Biodiversity differs greatly between biomes, with ecosystem types sharing similar species compositions (Gaston & Spicer, 2013).
Elevation	Conservation area extent tends to increase at higher elevations (Joppa & Pfaff, 2009).	Species composition varies across elevation gradients (Gaston & Spicer, 2013).
Government effectiveness	Stable countries with higher bureaucratic quality have greater capacity to expand conservation area networks (Laurance, 2004).	
Income (per capita)	Wealthier countries have more resources to fund the expansion of conservation area networks (Waldron et al., 2013).	
Islands and continents		Islands are often geographically and biologically distinct, with unique and highly threatened biodiversity (Gaston & Spicer, 2013).
Landcover	Conservation area extent differs between landcover types (Joppa & Pfaff, 2009).	Species composition varies between vegetation types and land-uses (Gaston & Spicer, 2013).
Latitude	Conservation area extent is higher at latitudes with less land suitable for agriculture, such as closer to the poles (Hoekstra et al., 2005).	Species composition shows strong latitudinal gradients (Gaston & Spicer, 2013).
Population density	Conservation area extent is lower in regions with high human population density (Joppa & Pfaff, 2009).	
Realms		Biodiversity shows strong biogeographic patterns at the continental scale (Gaston & Spicer, 2013).
Subregions	Sub-sections of continents have relatively similar histories, economies and legislative frameworks (Siegfried et al., 1998).	Biodiversity shows strong biogeographic patterns at the sub-continental scale (Gaston & Spicer, 2013).

SUPPLEMENTARY MATERIAL 1 Sensitivity analysis to set targets

The sensitivity analysis explored the trade-off between the area of the terrestrial realm selected to be a potential sample for future studies on conservation area extent and representativeness, and the number of sampling units selected (where each sampling unit was a country or, for countries with an area ≥1 million km^2, sub-national units such as provinces and states). This was based on the premise that selecting a larger percentage of the planet would produce a more robust sample but selecting more countries and provinces would increase the time and resources needed to collect the conservation area data. So, we used the conservation planning system developed for Stage 1 to run eight Marxan analysis using the same percentage target for each feature in each analysis. These different targets were 1%, 2%, 5%, 10%, 20%, 30%, 40% and 50% of the total extent of each feature, and each analysis consisted of 100 runs of 10,000,000 iterations. We used a Boundary Length Modifier of 1.5 (Ball et al., 2009), a value that we determined through testing to best ensure that Marxan chose enough sub-national units from the same countries to meet the targets. We then counted the number of whole countries and the number of sampling units in the 'best' solution for each of the eight analyses.

The number of sampling units selected by Marxan to meet the targets for the 89 conservation features ranged from 23 for the 1% targets to 206 for the 40% targets (Table S3). The number of sampling units more than doubled when comparing results from using 10% and 20% targets, with a levelling off when the targets were ≥ 30%. Based on these results, we decided to use 10% targets for the main analyses.

SUPPLEMENTARY TABLE 3 The number of sampling units and countries selected to meet specific percentage targets for each of the 89 features. Sampling units consisted of whole countries for nations with an area <1 million km^2 and highest level sub-national units (provinces, states, etc) for countries with an area ≥1 million km^2.

Conservation feature targets (%)	Number of sampling units selected	Number of countries selected
1	23	22
2	24	22
5	30	24
10	50	25
20	117	27
30	204	32
40	206	32
50	205	32

SUPPLEMENTARY MATERIAL 2 Marxan analysis

We used Marxan for a two-stage analysis: Stage 1 identified the minimum set of countries needed to meet targets for each feature and Stage 2 identified sets of 10,000 km^2 grid squares that meet these targets within this subset of countries. This involved setting Species Penalty Factors to ensure that all the targets were met and we used a value of 10 for every feature for both analyses, as our initial testing showed this value produced efficient results.

For the Stage 1 analysis, we sought to select a set of national and sub-national sampling units that represented all the features, while also minimising the number of countries selected. To do this we set the combined sampling unit cost of each country as 1, so that selecting more countries was more costly. To account for the larger nations being split into several sampling units, based on the sub-national administrative units, we set the sampling unit costs as the inverse of the number of sub-national units in the country. For example, each of South Africa's nine provinces had a sampling unit cost of 0.111. In addition, we needed to ensure that Marxan met targets by selecting the sub-national sampling units from the same countries whenever possible. To do this we manipulated the Marxan boundary cost file so it appeared that every sub-national sampling unit in the same country shared a boundary. This meant that if Marxan selected one sub-national sampling unit in a particular country then it would be less costly to select subsequent sub-national sampling units from the same country. To make sure this cost would be the same per country, we set the boundary length equal to the inverse of the number of different sub-national boundary pairs in each country so, for instance, the nine provinces in South Africa produced 36 combinations of sub-national pairs and so the boundary length was 0.0278. This manipulation of the boundary cost data has been used in previous studies to ensure that certain sampling units are more likely to be selected together, even when they are not physically adjacent (Possingham et al., 2005; Hermoso et al., 2011).

We ran the Stage 1 analysis using Marxan, which consisted of 1,000 runs of 10,000,000 iterations and used a Boundary Length Modifier value of 1.5. These parameters were selected to produce results that minimised the number of countries and sampling units selected. Of the resulting 1,000 portfolios, 284 had equally low costs, i.e., contained exactly the same number of countries and sampling units. To produce our final list of sample countries we therefore needed to develop our own scoring system to choose between these low-cost portfolios. We did this by first selecting portfolios with the most even spread of countries selected across the continents to further improve the representativeness of the sample. We then identified the portfolios containing sampling units that were selected most often in the 1,000 runs, based on calculating their mean selection frequency score. This provided us with our final set of national and sub-national sampling units that were then used in the Stage 2 analysis.

Thus, our first step in Stage 2 was to update the planning system to specify in CLUZ that all of the 100 km x 100 km sampling units found outside the national and sub-national regions selected in Stage 1 should be excluded from subsequent Marxan analyses. The Stage 2 Marxan analysis also consisted of 1,000 runs but we used 100,000,000 iterations after carrying out a sensitivity analysis that showed more iterations were needed to produce efficient results because Stage 2 involved a larger number of planning units than Stage 1. For Stage 2 we used a Boundary Length Modifier value of 0 because we were not interested in selecting adjacent sampling units. For this finer-scale analysis we used the sampling unit area as the cost metric. This was because in Stage 2 we were simply seeking to identify the smallest area of land needed to meet the targets, as the logistical cost of collecting PA coverage data is not affected by whether the Stage 2 sampling units neighbour each other.

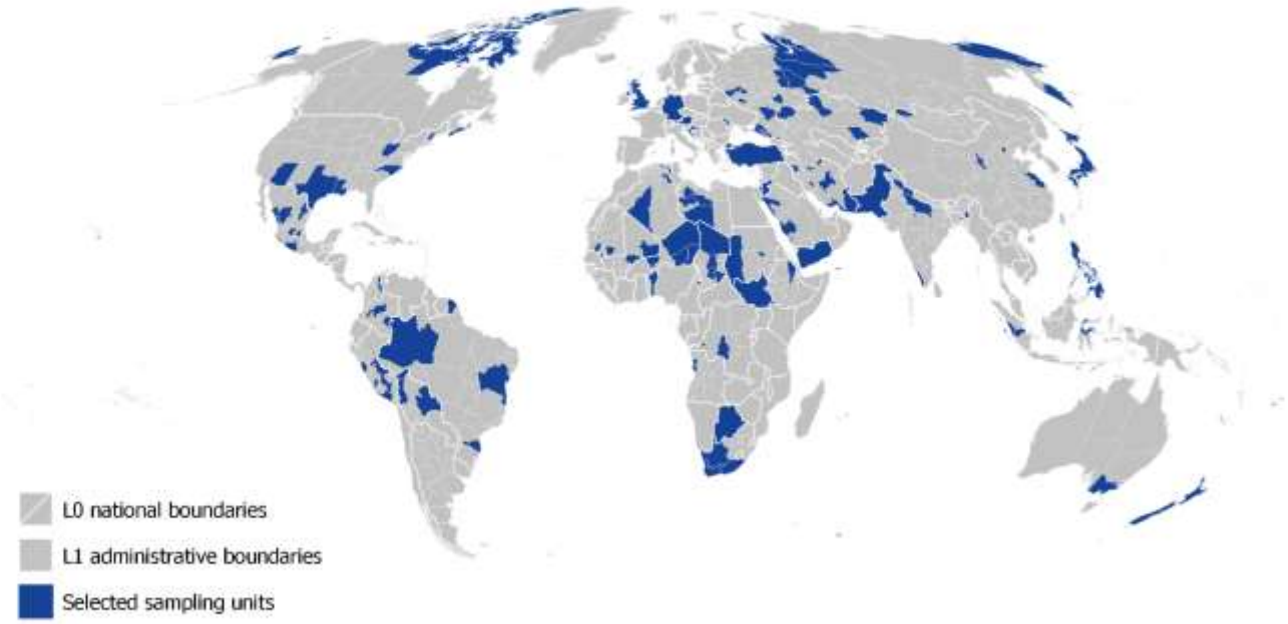
SUPPLEMENTARY TABLE 4 Details of all the features used in the analysis, their total extent, the proportion of the Stage 1 and Stage 2 best outputs covered by each, and the proportion of the terrestrial realm covered by the Stage 1 and Stage 2 best outputs.

Category	Feature	Global extent (km^2)	Terrestrial realm covered by feature (%)	Stage 1 sample covered by feature (%)	Stage 2 sample covered by feature (%)	Global extent found in Stage 1 sample (%)	Global extent found in Stage 2 sample (%)
Biomes	Tropical & subtropical moist broadleaf forest	19,847,759	14.67	10.78	13.49	11.40	10.00
Biomes	Tropical and subtropical dry broadleaf forest	3,017,092	2.23	1.92	2.54	13.36	12.32
Biomes	Tropical and subtropical coniferous forest	711,296	0.53	0.34	0.48	9.98	9.98
Biomes	Temperate broadleaf and mixed forest	12,772,448	9.44	6.64	8.68	10.91	10.01
Biomes	Temperate conifer forest	4,075,868	3.01	1.97	2.77	10.16	10.01
Biomes	Boreal Forest/taiga	15,046,636	11.12	14.11	10.99	19.68	10.73
Biomes	Trop. & Subtrop. grasslands, savannas & shrubland	20,285,917	14.99	14.04	15.73	14.53	11.29
Biomes	Temperate grasslands, savannas & shrublands	10,098,291	7.46	4.92	6.86	10.22	10.00
Biomes	Flooded grasslands and savannas	1,094,839	0.81	0.63	0.83	12.03	11.58
Biomes	Montane grasslands and shrublands	5,203,199	3.85	3.28	3.58	13.23	10.19
Biomes	Tundra	8,206,496	6.07	9.22	7.90	23.59	14.10
Biomes	Mediterranean forests, woodlands & scrub	3,210,402	2.37	3.59	2.34	23.50	10.00
Biomes	Deserts and xeric shrublands	27,969,796	20.67	25.21	21.03	18.92	11.13
Biomes	Mangroves	320,823	0.24	0.21	0.23	13.99	10.95
Biomes	Inland water	1,039,692	0.77	0.84	0.96	16.96	12.47
Biomes	Rock and ice	1,973,619	1.46	1.99	1.34	21.16	10.05
Realms	Australasia	9,232,561	6.82	15.77	8.78	35.85	13.82
Realms	Antarctic	11,159	0.01	0.02	0.01	33.00	15.72

Realms	Afrotropics	21,769,183	16.09	13.08	16.22	12.62	10.99
Realms	Indomalay	8,513,981	6.29	4.08	5.79	10.06	10.00
Realms	Nearctic	20,398,341	15.08	12.92	13.86	13.30	10.00
Realms	Neotropics	19,368,174	14.31	10.32	13.16	11.19	10.00
Realms	Oceania	43,247	0.03	0.09	0.10	45.13	41.67
Realms	Palearctic	52,705,510	38.95	40.89	39.84	16.28	11.07
Realms	Snow and ice	2,832,017	2.09	2.52	2.01	18.66	10.15
Elevation	0 – 299 m	55,813,693	41.25	37.82	39.26	14.23	11.61
Elevation	300 – 799 m	43,299,328	32.00	35.59	33.97	17.26	11.88
Elevation	800 – 1399 m	19,827,397	14.65	16.57	15.77	17.54	10.07
Elevation	1400 – 1999 m	7,279,095	5.38	4.47	4.95	12.88	10.08
Elevation	>= 2000 m	8,627,189	6.38	5.32	5.86	12.94	10.00
Islands & continents	< 1,000 km^2	487,462	0.36	0.29	0.33	12.28	12.22
Islands & continents	1,000 to 10,000 km^2	660,808	0.49	0.60	0.50	18.95	10.02
Islands & continents	10,000 to 100,000 km^2	1,621,613	1.20	0.86	1.11	11.11	11.27
Islands & continents	100,000 to 1,000,000 km^2	5,009,245	3.70	4.04	3.95	16.92	10.84
Islands & continents	> 1,000,000 km^2	127,492,420	94.23	94.20	94.10	15.51	13.69
Landcover	Croplands	10,044,523	7.42	7.92	9.62	16.54	10.47
Landcover	Croplands mosaic	17,948,478	13.27	10.76	12.81	12.59	10.00
Landcover	Closed forest	25,436,142	18.80	13.85	17.29	11.43	13.02
Landcover	Open forest	12,323,377	9.11	12.82	11.32	21.85	10.50
Landcover	Mosaic grassland/shrubland	26,265,135	19.41	20.05	18.32	16.02	10.16
Landcover	Sparse vegetation	13,551,920	10.02	12.60	9.22	19.52	10.66
Landcover	Flooded forest/grassland	1,902,386	1.41	1.53	1.45	16.92	10.21

Landcover	Artificial surfaces	317,365	0.23	0.20	0.22	12.94	10.64
Landcover	Bare areas	21,608,578	15.97	15.35	15.53	14.91	10.18
Landcover	Water bodies	2,980,599	2.20	2.08	2.18	14.68	10.21
Landcover	Snow and ice	2,913,595	2.15	2.82	2.02	20.29	15.85
Landcover	No data	14,186	0.01	0.02	0.02	29.48	10.53
Latitude	50N to 90N	31,826,862	23.52	27.39	22.89	18.06	10.00
Latitude	30N to 50N	32,126,360	23.74	20.68	21.83	13.51	11.75
Latitude	10N to 30N	26,501,375	19.59	15.65	21.21	12.40	11.31
Latitude	-10S to 10N	20,617,051	15.24	13.90	16.00	14.15	11.09
Latitude	-30S to -10S	18,842,279	13.93	18.04	14.11	20.10	10.12
Latitude	-50S to -30S	5,146,310	3.80	4.04	3.54	16.48	28.55
Latitude	-90S to -50S	214,058	0.16	0.30	0.41	29.83	14.29
Income group	Low income	14,417,961	10.66	11.06	14.00	16.10	10.56
Income group	Lower middle income	22,038,475	16.29	12.63	15.92	12.03	10.00
Income group	Upper middle income	60,767,325	44.91	40.77	41.32	14.08	11.07
Income group	High income	38,082,584	28.15	35.54	28.76	19.59	10.78
Population density	0 to 0.9	53,883,215	39.82	46.44	39.53	18.09	11.62
Population density	1 to 9.9	39,359,881	29.09	28.03	31.21	14.95	10.02
Population density	10 to 99.9	27,781,643	20.53	16.15	18.89	12.20	11.12
Population density	100 to 999.9	9,292,487	6.87	5.54	7.02	12.52	10.13
Population density	1000+	1,070,380	0.79	0.56	0.73	11.05	10.00
Govt. Effectiveness	0 - 24.9	23,463,373	17.34	11.34	15.95	10.15	10.42
Govt. Effectiveness	25 - 49.9	48,702,809	35.99	33.62	34.59	14.49	13.09
Govt. Effectiveness	50 - 74.9	28,037,538	20.72	23.55	24.89	17.64	10.23

Govt. Effectiveness	75 – 100	35,102,625	25.94	31.49	24.58	18.83	10.30
Subregions	Australia and New Zealand	7,985,635	5.90	12.08	5.43	31.75	10.00
Subregions	Caribbean	233,427	0.17	0.23	0.33	20.70	20.70
Subregions	Central America	2,481,651	1.83	1.25	1.70	10.57	10.11
Subregions	Central Asia	4,380,003	3.24	2.29	2.98	10.99	10.02
Subregions	Eastern Africa	7,049,679	5.21	4.52	4.79	13.45	10.00
Subregions	Eastern Asia	11,598,707	8.57	10.87	9.46	19.68	11.95
Subregions	Eastern Europe	18,604,967	13.75	14.62	12.64	16.49	10.00
Subregions	Melanesia	544,908	0.40	2.22	1.38	85.63	34.56
Subregions	Micronesia	3,576	0.00	0.00	0.00	27.68	10.26
Subregions	Middle Africa	6,608,246	4.88	3.55	5.01	11.27	11.25
Subregions	Northern Africa	7,647,985	5.65	4.80	6.74	13.18	12.96
Subregions	Northern America	21,581,549	15.95	14.61	14.67	14.21	10.00
Subregions	Northern Europe	1,803,994	1.33	2.13	1.23	24.83	10.00
Subregions	Polynesia	8,613	0.01	0.02	0.01	46.37	18.77
Subregions	South America	17,845,353	13.19	9.80	12.40	11.53	10.23
Subregions	South-eastern Asia	4,483,416	3.31	2.24	3.05	10.50	10.01
Subregions	Southern Africa	2,681,065	1.98	1.73	1.82	13.54	10.00
Subregions	Southern Asia	6,710,677	4.96	3.35	4.75	10.49	10.41
Subregions	Southern Europe	1,316,461	0.97	1.43	1.11	22.85	13.23
Subregions	Western Africa	6,082,789	4.50	2.99	4.20	10.33	10.06
Subregions	Western Asia	4,528,985	3.35	2.62	3.08	12.16	10.00
Subregions	Western Europe	1,102,673	0.81	2.62	3.24	49.81	40.67



SUPPLEMENTARY FIGURE 2 Representative example of the countries (national sampling units) and administrative units (sub-national sampling units) selected when using a random sampling approach

SUPPLEMENTARY FIGURE 3 Representative example of the 100 km x 100 km sampling units (analogous to the Stage 2 Marxan analysis but based on all the sampling units across the global terrestrial realm)

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