

Applying deep learning on social media to investigate cultural ecosystem services in protected areas worldwide

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A Abiotic (Transport)

Top 10 AI-generated tags (decreasing order)				
1 vehicle	3 outdoor	5 car	7 road	9 auto part
2 land vehicle	4 wheel	6 sky	8 tree	10 tire

Manually Identified Objects		
Driving	Train	Train station
Flying	Hot air balloon	Car



B Abiotic (Sports)

Top 10 AI-generated tags (decreasing order)				
1 outdoor	3 nature	5 mountain	7 landscape	9 plant
2 sky	4 tree	6 water	8 cloud	10 grass

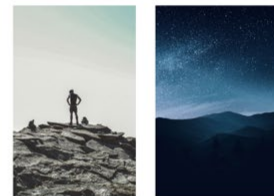
Manually Identified Objects		
Mountain Climbing	Watersports	Cycling
Hiking	Skiing	Cave
Scuba Diving		



C Abiotic (Watching)

Top 10 AI-generated tags (decreasing order)				
1 astronomy	3 moon	5 star	7 outdoor	9 sun hat
2 sky	4 night	6 hat	8 fashion accessory	10 clothing

Manually Identified Objects	
Stargazing	Lake
Walking Outdoors	Mountain Fog



D Biotic (Watching)

Top 10 AI-generated tags (decreasing order)				
1 animal	3 bird	5 branch	7 wildlife	9 perched
2 outdoor	4 tree	6 water	8 plant	10 aquatic bird

Manually Identified Object				
Bird	Butterfly	Reptile	Palm Tree	Mushroom
Gardening	Monkey	Wildlife	Fruit Tree	Animal



E Humans (Heritage)

Top 10 AI-generated tags (decreasing order)				
1 building	3 sky	5 window	7 cloud	9 old
2 outdoor	4 house	6 tree	8 stone	10 church

Manually Identified Object		
Old Building	Old Bridge	Urban Exploration
Old Statue	Walking Urban	Old Ruins
Old Church	Art	Museum



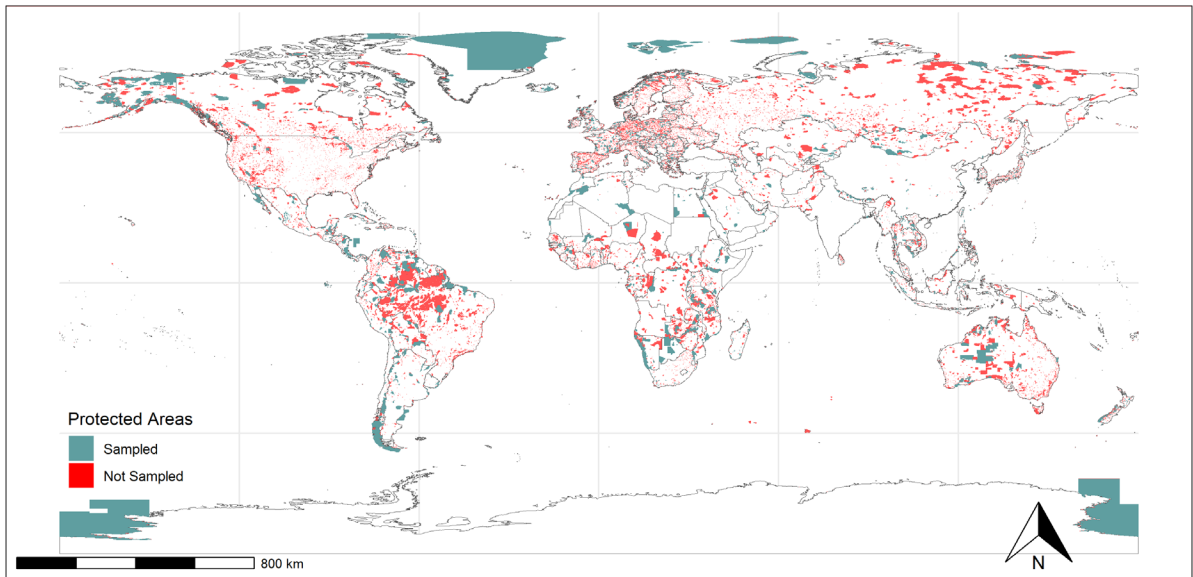
F Humans (Socializing)

Top 10 AI-generated tags (decreasing order)				
1 indoor	3 drawing	5 table	7 chair	9 text
2 food	4 painting	6 art	8 floor	10 furniture

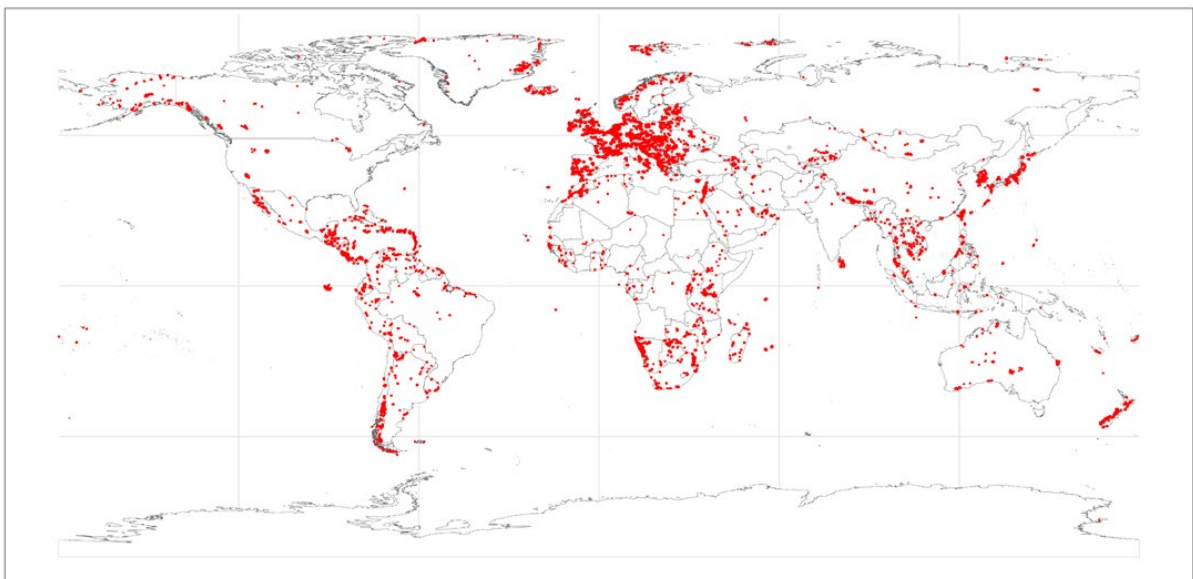
Manually Identified Object				
House	Cooking	Beach	Market	Dining
Art	Beer	Camping	Belly	Birthday
	Drinking		Dancing	Celebration



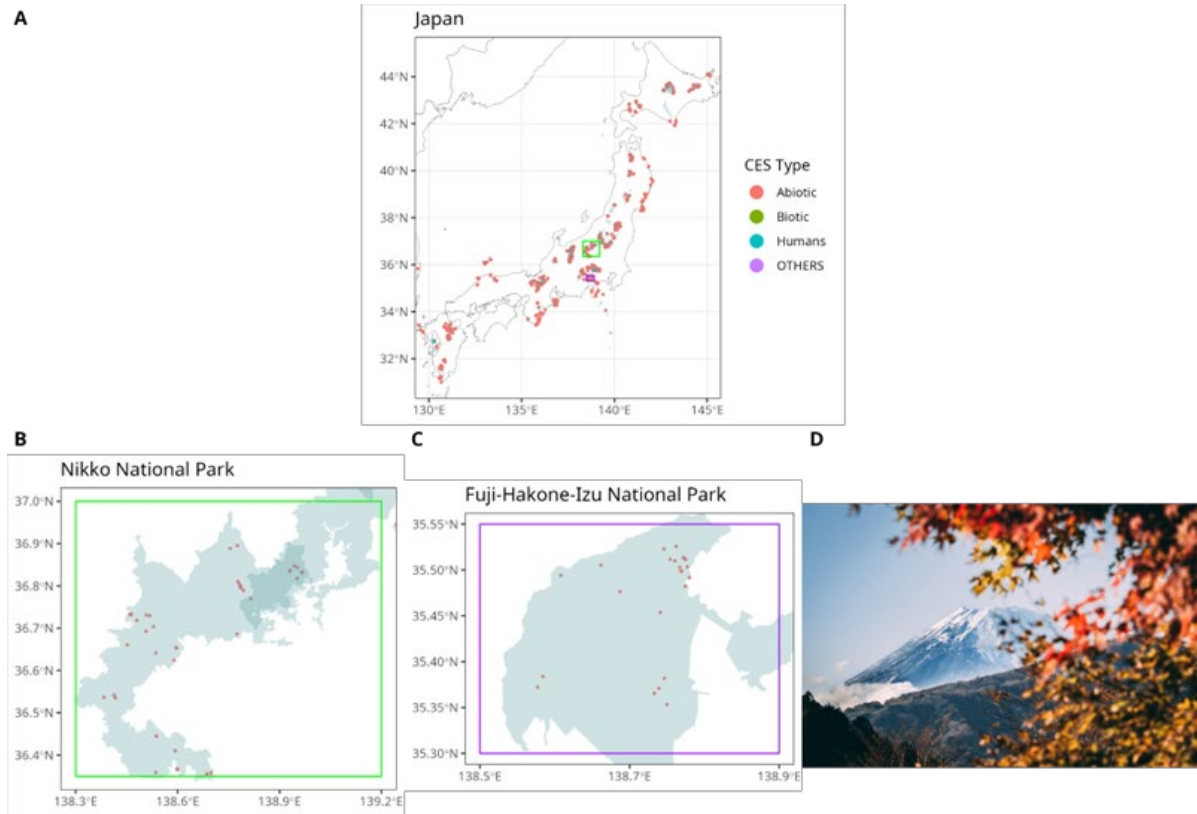
Supplementary Figure S1. The top 10 tags as identified by AI, arranged in decreasing order (top), all identified objects that were manually interpreted (middle), and example photo(s) (bottom), for each CES subcategory (A to F). Example photos were from pexels.com, a free stock photo website where photos can be used without attribution. Due to privacy concerns, no photos from the actual Flickr sample are shown.



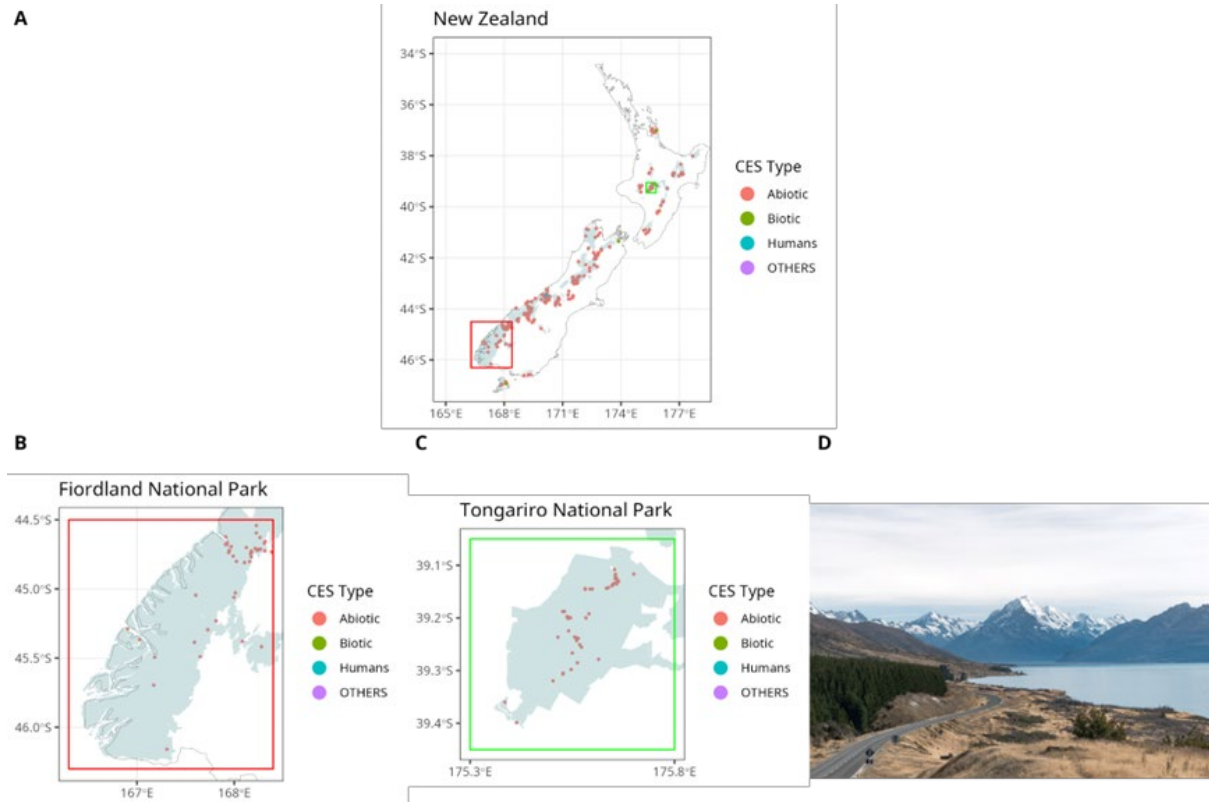
Supplementary Figure S2. Global map of all PAs that were in the WDPA (May 2022) with those that were sampled (in green), and those that were not sampled (in red).



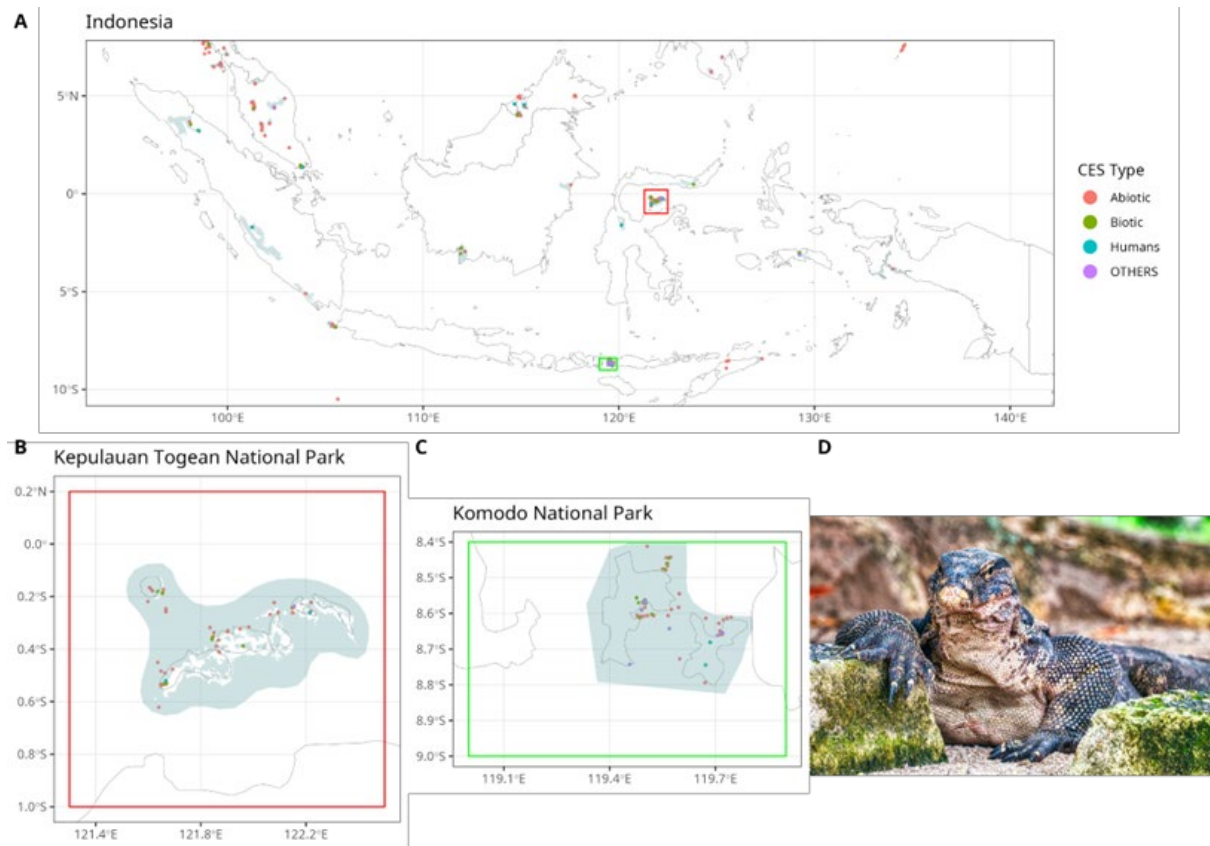
Supplementary Figure S3. Global map of all photos (in red) downloaded from Flickr and included in the final sample.



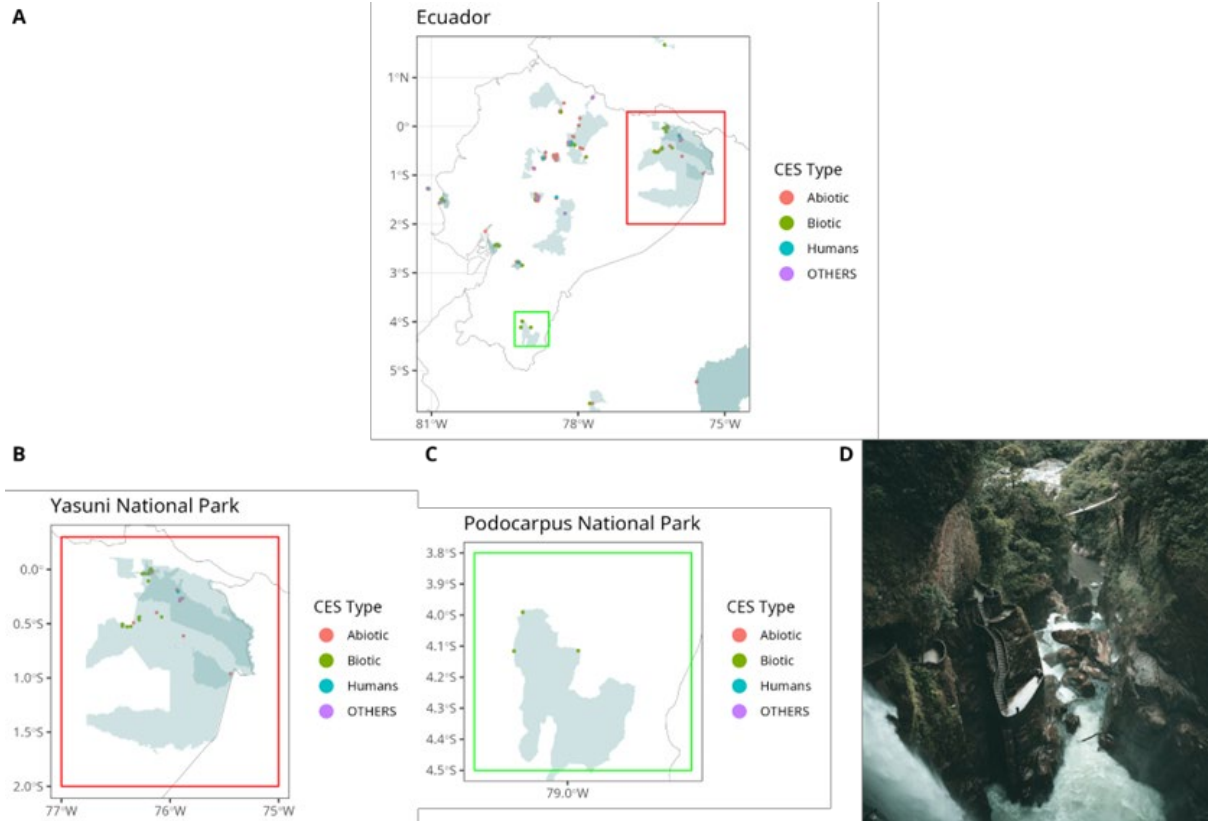
Supplementary Figure S4. Maps of all photos sampled in Japan (A) and labelled by their CES type. Spatial range of sampled PAs are added as a green overlay. Photos taken in popular PAs are highlighted, with Nikko National Park (B, in green), and Fuji-Hakone-Izu National Park (C, in purple) as examples. A sample photo (D) is also provided.



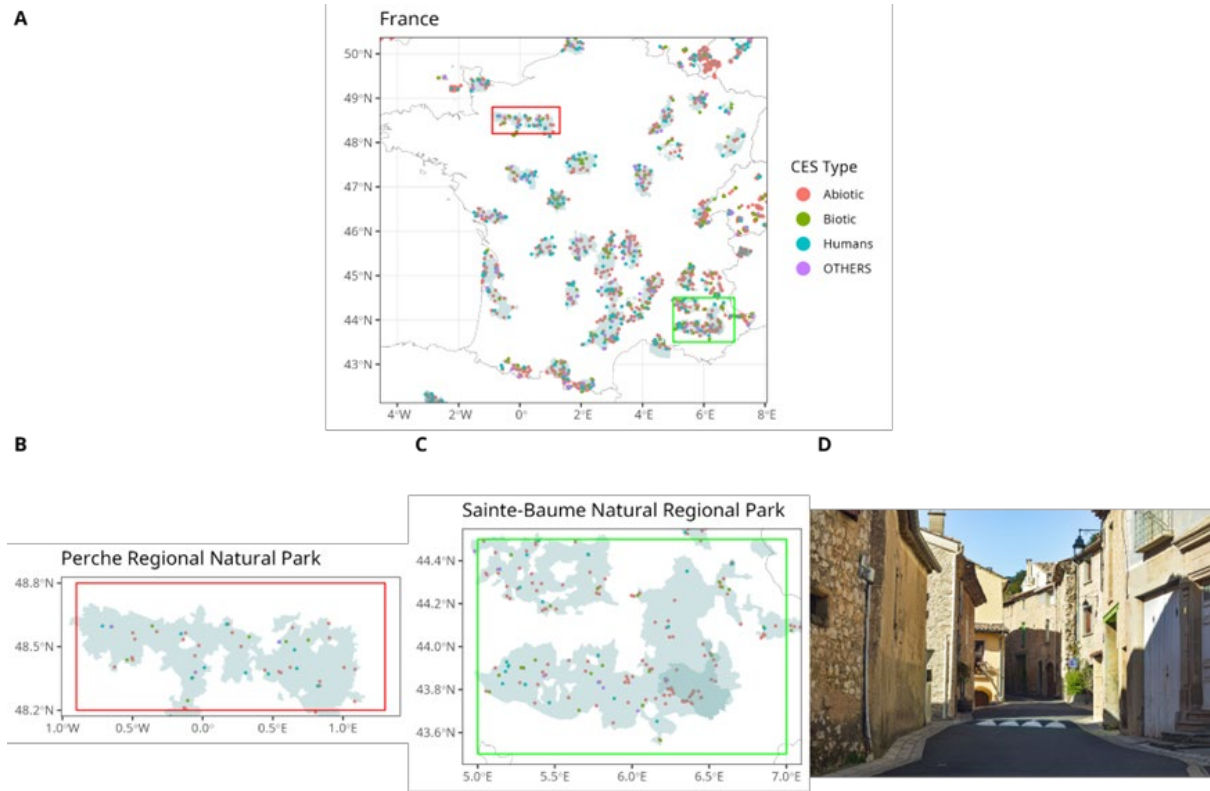
Supplementary Figure S5. Maps of all photos sampled in New Zealand (A) and labelled by their CES type. Spatial range of sampled PAs are added as a green overlay. Photos taken in popular PAs are highlighted, with Fiordland National Park (B, in red), and Tongariro National Park (C, in purple) as examples. A sample photo (D) is also provided.



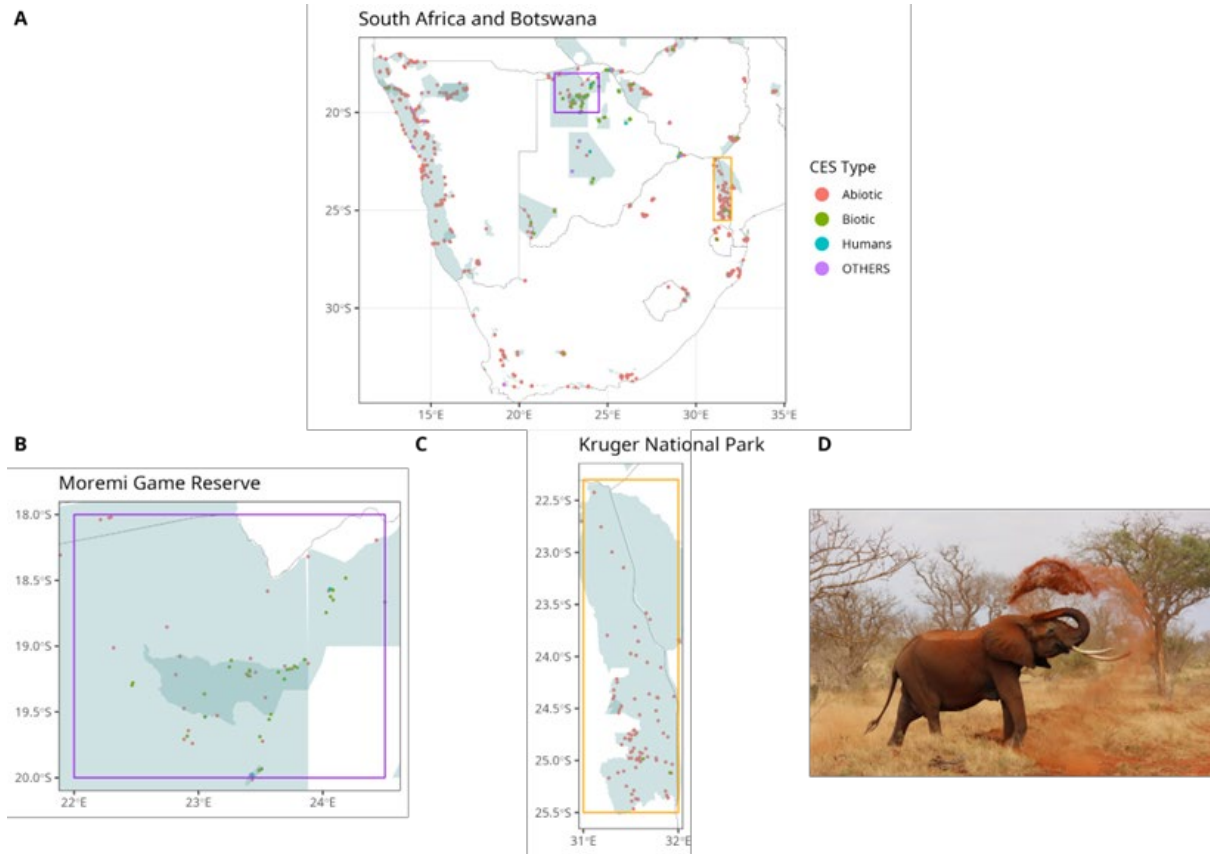
Supplementary Figure S6. Maps of all photos sampled in Indonesia (A) and labelled by their CES type. Spatial range of sampled PAs are added as a green overlay. Photos taken in popular PAs are highlighted, with Kepulauan Togean National Park (B, in red), and Komodo National Park (C, in green). A sample photo (D) is also provided.



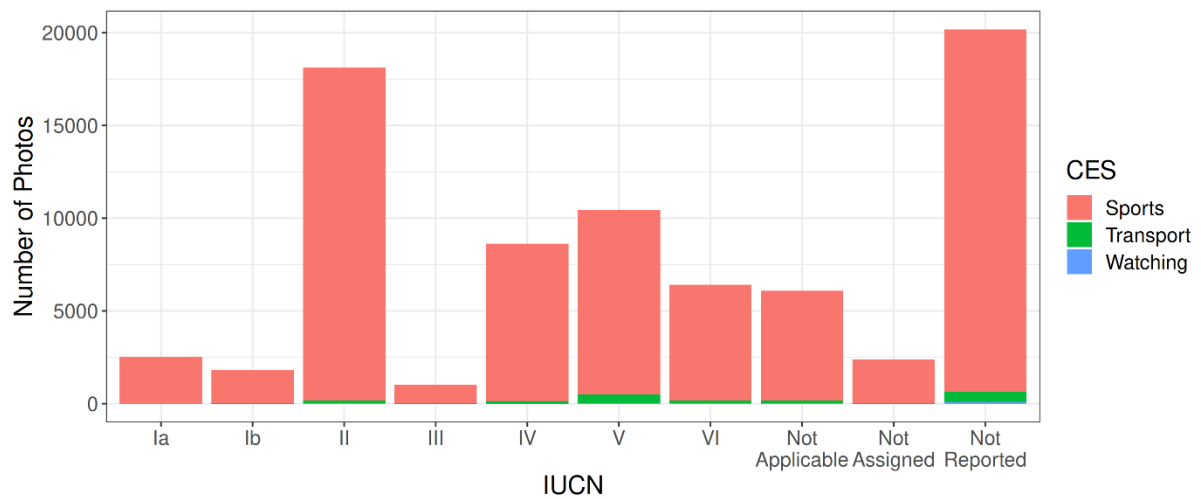
Supplementary Figure S7. Maps of all photos sampled in Ecuador (A) and labelled by their CES type. Spatial range of sampled PAs are added as a green overlay. Photos taken in popular PAs are highlighted, with Yasuní National Park (B, in red), and Podocarpus National Park (C, in green). A sample photo (D) is also provided.



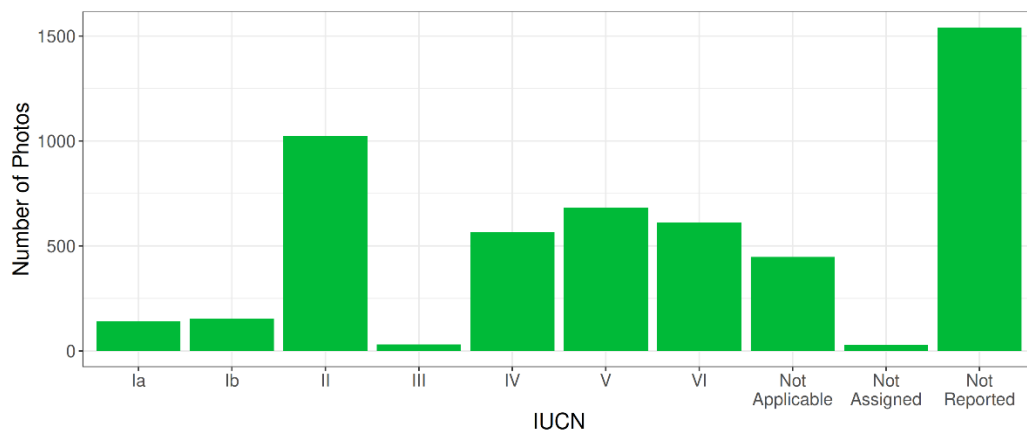
Supplementary Figure S8. Maps of all photos sampled in France (A), and labelled by their CES type. Spatial range of sampled PAs are added as a green overlay. Photos taken in popular PAs are highlighted, with Perche Regional Natural Park (B, in red), and Sainte-Baume Natural Regional Park (C, in green). A sample photo (D) is also provided.



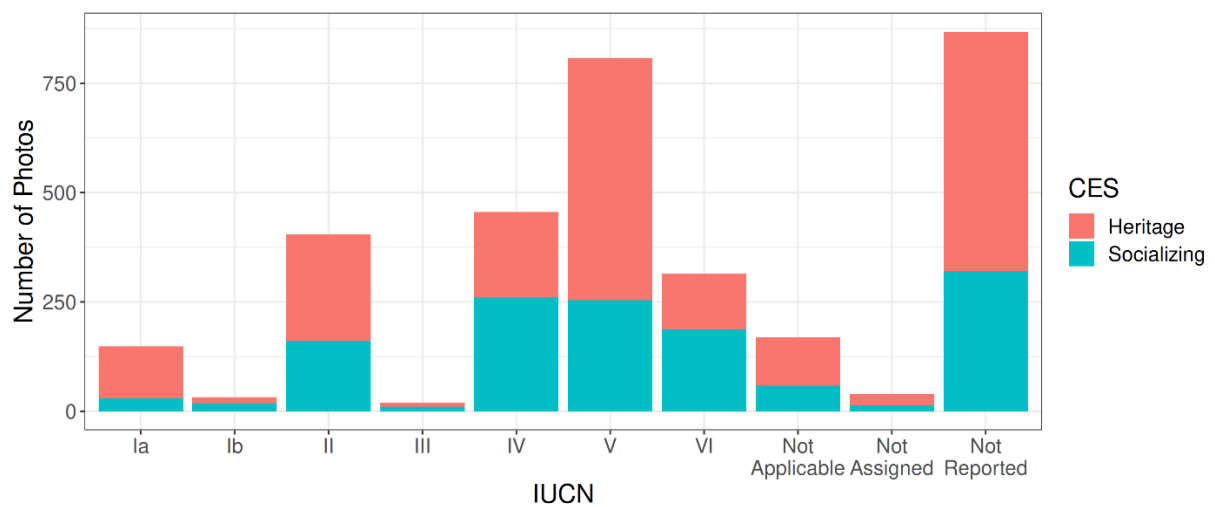
Supplementary Figure S9. Maps of all photos sampled in South Africa and Botswana (A) and labelled by their CES type. Spatial range of sampled PAs are added as a green overlay. Photos taken in popular PAs are highlighted, with Moremi Game Reserve (B, in red), and Kruger National Park (C, in green). A sample photo (D) is also provided.



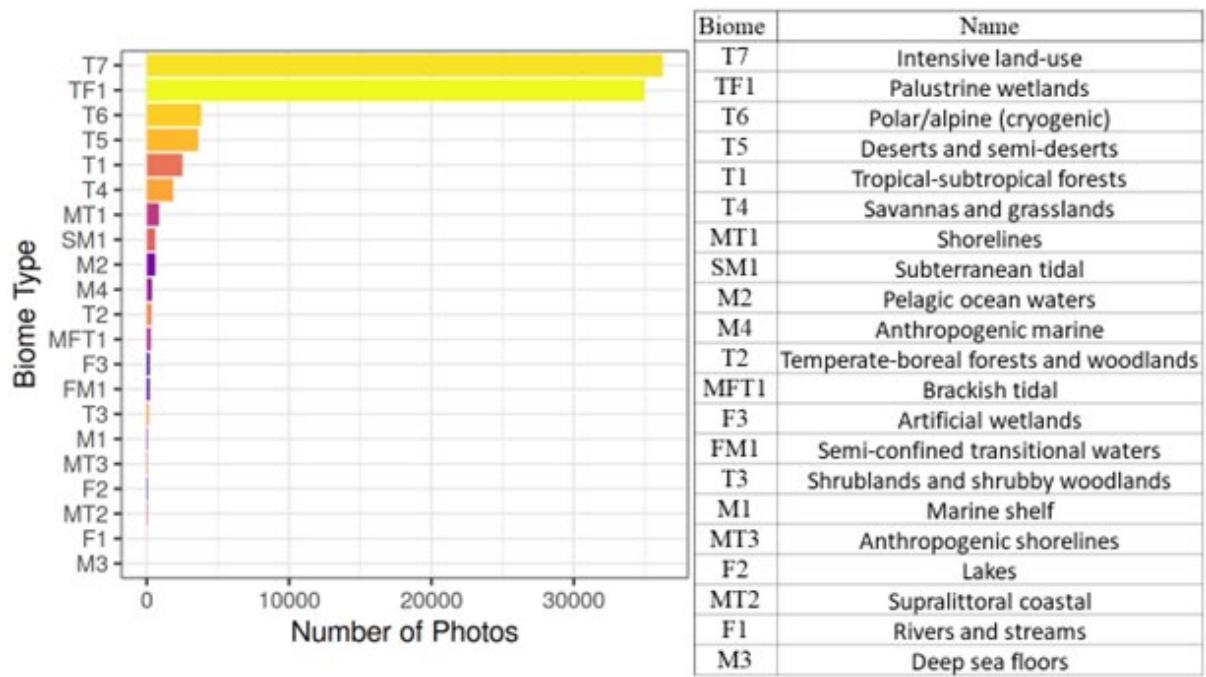
Supplementary Figure S10. Number of photos in sampled PAs sorted by IUCN category, for Abiotic CES type.



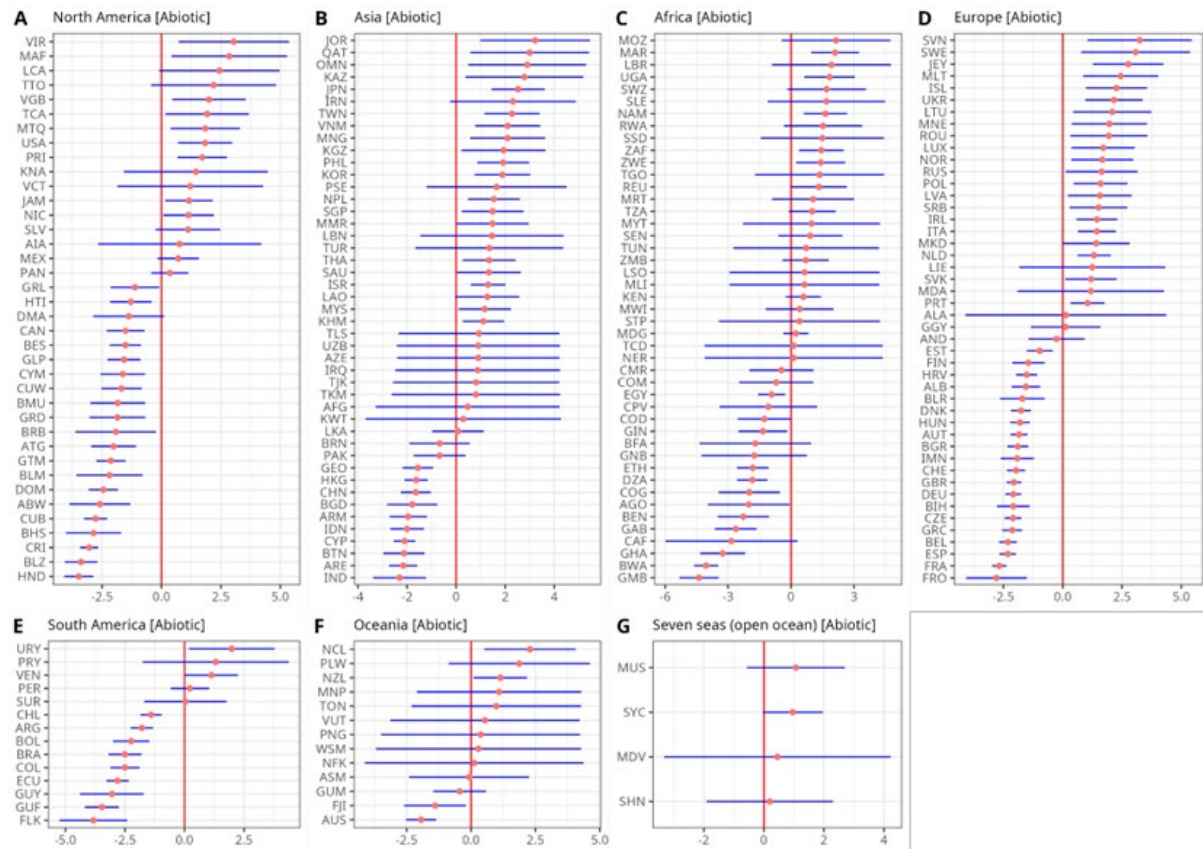
Supplementary Figure S11. Number of photos in sampled PAs sorted by IUCN category, for Biotic CES type.



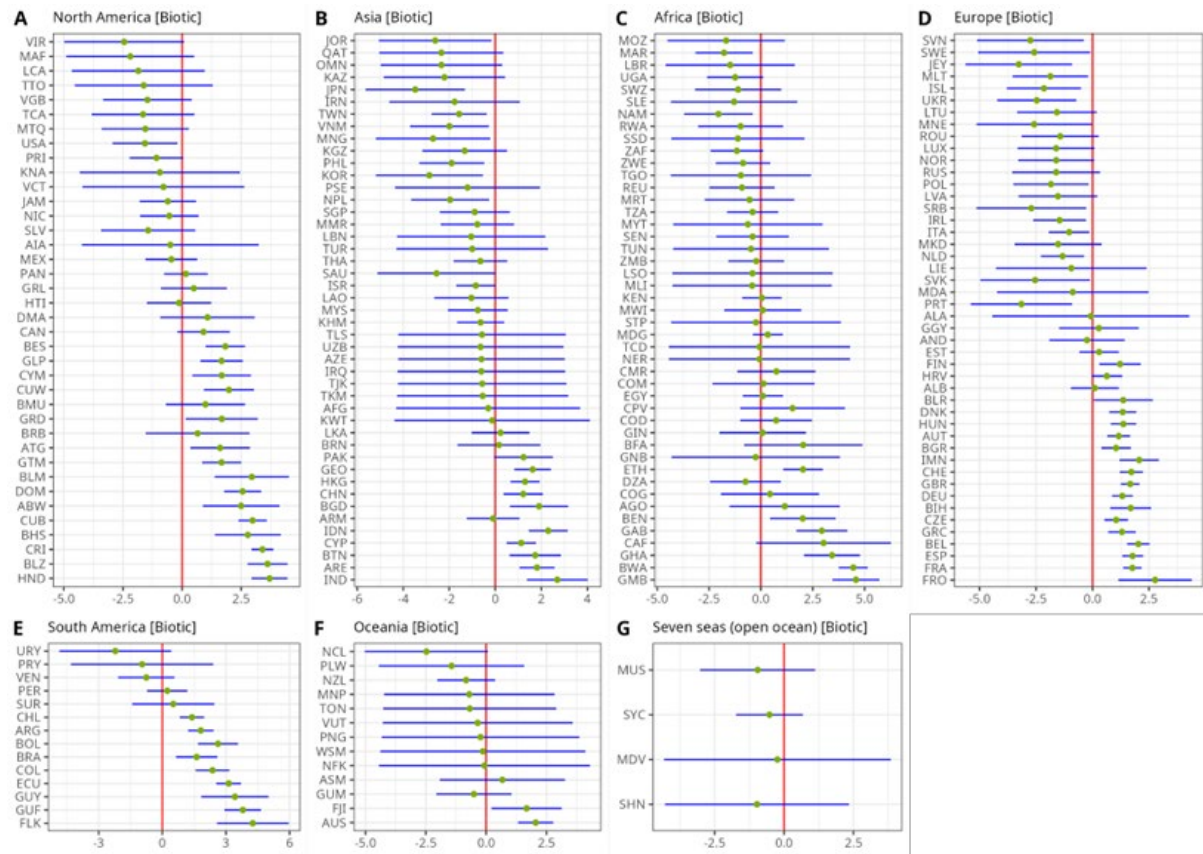
Supplementary Figure S12. Number of photos in sampled PAs sorted by IUCN category, for Humans CES type.



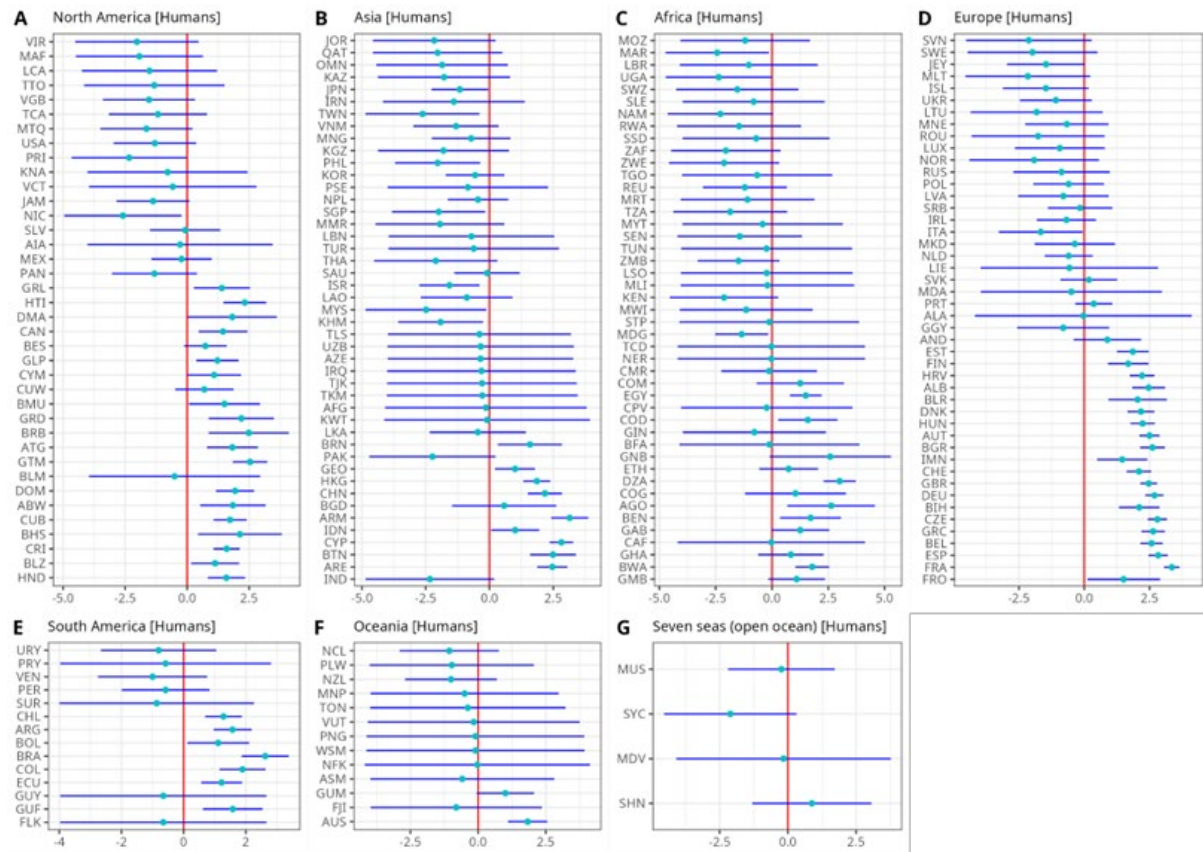
Supplementary Figure S13. Number of photos taken in each biome type in the global sample (left), and the IUCN Global Ecosystem Typology name for each biome (right).



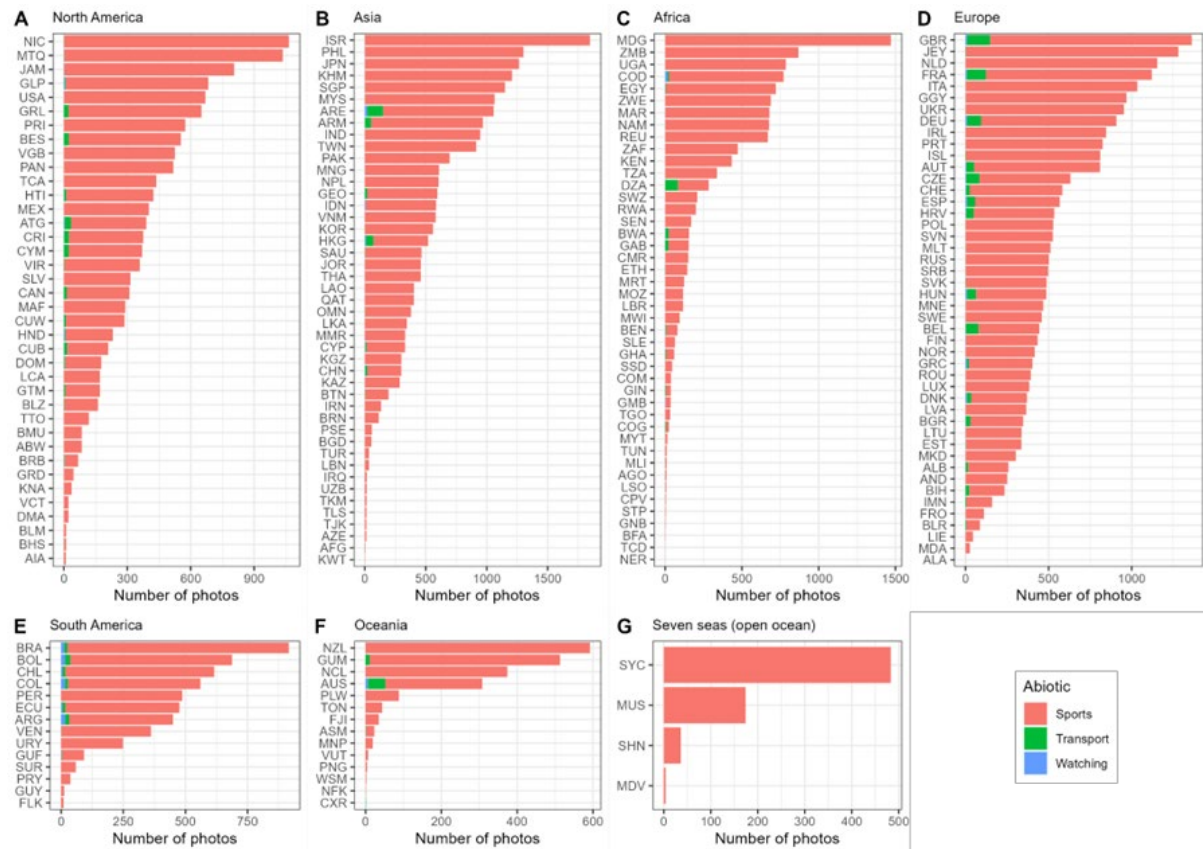
Supplementary Figure S14. Random intercepts in the Abiotic mixed-effects model for all sampled countries worldwide, as grouped by continents and sorted by decreasing values in each continent. Error bars (in blue) for all countries indicate standard errors of their estimates. Countries are referenced by their ISO 3166-1 alpha-3 codes.



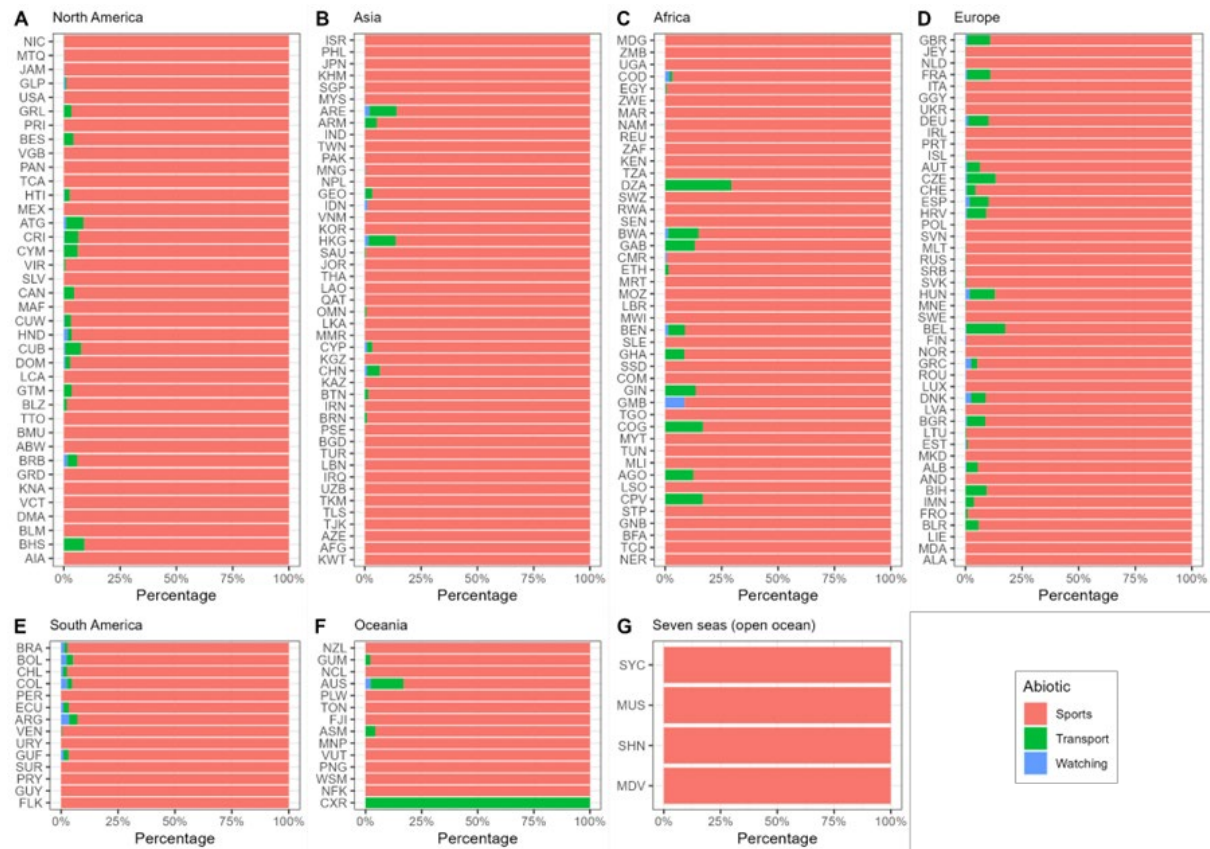
Supplementary Figure S15. Random intercepts in the Biotic mixed-effects model for all sampled countries worldwide, as grouped by continents and sorted by decreasing values in the Abiotic model (S11 Fig) in each continent. Error bars (in blue) for all countries indicate standard errors of their estimates. Countries are referenced by their ISO 3166-1 alpha-3 codes.



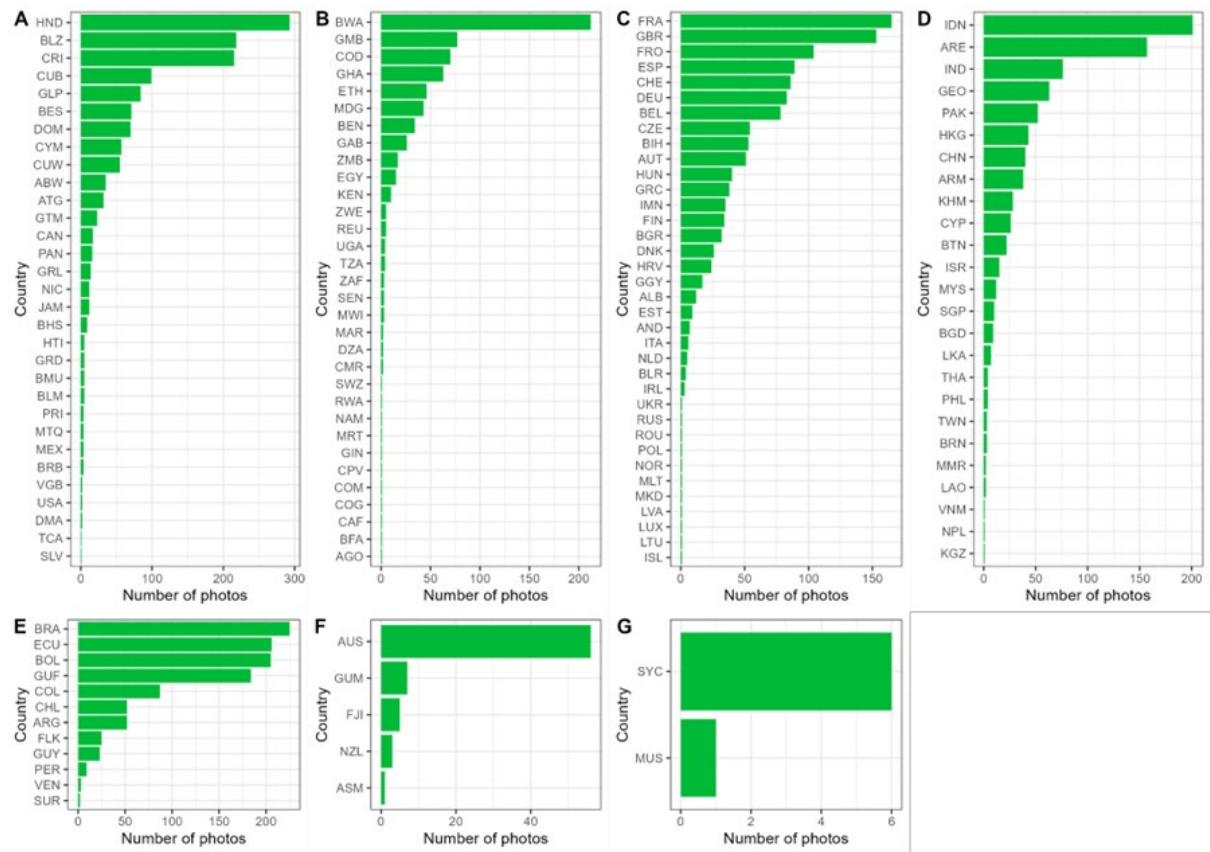
Supplementary Figure S16. Random intercepts in the Humans mixed-effects model for all sampled countries worldwide, as grouped by continents and sorted by decreasing values in the Abiotic model (S11 Fig) in each continent. Error bars (in blue) for all countries indicate standard errors of their estimates. Countries are referenced by their ISO 3166-1 alpha-3 codes.



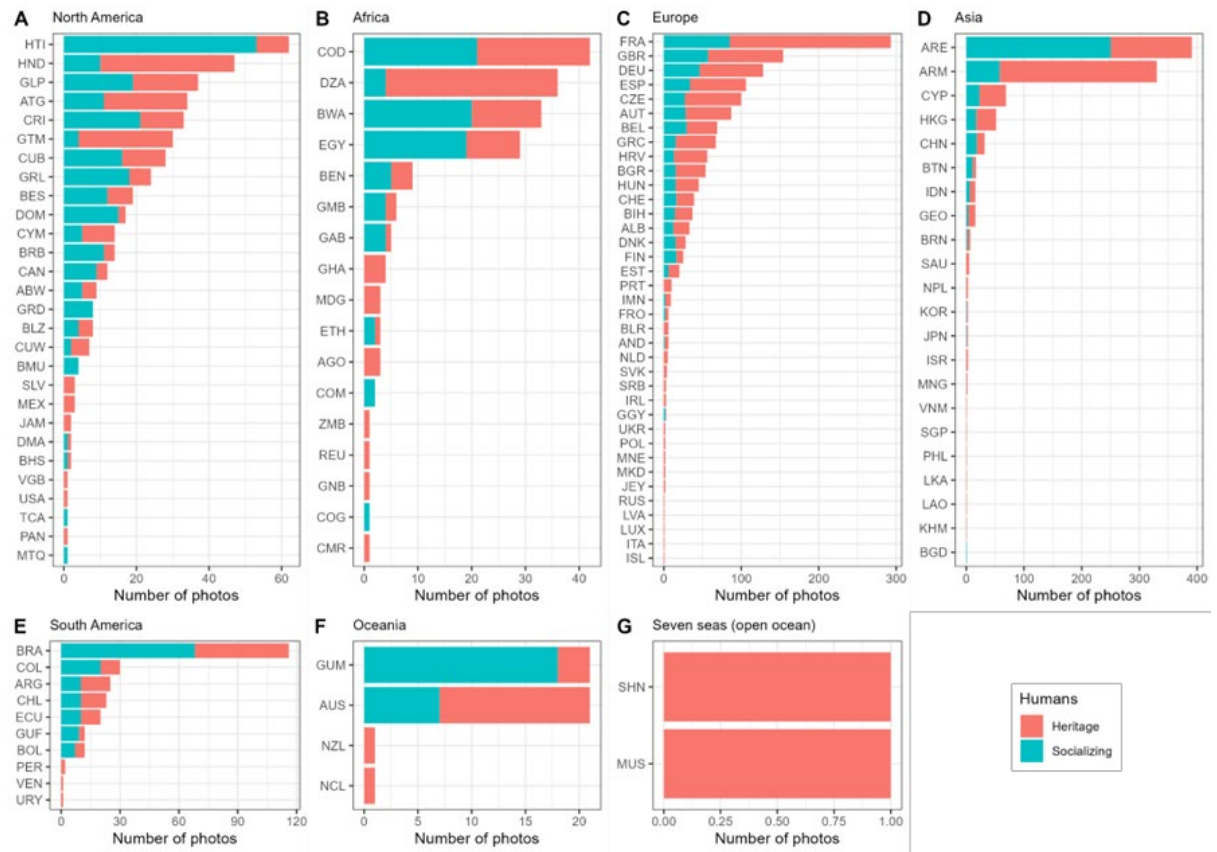
Supplementary Figure S17. Number of photos of each subcategory of Abiotic CES type in each country separated by continent.



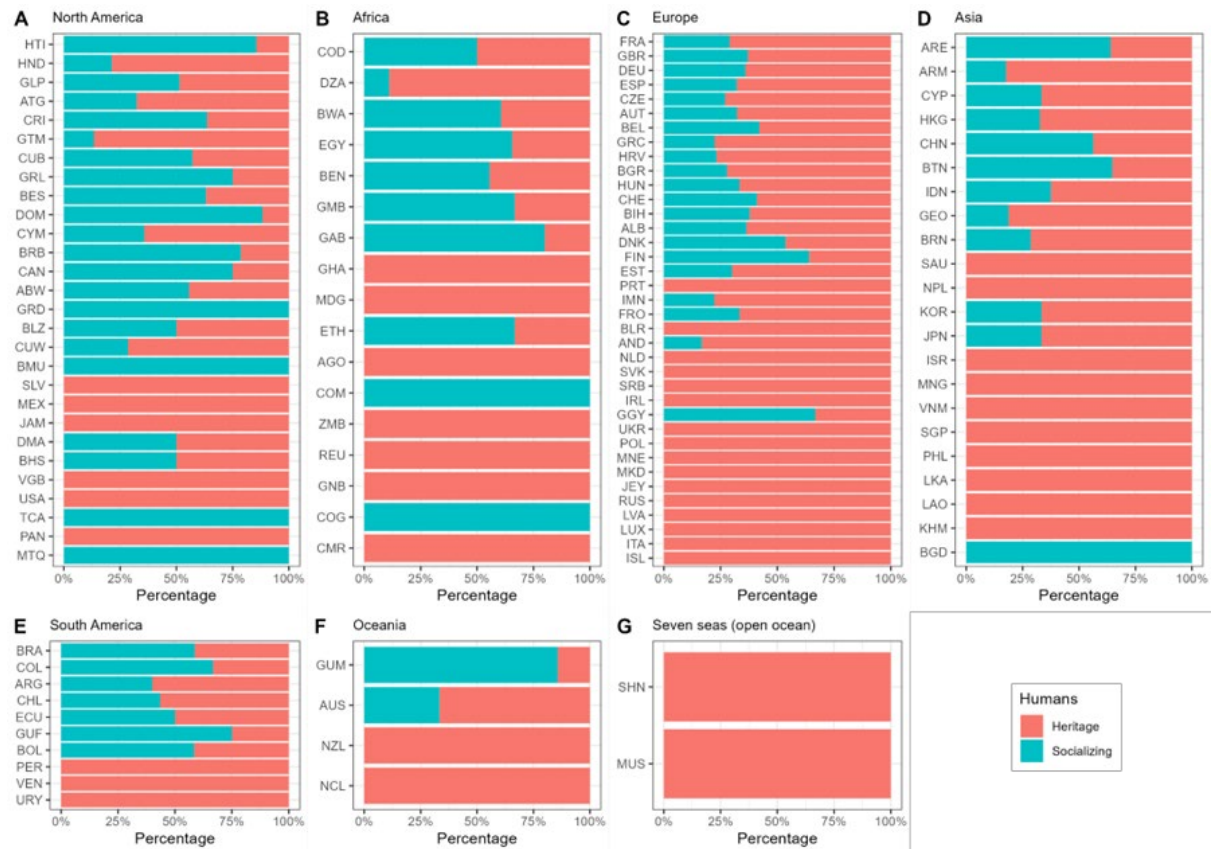
Supplementary Figure S18. Percentage of photos of each subcategory of Abiotic CES type in each country separated by continent.



Supplementary Figure S19. Number of photos of Biotic CES type in each country separated by continent.



Supplementary Figure S20. Number of photos of each subcategory of Humans CES type in each country separated by continent.



Supplementary Figure S21. Percentage of photos of each subcategory of Humans CES type in each country separated by continent.

Supplementary Table S1. Summary of all three generalized linear regression models for biome type.

<i>Predictors</i>	abiotic			biotic			humans		
	<i>Odds Ratios</i>	<i>CI</i>	<i>p</i>	<i>Odds Ratios</i>	<i>CI</i>	<i>p</i>	<i>Odds Ratios</i>	<i>CI</i>	<i>p</i>
(Intercept)	34.09	24.09 – 48.23	< 0.001	0.02	0.01 – 0.02	< 0.001	0.01	0.00 – 0.01	< 0.001
T7-3: Plantations	0.84	0.70 – 1.01	0.068	1.08	0.86 – 1.35	0.514	1.32	0.93 – 1.86	0.122
T7-4: Urban and Industrial	0.70	0.61 – 0.81	< 0.001	1.05	0.88 – 1.26	0.563	1.92	1.54 – 2.38	< 0.001
T7-5: Semi-natural Old Fields	0.74	0.65 – 0.85	< 0.001	1.24	1.06 – 1.46	0.007	1.54	1.23 – 1.94	< 0.001
TF1-2: Temp Forested Wetlands	0.89	0.73 – 1.07	0.219	1.15	0.89 – 1.50	0.287	1.21	0.93 – 1.56	0.151
TF1-6: Boreal Temperate Bogs	1.43	1.09 – 1.87	0.010	0.74	0.52 – 1.06	0.101	0.80	0.55 – 1.17	0.258
TF1-7: Boreal Temperate Ferns	0.93	0.74 – 1.18	0.555	1.06	0.76 – 1.48	0.737	1.17	0.86 – 1.59	0.307
Random Effects									
σ^2	3.29			3.29			3.29		
τ_{00}	0.78	ProtectedPlace:Country		1.31	ProtectedPlace:Country		0.68	ProtectedPlace:Country	
	5.04	Country		5.10	Country		4.44	Country	
ICC	0.64			0.66			0.61		
N	2795	ProtectedPlace		2795	ProtectedPlace		2795	ProtectedPlace	
	205	Country		205	Country		205	Country	
Observations	87016			87016			87016		
Marginal R ² / Conditional R ²	0.003 / 0.640			0.001 / 0.661			0.007 / 0.611		

Supplementary Table S2. Abiotic CES category and subcategories with definitions.

CES Category	Proposed definition in this paper	Definition in CICES (Haines-Young & Potschin, 2018)
Abiotic	Photos containing: 1. nonliving parts of an ecosystem, or 2. human activities that interact with the nonliving parts of an ecosystem	Cultural (Abiotic) "Direct, in-situ and outdoor interactions with natural physical systems that depend on presence in the environmental setting"
Transport	Photos involve human activities that directly interact with the abiotic environment through some mode of transport. These can include motor vehicles, or other forms of transportation such as airplanes and trains.	Cultural (Abiotic) — Recreation "things in the physical environment that we can study or think about" "natural, abiotic characteristics of nature that ... enable intellectual activities"
Sports	Photos depicting humans that engage in some recreational activity that can only be done in nature. These include sports such as skiing and hiking.	Cultural (Biotic) — Recreation "using the environment for sport and recreation; using nature to help stay fit" "the biophysical characteristics or qualities of species or ecosystems (settings/ cultural spaces) ... that are engaged with, used or enjoyed in ways that require physical and cognitive effort"
Watching	Photos emphasizing human interaction with the abiotic environment through means that do not involve direct physical contact. This includes observing the natural environment for various reasons, such as aesthetic appreciation, or spiritual/religious reasons.	Cultural (Abiotic) — Ecotourism "things in the physical environment that we can study or think about" "natural, abiotic characteristics of nature that ... enable active or passive physical and experiential interactions"

Supplementary Table S3. Biotic CES category and subcategory with definitions.

CES Category	Proposed definition in this paper	Definition in CICES (Haines-Young & Potschin, 2018)
Biotic	Photos containing: 1. tags that mainly describe a specific animal or plant, or 2. humans interacting with a specific animal or plant as the focus	Cultural (Biotic) "Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting"
Watching	Same as Biotic	Cultural (Biotic) — Ecotourism “watching plants and animals where they live; using nature to destress”” “the biophysical characteristics or qualities of species or ecosystems (settings/cultural spaces)... that are viewed/ observed by people or enjoyed in other passive ways by virtue of sounds and smells etc.”

Supplementary Table S4. Humans CES category and subcategories with definitions.

CES Category	Proposed definitions in this paper	Definition in Chan et al. (2016)
Humans	Photos containing: 1. human subjects as the key focus, or 2. activities involving interactions between humans, or 3. man-made locations	“Relational values (involving the human collective) ... pertain to all manner of relationships between people and nature, including relationships that are between people but involve nature”
Heritage	Photos mainly highlight old buildings of historical importance.	“Being in nature provides a vehicle for me to connect with people (Social cohesion)”
Socialising	Photos mainly highlight interactions between people.	“Place is important to my people, to who we are as a people (Cultural identity)”

Supplementary Table S5. Number of photos of each biome type.

	Biome Type	Number of Photos
1	T7-5: Semi-natural old fields	19445
2	TF1-2: Temp forested wetlands	15346
3	T7-4: Urban and industrial	10565
4	TF1-7: Boreal temperate fens	8282
5	T7-3: Plantations	4165
6	TF1-6: Boreal temperate bogs	4050
7	TF1-4: Seasonal floodplain marshes	3462
8	TF1-1: Trop flooded peat forests	2667
9	T6-4: Temp alpine grasslands	2435
10	T5-5: Hyper-arid deserts	2260

11	T4-2: Pyric tussock savannas	1768
12	T1-3: Trop montane rainforests	1565
13	T7-2: Sown pastures and fields	1552
14	TF1-3: Permanent marshes	989
15	MT1-2: Muddy shores	834
16	T5-1: Semi-desert steppe	742
17	T6-3: Polar tundra	681
18	T1-1: Trop lowland rainforests	649
19	SM1-3: Sea caves	598
20	M2-1: Epipelagic waters	561
21	T7-1: Croplands	537
22	T6-2: Polar alpine rock	433

23	T6-5: Trop alpine grassland	299
24	T5-2: Succulent Thorny deserts	297
25	MFT1-2: Intertidal forests	261
26	T5-4: Cool temperate deserts	253
27	M4-2: Marine aquafarms	248
28	T2-4: Warm temp rainforests	226
29	T1-2: Trop dry forests	213
30	TF1-5: Episodic arid floodplains	186
31	M4-1: Submerged artificial structures	144
32	FM1-2: Riverine estuaries and bays	132
33	T3-4: Rocky pavements	123
34	T2-1: Boreal montane forests	109

35	T1-4: Trop heath forests	78
36	MT3-1: Artificial shores	76
37	F3-5: Canals and drains	74
38	M1-8: Subtidal mud plains	73
39	F3-2: Constructed lacustrine wetlands	71
40	T5-3: Sclerophyll hot deserts	67
41	F3-3: Rice paddies	45
42	FM1-3: Closed open inlets	42
43	MT2-1: Coastal shrublands and grasslands	41
44	F2-6: Perm salt lakes	37
45	MFT1-3: Coastal saltmarsh	34
46	F1-6: Episodic arid rivers	33

47	T4-4: Temp woodlands	29
48	T4-3: Hummock savannas	28
49	M3-1: Continental slopes	25
50	M2-5: Sea ice	24
51	T3-1: Seas dry trop shrublands	23
52	M2-2: Mesopelagic ocean waters	21
53	T4-5: Temperate grasslands	21
54	F2-9: Geothermal wetlands	19
55	FM1-1: Deepwater coastal inlets	16
56	SM1-2: Anchialine pools	13
57	F2-4: Freeze-thaw lakes	10
58	M1-2: Kelp forests	6

59	F2-8: Artesian springs oases	5
60	F3-4: Freshwater aquafarms	5
61	T4-1: Trophic savannas	5
62	T6-1: Permanent snow	5
63	F2-1: Large perm lakes	4
64	T3-2: Seas dry temp shrublands	4
65	M3-5: Deepwater biogenic beds	1
66	M3-6: Hadal	1
67	M3-7: Chemosynthetic	1
68	MFT1-1: River deltas	1
69	MT1-3: Sandyshores	1