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Bastin, JF, Berrahmouni, N, Grainger, A et al. (2017) The extent of forest in dryland biomes. *Science*, 356 (6338). pp. 635-638. ISSN: 0036-8075

<https://doi.org/10.1126/science.aam6527>

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1 **Title: The extent of forest in dryland biomes**

2 **One sentence summary:**

3 Previously unreported forest areas in dryland biomes increase current estimates of the
4 global forest cover by at least 9 %.

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45 **Abstract**

46 Dryland biomes cover two fifths of the Earth's land surface but their forest area is
47 poorly known. Here, we report an estimate of global forest extent in dryland biomes,
48 based on analysing more than 210,000 0.5 ha sample plots through a photo-
49 interpretation approach using large databases of satellite imagery at (i) very high spatial
50 resolution and (ii) very high temporal resolution which are available through the Google
51 Earth platform. We show that, in 2015, 1,327 million ha of drylands had more than 10%
52 tree-cover, and 1,079 million ha comprised forest. Our estimate is 40-47 % higher than
53 previous estimates, corresponding to 467 million ha of forest that have never been
54 reported before. This increases current estimates of global forest cover by at least 9 %.

55 **Main text**

56 Dryland biomes cover about 41.5 % of the Earth's land surface (1). They contain some
57 of the most threatened, yet disregarded, ecosystems (2, 3), including seven of the twenty
58 five biodiversity hotspots (4), while facing pressure from climate change and human
59 activity (5, 6). The most recent climate model simulations, based on contrasted
60 Representative Concentration Pathways (RCPs), i.e. RCP 8.5 and RCP 4.5, show that
61 global climate change could cause dryland biomes to expand by 11% to 23% by the end
62 of the 21st century (7). If this occurs, dryland biomes could cover more than half of the
63 global land surface (7). Climate change will lead to extended droughts, regional
64 warming (8, 9) and, combined with a growing human population, to an increased risk
65 of land degradation and desertification in the drylands (7). Such changes will
66 particularly affect developing countries, where most dryland expansion is expected to
67 occur (7, 10) and where woody resources provide key goods and services to support
68 human livelihoods (11).

69

70 However, our current knowledge of the extent of tree cover and forests in drylands is
71 limited. This is illustrated by significant spatial disagreements between recent satellite-
72 based global forest maps (12–14) and by the scarcity of large-scale studies of dryland
73 biomes (3). The most recent estimates of tropical dry forest extent based on remote
74 sensing surveys vary greatly, from 105 Mha for the year 2000, derived from a wall-to-
75 wall map at coarse resolution (5) to 542 Mha for the year 2010 derived from a global
76 sample of medium resolution images (15). This disparity can partly be explained by
77 differences in satellite data characteristics (e.g. spatial resolution), mapping approaches
78 (e.g. mapping unit) and forest definitions (e.g. tree cover thresholds). It has led to major

79 doubts about the reliability of global forest area estimates, and to questions about the
80 real contribution made by forests to the global carbon cycle (12).

81

82 To address these uncertainties, we established a global initiative to undertake a Global
83 Dryland Assessment of forest. The geographical scope of this assessment is framed by
84 the delineation adopted by the United Nations Environment Programme World
85 Conservation Monitoring Centre (1), i.e. lands having an Aridity Index (AI) lower than
86 0.65. The AI is the ratio between average annual precipitation and total annual potential
87 evapotranspiration (16). The dryland domain is typically divided into four distinct
88 “zones” based on their AI: (i) the “hyperarid” zone (AI = <0.05), (ii) the “arid” zone
89 (AI = 0.05-0.2), (iii) the “semi-arid” zone (AI = 0.2-0.5) and (iv) the “dry subhumid”
90 zone (AI = 0.5-0.65). Using this definition, drylands cover 6,132 Mha, or 41.5% of the
91 Earth's land surface (1) (Fig. S1). Our study aims to determine accurately how much
92 forest and tree cover remains in dryland biomes.

93

94 Mapping forests in the drylands using satellite data is challenging, even with high
95 spatial resolution imagery (10-30 m). This is due to difficulties in (i) disentangling the
96 reflectance of trees, bare soil and the darkening effect of tree crown shadows in open
97 forests (17, 18), and (ii) detecting forest presenting a closed canopy with a low
98 vegetative reflectance, such as *Acacia* or *Eucalyptus* species (18, 19). To overcome
99 these limitations, we took advantage of recent developments in cloud computing (20),
100 especially the suite of Google geospatial tools, which have greatly increased the
101 capacity to access and analyse large remote sensing databases of Very High spatial
102 Resolution (VHR) images (with a pixel width ≤ 1 m). VHR images allow scientists to
103 visually identify individual tree crowns in dry areas, e.g. of common genera such as

104 *Adansonia* (baobab) in Africa (21) and *Acacia* in Australia (Figs. S2 and S3). Terrestrial
105 land coverage with VHR images is nearly complete (22), and this is the first study to
106 use them for global mapping purposes.

107

108 To determine the extent of forests and tree cover throughout the world's dryland
109 biomes, we assessed a large sample of 0.5 ha plots through visual interpretation of VHR
110 images available from Google Earth. We designed a stratified systematic sample with
111 higher sampling intensity from hyperarid to dry subhumid zones, leading to 213,795
112 sample plots (17; Fig. S4). To interpret the VHR images over such a large number of
113 plots we divided the world's dryland domain into 12 regions and employed a
114 participatory approach. Scientists and students in 15 organizations around the world
115 (Fig. S5) were trained to use a dedicated interpretation tool called Collect Earth (23)
116 with a common framework to assess the sample plots in which they had expertise.

117

118 Over 70 land attributes were assessed in each plot, but only forest and tree cover results
119 are reported here. Forest area and tree cover percentage were considered independently
120 to enable comparison with previous estimates. The tree cover percentage is assessed at
121 each plot irrespective of its land use type. Time series of vegetation indices for the
122 period 2000-2015 were computed from high temporal resolution satellite imagery
123 (MODIS and Landsat), and are used here to assist visual interpretation of VHR satellite
124 imagery (17; Fig. S2D). Trees were distinguished from shrubs by considering crown
125 shadows, which are related to vegetation height, and by using field-based photographs
126 available from the Web. Where information or knowledge was not sufficient for
127 distinguishing trees from shrubs, a tree crown diameter threshold of 3 m was applied.

128

129 Data quality was controlled through a semi-automated data cleansing procedure that
130 automatically identified potential inconsistent plots that were then manually reassessed.
131 Uncertainties were assessed by accounting for the sampling and interpretation errors,
132 the latter being assessed from 441 reference field plots (16).

133

134 Our results show that in 2015 there were 1,327 (± 98) Mha of dryland where tree canopy
135 cover percentage is over 10%, of which 777 Mha (57%) present a closed canopy (Table
136 1, Table S1), i.e. with a tree canopy cover over 40% (24). There are significant
137 differences between continents, e.g. half the total area with more than 10% tree cover
138 is located in Africa and Asia, and more than one third in North and South America
139 (Table 1; Figs S6-7). Of these 1,327 Mha, 1,079 (± 38) Mha are considered as "forest"
140 according to the FAO definition (24): land spanning an area of more than 0.5 ha with a
141 tree cover over 10% that is not predominantly used for agriculture or urban land use, as
142 well as land on which tree cover is temporarily under 10% but is expected to recover
143 (Table S1, Fig. 1). Our estimates for the area with more than 10% tree canopy cover
144 and the area of forest differ by 271 Mha, or 23% (Fig. S8). This might help to explain
145 the 19% difference between recent estimates of forest "land use" area (3,890 Mha) (25)
146 and the area with a "land cover" presenting more than 10% tree canopy cover derived
147 from a global tree cover map (4,628 Mha) (13).

148

149 Our findings show that the total area of dryland forest is similar to the area of tropical
150 moist forest, estimated at 1,156 Mha in 2000 (15). Its distribution is concentrated to the
151 south of the Sahara desert, around the Mediterranean sea, and in southern Africa, central
152 India, coastal Australia, western South America, northeast Brazil, northern Colombia

153 and Venezuela and in the northern belt of boreal forests in Canada and the Russian
154 Federation (Fig. 1).

155

156 Almost two thirds of all dryland forests are closed canopy forests (Table 1, Table S1).
157 Open forests cover 355 Mha and are dominant in Africa and Oceania, where they
158 account for 52% and 74% of all dry forest, respectively. Of the total area of 1,079 Mha
159 of dryland forest, 523 Mha are located in the tropics, of which 203 Mha (37%) are open
160 forest and 320 Mha (63%) are closed forest (Supplementary Table 2).

161

162 When we compared our maps of forest and tree cover, based on +210,000 sample plots,
163 to recent maps based on coarser resolution satellite imagery (13, 14, 25, 26), we found
164 that the latter maps were missing significant areas of tree cover and forest in dryland
165 biomes (Table 2, 17, Figs. S9-11). Our estimate of 1,327 Mha for areas with over 10%
166 tree canopy cover is 427 Mha (47%) and 378 Mha (38%) higher than estimates derived
167 from the full drylands extracts of Hansen et al.'s 2000 map (13) and Sexton et al.'s 2010
168 map (14), respectively (16). These differences are of the same order as the total area of
169 tropical moist forest in Amazonia. The gaps tend to increase in regions with a high
170 proportion of open forest (Fig. S12), which illustrates the limitations of using medium-
171 to-high resolution satellite images to identify low tree cover (27), and explains why the
172 gaps are particularly important in Africa and Oceania (Figs. S9-11). In Africa, for
173 example, we find 148 Mha (70%) more land with $\geq 10\%$ tree canopy cover than Hansen
174 et al., with the largest discrepancy observed in the Sahel and southern Africa (Fig. 2).
175 The differences for closed canopy forest (with $\geq 40\%$ tree cover) are even larger, as our
176 estimate for Africa is 151 Mha (Table 1), compared with only 18 Mha in Hansen et al.
177 and 2 Mha in Sexton et al. (Table S2, Fig. S11). We find even more tree cover and

178 forest than the 2009 Globcover product (27) and the FAO-FRA global Remote Sensing
179 Survey 2010 (26), respectively (Table 2).

180

181 The global maps of Hansen et al. (2013) and Sexton et al. (2013) show some areas of
182 $\geq 10\%$ tree canopy cover that are not apparent in our map, e.g. in NE Brazil and South-
183 Sudan (Fig. 2, Figs. S10, S13). We suspect that these are caused by a ‘greening effect’
184 related to meadows or wetlands, i.e. which might present a spectral signature similar to
185 forests and to which Landsat data are sensitive (17).

186

187 Our estimate is 40-47 % higher than previous estimates of the extent of forest in
188 drylands. This potentially increases by 9% the global area with over 10% tree canopy
189 cover (5,055 Mha instead of 4,628 Mha (13)) and by 11% the global area of forest
190 (4,357 Mha instead of 3,890 Mha (25)).

191

192 Using numbers on the carbon pools of woody savannas (28), further research could use
193 our publicly available data to increase estimates of global forest carbon stocks by 15 to
194 158.3 GtC, or by 2 to 20 % (29), thereby helping to reduce uncertainty about the global
195 carbon budget (30). Our findings could also lead to the development of innovative
196 conservation and land restoration actions in dryland biomes, i.e. in regions with low
197 opportunity cost, to mitigate climate change, combat desertification, and support the
198 conservation of biodiversity and ecosystem services that underpin human livelihoods
199 (31).

200 **Table 1.** Areas in the world's drylands in 2015 of forest (as defined by FAO(24)) and
 201 land under different percentages of tree canopy cover (Mha).

	Total area	Tree canopy cover ≥ 10%	Forest	Tree canopy cover ≥ 10 & < 40%	Open forest	Tree canopy cover ≥ 40%	Closed forest
Continent							
Africa	1961	364	286	213	151	151	135
Asia	1950	299	213	104	37	195	176
Europe	295	92	63	29	7	63	56
N America	694	238	204	77	49	161	155
Oceania	685	124	114	94	85	30	29
S America	546	208	197	33	26	175	171
Aridity zone							
Hyper-arid	978	13	3	9	2	4	1
Arid	1566	103	71	75	50	28	21
Semi-arid	2263	559	440	283	186	276	254
Dry sub-humid	1326	652	565	183	117	469	448
Drylands total	6132	1327	1079	550	355	777	724

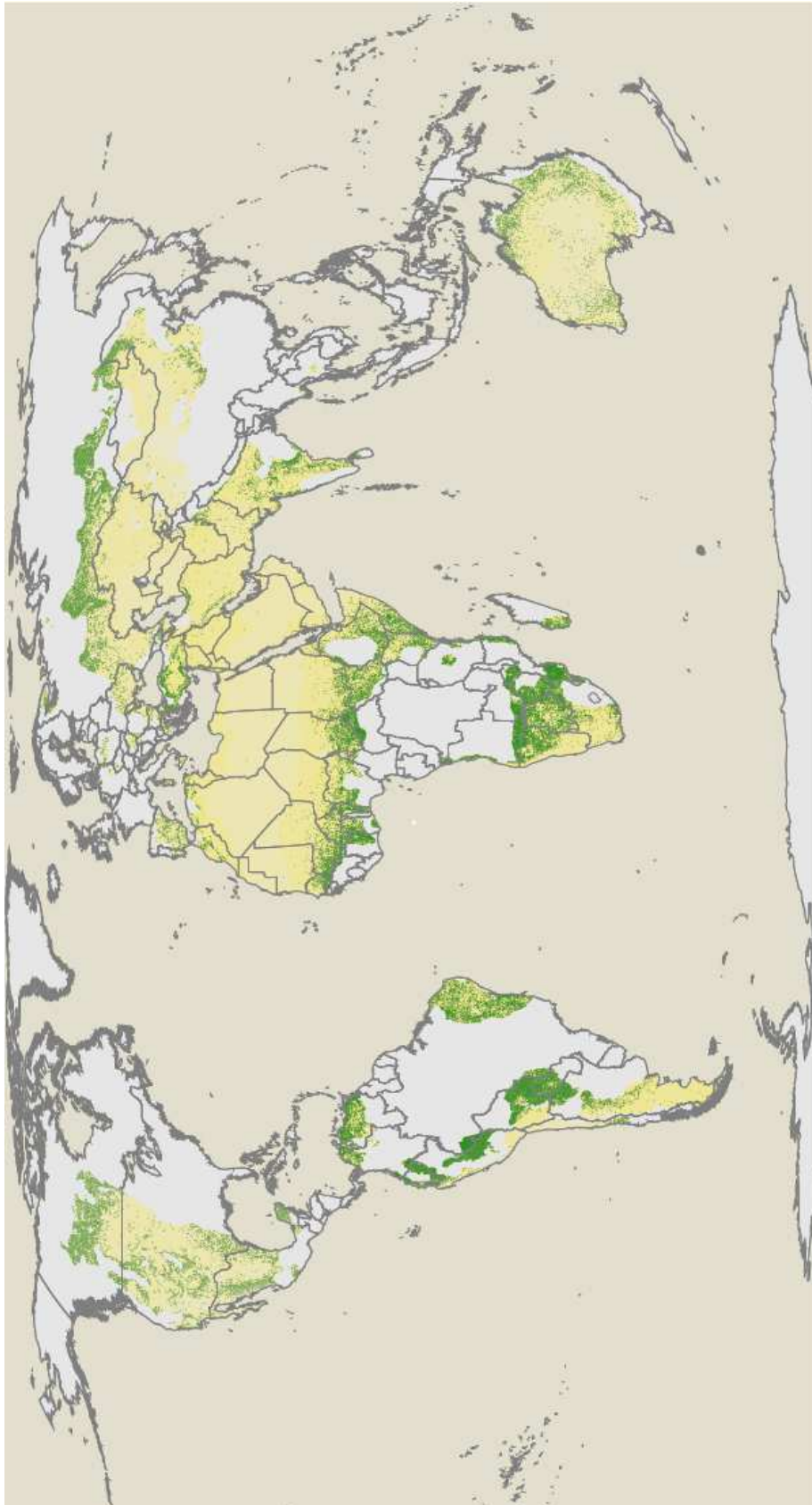
202

NB. Forest (column 3) is land with ≥10% tree canopy cover that is not used for agriculture or settlement, or has <10% tree canopy but is regenerating; open forest (column 4) is forest with 10-39% tree canopy cover; closed forest is forest with ≥40% tree canopy cover

203 **Table 2.** Comparison of the estimate in this paper (Global Dryland Assessment) of
 204 areas in the drylands in 2015 with forest and $\geq 10\%$ tree canopy cover (Table 1), with
 205 other estimates based on satellite images and following the same definition of dryland
 206 (Mha) (1).

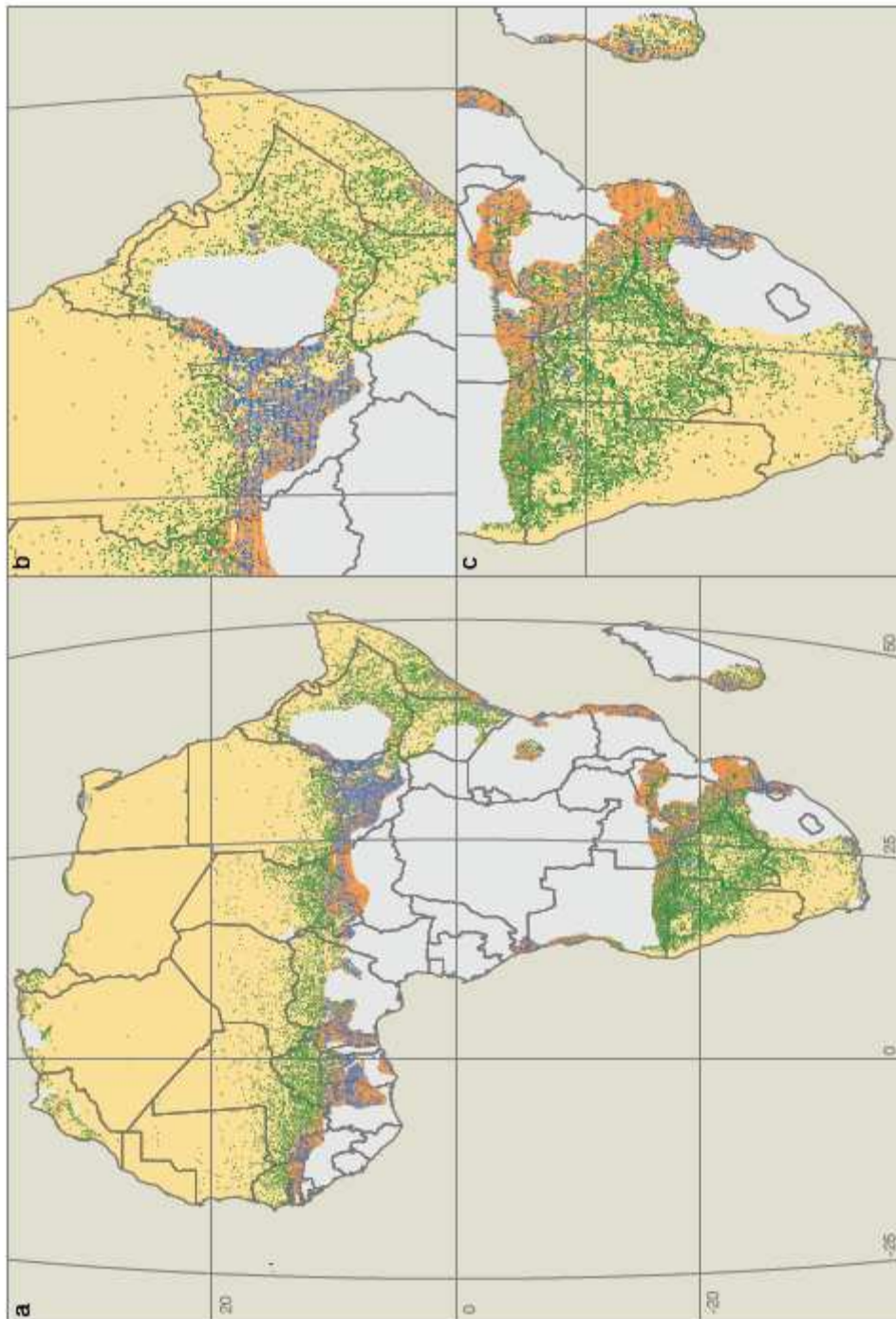
Source	FAO RSS (2010) (25)	Globcover (2009) (26)	Hansen et al. (2013) (13)	Sexton et al. (2013) (14)	Global Dryland Assessment (2016)		
Sensor	Landsat	MERIS	Landsat	Landsat	Very high resolution		
Method	sampling	wall-to- wall	wall-to- wall	wall-to- wall	sampling		
Year	2010	2008	2000	2010	2015	2015	2015
Forest	Yes	-	-	-	Yes	-	-
Tree cover	-	$\geq 15\%$	$\geq 10\%$	$\geq 10\%$	-	$\geq 20\%$	$\geq 10\%$
Africa	67	83	216	114	286	253	364
Asia	43*	148	154	200	213 (97*)	242	299
Europe	22*	49	97	116	63 (26*)	78	92
N America	166	155	173	196	204	201	238
Oceania	29	28	55	55	114	71	124
S America	123	46	205	268	197	192	208
Total	450	509	900	949	1079 (917*)	1037	1327

207 * Without Russian Federation



208

209 **Figure 1. Forest distribution in drylands.** Plots with forest are coloured in green,
210 and without forest in yellow.



211

212 **Figure 2. Comparison of $\geq 10\%$ tree cover in Africa's drylands as mapped by the**
 213 **Global Drylands Assessment (GDA) and Hansen et al. (13).** Green dots show plots
 214 are coloured green where the GDA reports $\geq 10\%$ tree cover but Hansen et al. reported
 215 a lower percentage; blue dots show plots where Hansen et al. reported $\geq 10\%$ tree cover
 216 but the GDA reports a lower percentage; and orange dots show plots where both
 217 assessments report $\geq 10\%$ tree cover. Figures 2b and 2c focus on two regions with large
 218 discrepancies between the maps.

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- 316

317 **Acknowledgments**

318 We thank the 239 operators who participated in the Global Dryland Assessment; all
319 FAO staff who supported it; Rachel Golder for help in English editing; Remi
320 D'Annunzio and Erik Lindquist for the use of RSS 2010 data; and Frederic Achard for
321 guidance in finalizing this paper. We thank the Terrestrial Ecosystem Research
322 Network of Australia for supplying the field dataset. This work was conducted under
323 the Global Forest Survey project of FAO, supported by the International Climate
324 Initiative of the Federal Ministry for the Environment, Nature Conservation, Building
325 and Nuclear Safety of Germany, and under the Action Against Desertification initiative,
326 implemented by FAO and funded by the European Union in support of Africa's Great
327 Green Wall and the United Nations Convention to Combat Desertification action
328 programmes.

329

330 **Author contributions**

331 J.-F.B., D.Ma. and D.Mo. conceived and designed the paper. J.-F.B., D.Mo., A.G. and
332 R.C. wrote the paper, J.-F.B. and N.P. did the statistical analyses. C.P and S.R
333 coordinated the data cleansing procedure. B.S., A.L. and G.G. coordinated the field
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336 I.S., A.S.-D.P., F.S. and V.S. coordinated the data collection through Collect Earth.
337 All authors assisted editing the manuscript.

338

339 **Competing financial interests**

340 The authors declare no competing financial interests.

341

342 **Supplementary materials**

343 Materials and Methods

344 Tables S1 to S3

345 Figs. S1 to S18

346 References (32-39)