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Title: The extent of forest in dryland biomes

One sentence summary:

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

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Abstract

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

Main text

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

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

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

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

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

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

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

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

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

Our findings show that the total area of dryland forest is similar to the area of tropical moist forest, estimated at 1,156 Mha in 2000 (*15*). Its distribution is concentrated to the south of the Sahara desert, around the Mediterranean sea, and in southern Africa, central India, coastal Australia, western South America, northeast Brazil, northern Colombia and Venezuela and in the northern belt of boreal forests in Canada and the Russian Federation (Fig. 1).

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

When we compared our maps of forest and tree cover, based on +210,000 sample plots, to recent maps based on coarser resolution satellite imagery (*13*, *14*, *25*, *26*), we found that the latter maps were missing significant areas of tree cover and forest in dryland biomes (Table 2, *17*, Figs. S9-11). Our estimate of 1,327 Mha for areas with over 10% tree canopy cover is 427 Mha (47%) and 378 Mha (38%) higher than estimates derived from the full drylands extracts of Hansen et al.'s 2000 map (*13*) and Sexton et al.'s 2010 map (*14*), respectively (*16*). These differences are of the same order as the total area of tropical moist forest in Amazonia. The gaps tend to increase in regions with a high proportion of open forest (Fig. S12), which illustrates the limitations of using medium-to-high resolution satellite images to identify low tree cover (*27*), and explains why the gaps are particularly important in Africa and Oceania (Figs. S9-11). In Africa, for example, we find 148 Mha (70%) more land with ≥10% tree canopy cover than Hansen et al., with the largest discrepancy observed in the Sahel and southern Africa (Fig. 2). The differences for closed canopy forest (with≥ 40% tree cover) are even larger, as our estimate for Africa is 151 Mha (Table 1), compared with only 18 Mha in Hansen et al. and 2 Mha in Sexton et al. (Table S2, Fig. S11). We find even more tree cover and forest than the 2009 Globcover product (27) and the FAO-FRA global Remote Sensing Survey 2010 (26), respectively (Table 2).

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

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

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

Table 1. Areas in the world's drylands in 2015 of forest (as defined by FAO(*24*)) and 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

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

Table 2. Comparison of the estimate in this paper (Global Dryland Assessment) of areas in the drylands in 2015 with forest and ≥10% tree canopy cover (Table 1), with other estimates based on satellite images and following the same definition of dryland (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	-	≥15%	≥10%	≥10%	-	≥20%	≥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**

* Without Russian Federation

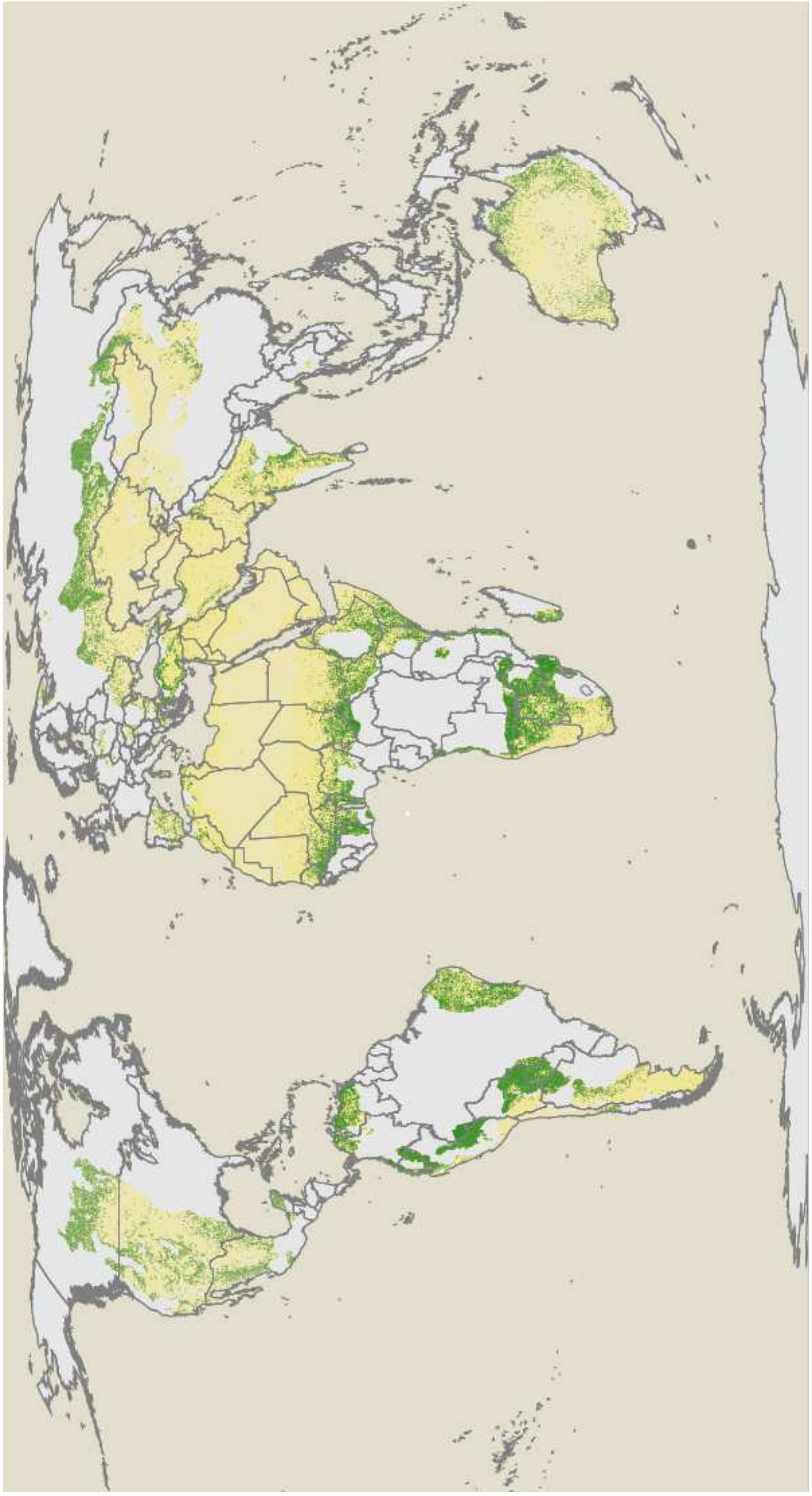

Figure 1. Forest distribution in drylands. Plots with forest are coloured in green, and without forest in yellow.

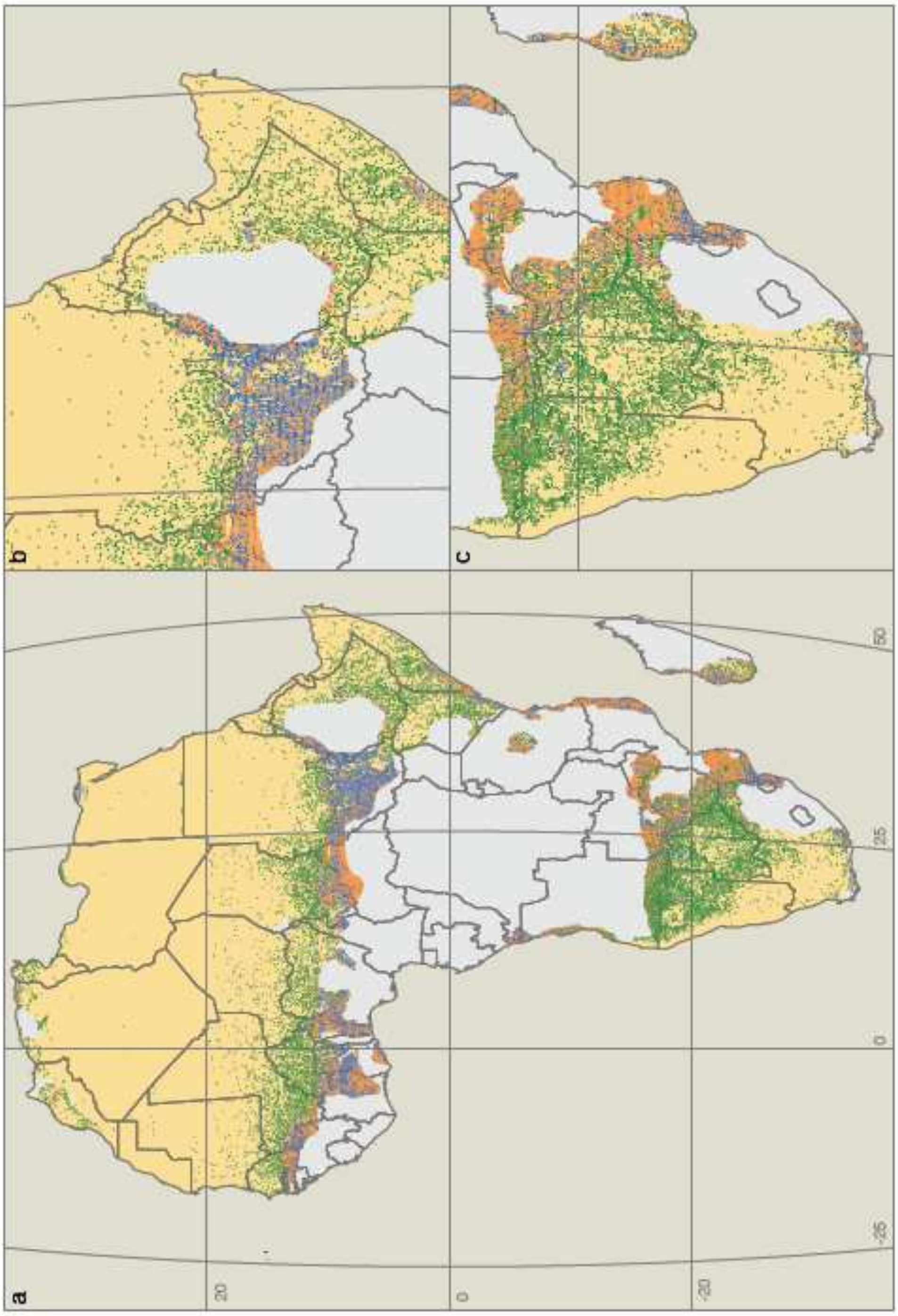

Figure 2. Comparison of ≥10% tree cover in Africa's drylands as mapped by the Global Drylands Assessment (GDA) and Hansen et al. (*13*)**.** Green dots show plots are coloured green where the GDA reports ≥10% tree cover but Hansen et al. reported a lower percentage; blue dots show plots where Hansen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

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Author contributions

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

Competing financial interests

The authors declare no competing financial interests.

Supplementary materials

Materials and Methods

Tables S1 to S3

Figs. S1 to S18

References (32-39)