FOREST ECOLOGY

The extent of forest in dryland biomes

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Dryland biomes cover two-fifths of 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 analyzing more than 210,000 0.5-hectare 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, 1327 million hectares of drylands had more than 10% tree-cover, and 1079 million hectares comprised forest. Our estimate is 40 to 47% higher than previous estimates, corresponding to 467 million hectares of forest that have never been reported before. This increases current estimates of global forest cover by at least 9%.

Dryland biomes cover ~41.5% of Earth's land surface (*1*). They contain some of the most threatened, yet disregarded, ecosystems (*2*, *3*), including 7 of the 25 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)—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, 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 substantial 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 (such as spatial resolution), mapping approaches (such as mapping unit) and forest definitions (such as 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 Drylands 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*)—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" according to their AI: (i) the "hyperarid" zone (AI < 0.05), (ii) the "arid" zone (AI = 0.05 to 0.2), (iii) the "semi-arid" zone (AI = 0.2 to 0.5), and (iv) the "dry subhumid" zone (AI = 0.5 to 0.65). Using this definition, drylands cover 6132 Mha, or 41.5% of Earth's land surface (fig. S1) (*1*). Our study aims to accurately determine how much forest and tree cover remains in dryland biomes.

Mapping forests in the drylands by using satellite data is challenging, even with high spatial resolution imagery (10 to 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 analyze 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 area—for example, that 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 (fig. S4) (*17*). To interpret the VHR images over such a large number of plots, we divided the world's dryland domain into 12 regions and used 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.

More than 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 were used in this study to assist visual interpretation of VHR satellite imagery (fig. S2D) (*17*). 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

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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 1327 (±98) Mha of dryland where tree canopy cover percentage is over 10%, of which 777 Mha (57%) present a closed canopy (Table 1 and table S1), with a tree canopy cover over 40% (*24*). There are important differences between continents; for example, 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 and figs S6 and S7). Of these 1327 Mha, 1079 (±38) Mha are considered as "forest" according to the Food and Agriculture Organization of the United Nations (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 (Fig. 1 and table S1). 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 global estimates of forest "land use" area (3890 Mha) (*25*) and the area with a "land cover" presenting more than 10% tree canopy cover derived from a global tree cover map (4628 Mha) (*13*).

Our findings show that the total area of dryland forest is similar to the area of tropical moist forest, which is estimated at 1156 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 and table S1).

Table 1. Areas of forest in the world's drylands in 2015 and land under different percentages of tree canopy cover. Data are in megahectares. "Forest" as defined by FAO (*24*) 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" is forest with 10 to 39% tree canopy cover; and "closed forest" is forest with ≥40% tree canopy cover.

	Total area	Tree canopy cover ≥10%	Forest	Tree canopy cover ≥10 and <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
North America	694	238	204	77	49	161	155
Oceania	685	124	114	94	85	30	29
South America	546	208	197	33	26	175	171
Aridity zone							
Hyperarid	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 subhumid	1326	652	565	183	117	469	448
Drylands total	6132	1327	1079	550	355	777	724

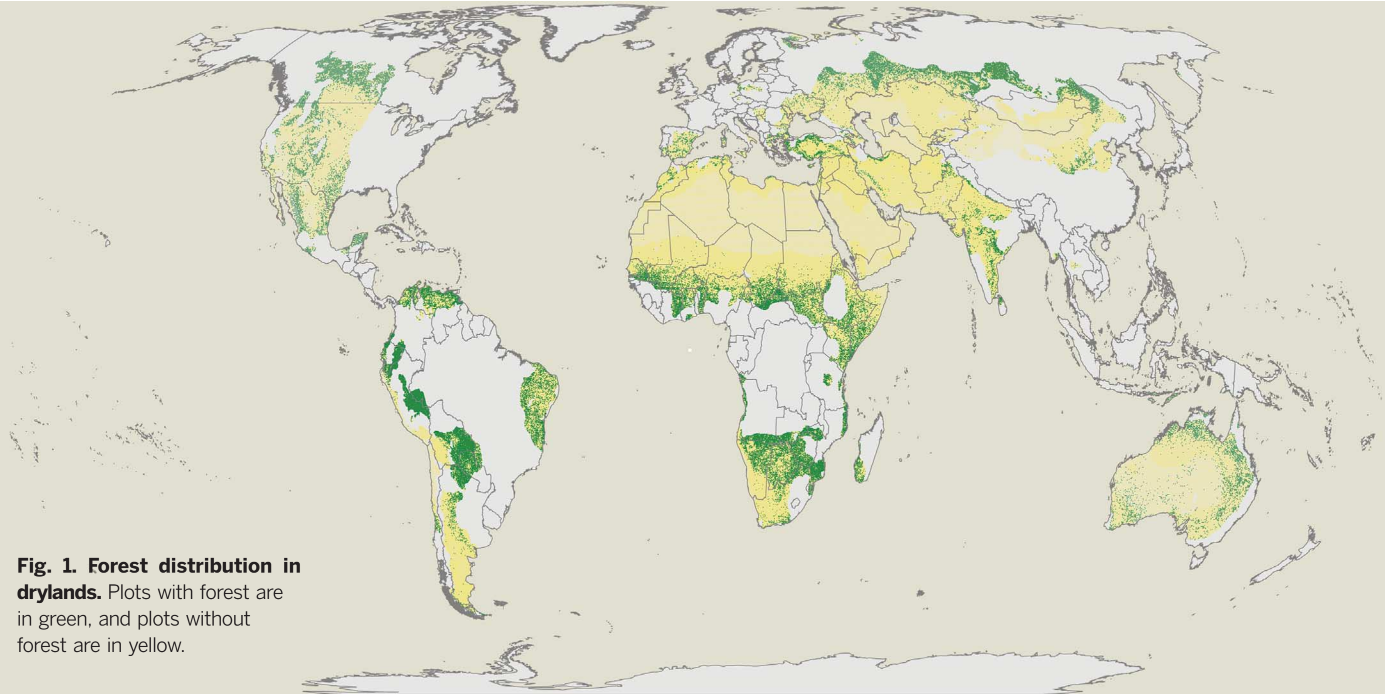

Fig. 1. Forest distribution in drylands. Plots with forest are in green, and plots without forest are in yellow.

Corrected 12 May 2017. See full text.

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 1079 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 (table S2).

When we compared our maps of forest and tree cover, based on more than 210,000 sample plots, with 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 and figs. S9 to S11) (*17*). Our estimate of 1327 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 to S11). In Africa, for example, we found 148 Mha (70%) more land with ≥10% tree canopy cover than found by 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; 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 and fig. S11). This might indicate that such closed canopies in dryland have reflectance properties that do not allow to classify them as forests from Landsat imagery. We found even more tree cover and forest than did the 2009 Globcover product (27) and the FAO–Global Forest Resources Assessments (FRA) Remote Sensing Survey 2010 (26), respectively (Table 2).

The global maps of Hansen *et al.* (*13*) and Sexton *et al.* (*14*) show some areas of ≥10% tree canopy cover that are not apparent in our map, such as in NE Brazil and South-Sudan (Fig. 2 and

Table 2. Comparison of estimates of areas in the drylands in 2015 with forest and ≥10% tree canopy cover. Compared are the estimates in this paper (Global Drylands Assessment) and other estimates based on satellite images and following the same definition of dryland (in megahectares) (*1*). Dashes indicate nonexisting information for a given source because estimates are expressed either in terms of "Tree cover" or in terms of "Forest."

Source	FAO RSS (2010) (*25*)	Globcover (2009) (*26*)	Hansen *et al.* (2013) (*13*)	Sexton *et al.* (2013) (*14*)	Global Drylands Assessment (2016)		
Sensor	Landsat	MERIS	Landsat	Landsat	Very high resolution		
Method	Sampling	Wall-to-wall	Wall-to-wall	Wall-to-wall	Sampling		
Year	2005	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.

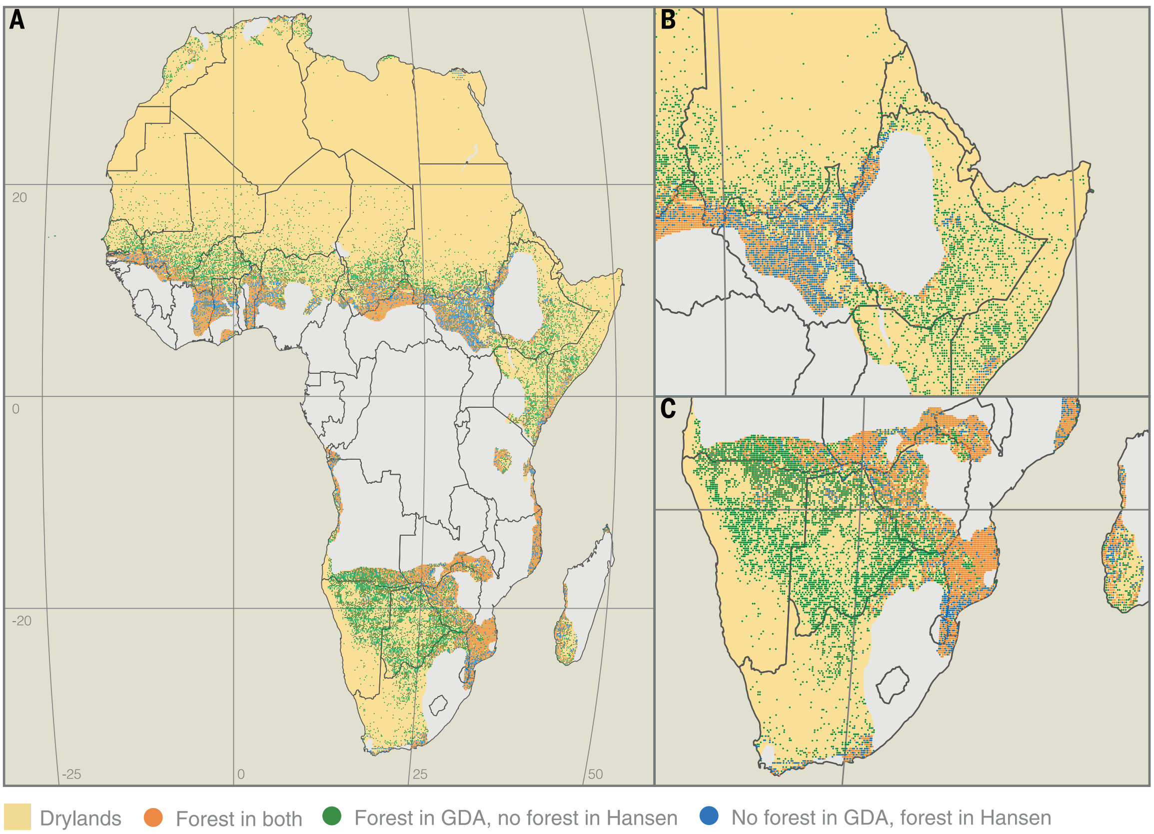

Fig. 2. Comparison of ≥10% tree cover in Africa's drylands. (**A** to **C**) Compared are maps by the Global Drylands Assessment (GDA) and Hansen *et al*. (*13*). Green dots indicate plots where the GDA reports ≥10% tree cover but Hansen *et al*. reported a lower percentage; blue dots indicate plots where Hansen *et al*. reported ≥10% tree cover but the GDA reports a lower percentage; and orange dots indicate plots where both assessments report ≥10% tree cover. (B) and (C) focus on two regions with large discrepancies between the maps.

figs. S10 and S13). We suspect that these are caused by a "greening effect" related to meadows or wetlands, which might present a spectral signature similar to forests and to which Landsat data are sensitive (*17*).

Our estimate is 40 to 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 [5055 Mha instead of 4628 Mha (*13*)] and by 11% the global area of forest [4357 Mha instead of 3890 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 gigatons carbon (GtC), or by 2 to 20% (*29*), 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—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*).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/356/6338/635/suppl/DC1
Materials and Methods
Figs. S1 to S18
Tables S1 to S3
References (*32*–*39*)
Database S1

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The extent of forest in dryland biomes

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Mapping the world's dry forests

The extent of forest area in dryland habitats, which occupy more than 40% of Earth's land surface, is uncertain compared with that in other biomes. Bastin *et al.* provide a global estimate of forest extent in drylands, calculated from high-resolution satellite images covering more than 200,000 plots. Forests in drylands are much more extensive than previously reported and cover a total area similar to that of tropical rainforests or boreal forests. This increases estimates of global forest cover by at least 9%, a finding that will be important in estimating the terrestrial carbon sink.

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