https://doi.org/10.1038/d41586-020-02830-3

News & views

Ecology

Satellites could soon map every tree on Earth

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An analysis of satellite images has pinpointed individual tree canopies over a large area of West Africa. The data suggest that it will soon be possible, with certain limitations, to map the location and size of every tree worldwide.

Terrestrial ecosystems are defined in large part by their woody plants. Grasslands, shrublands, savannahs, woodlands and forests represent a series of gradations in tree and shrub density, from ecosystems with low-density, low-stature woody plants to those with taller trees and overlapping canopies. Accurate information on the woody-vegetation structure of ecosystems is, therefore, fundamental to our understanding of global-scale ecology, biogeography and the biogeochemical cycles of carbon, water and other nutrients. Writing in *Nature*, Brandt *et al.*[1] report their analysis of a massive database of high-resolution satellite images covering more than 1.3 million square kilometres of the western Sahara and Sahel regions of West Africa. The authors mapped the location and size of more than 1.8 billion individual tree canopies; never before have trees been mapped at this level of detail across such a large area.

The spatial resolution of most satellite data is relatively coarse, with individual image pixels generally corresponding to areas on the ground that are larger than 100 square metres, and often larger than one square kilometre. This limitation has forced researchers in the field of Earth observation to focus on measuring bulk properties, such as the proportion of a landscape covered by tree canopies when viewed from above (a measurement known as canopy cover).

However, during the past two decades, a variety of commercial satellites have begun to collect data at a higher spatial resolution, capable of capturing ground objects measuring one square metre or less. This resolution improvement places the field of terrestrial remote sensing on the threshold of a fundamental leap forward: from focusing on aggregate landscape-scale measurements to having the potential to map the location and canopy size of every tree over large regional or global scales. This revolution in observational capabilities will undoubtedly drive fundamental changes in how we think about, monitor, model and manage global terrestrial ecosystems.

Brandt *et al.* provide a striking demonstration of this transformation in terrestrial remote sensing. The authors analysed more than 11,000 images, at a spatial resolution of 0.5 m, to identify individual trees and shrubs with canopy diameters of 2 m or more. The authors completed this giant task using artificial intelligence — exploiting a computational approach that involves what are called fully convolutional neural networks. This deep-learning method is designed to recognize objects (in this case, tree canopies) on the basis of their characteristic shapes and colours within a larger image. Convolutional networks rely on the availability of training data, which in this case consisted of satellite images in which the visible outlines of tree and shrub

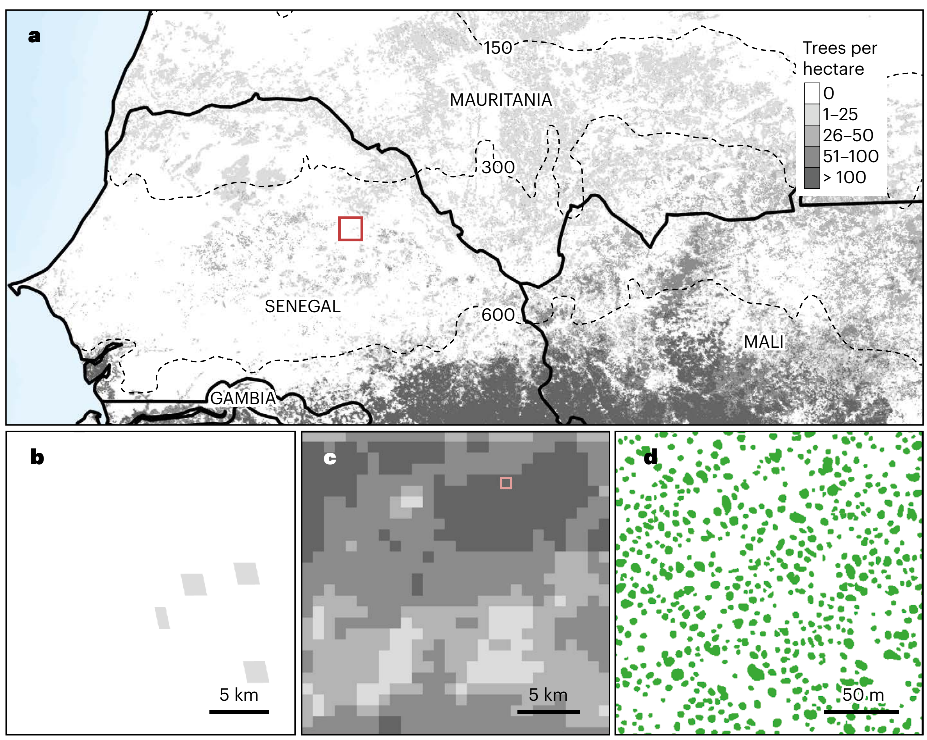

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Figure 1 | Large-scale tree mapping. Accurate information about tree distribution provides useful ecological insights, but such data are difficult to obtain for large areas of land. **a**, A previous study[2] estimating global tree density per hectare relied on data from field plots — samples of these data are shown for western Africa. The inset box in **a** is in a dry region (with an average annual rainfall of less than 600 millimetres per year), and corresponds to **b**. Dotted lines indicate the boundaries of average rainfall in millimetres per year. **c**, **d**, Brandt *et al.*[1] report the detection of individual tree canopies across western Africa, obtained using an artificial-intelligence approach to analyse high-resolution satellite images. The authors found a higher tree density in dry regions of Africa than did the earlier study. For example, Brandt and colleagues' analysis of the area corresponding to the inset box in **a** produced the tree density per hectare shown in **c**. They identified the size and location of individual tree canopies (green), as shown in **d** for an area corresponding to the inset box in **c**. Tree information at this level of detail was not available in the earlier study. (Images made using data from refs 1 and 2.) (Springer Nature remains neutral with regard to jurisdictional claims in published maps.)

canopies were manually traced. Through training using these samples, the computer learnt how to identify individual tree canopies with high precision in other images. The result is a wall-to-wall mapping of all trees larger than 2 m in diameter across the whole of southern Mauritania, Senegal and southwestern Mali.

A previous estimate[2] of the total number of trees on a global scale was obtained using field data from approximately 430,000 forest plots around the world. The authors of that study used statistical regression models to estimate tree density between the field sites, on the basis of vegetation type and climate. Their analysis suggested that there are approximately three trillion trees globally. However, this approach to tree-density estimation has inherent errors and uncertainties, particularly for drylands, for which relatively few field measurements are available to calibrate the models.

A comparison (Fig. 1) of that earlier result with Brandt and colleagues' findings in the western Sahel, for example, shows that the previous study tended to underestimate the number of trees in the drier regions (areas with annual rainfall of less than 600 millimetres). Moreover, the previous estimates provided no information on the location and size of individual trees within each square kilometre, whereas Brandt and colleagues provide detailed information on the location and size of every individual canopy. The improvement provided in the latest study can also be seen in the much higher level of detail it gives for the wetter regions (those with annual rainfall greater than 600 mm), and shows local spatial variability in trees that is presumably associated with contrasting soil types, water availability, land use and land-use history.

There are, of course, caveats and limitations to Brandt and colleagues' work and the potential for scaling up their approach to a global analysis. Successful canopy detection declined drastically below a canopy diameter of 2 m, owing to constraints imposed by the spatial resolution of the imagery, and consistent with earlier work[3]. Although we can expect further improvements in the spatial resolution of satellite images, it becomes pertinent to ask what minimum canopy size is needed to characterize woody-plant communities in various regions. For global tree-canopy mapping, if we assume that the computational and storage challenges associated with large data volumes can be overcome, the biggest roadblock would lie in developing efficient approaches for automated classification and delineation of canopies. Brandt and colleagues' deep-learning method required an input of approximately 90,000 manually digitized training points. This approach becomes untenable for work on a global scale, and more-automated (unsupervised) methods for extracting information from satellite imagery would be necessary[4].

A related problem is the ability to distinguish between what might look like one large canopy and adjacent, overlapping canopies of different individual trees. To improve canopy separation, Brandt *et al.* used a weighting scheme in training their convolutional neural network, but still resorted to a 'canopy clump' class to describe aggregated canopy areas of more than 200 m^2, suggesting that the separation approach was not always effective. For application in wetter regions, where overlapping canopies in woodlands and forests are common, canopy delineation and separation methods will need refinement and automation to be feasible at global scales.

Yet more challenging is the identification of tree species. Although feasible, on the basis of canopy colour, shape and texture[5], it will be particularly tricky at regional and global scales and across biodiverse ecosystems. The mapping of individual tree canopies by species will probably remain at the top of the Earth-observation research community's wish list for some time[6].

In the years ahead, remote sensing will undoubtedly provide unprecedented detail about vegetation structure as data from a range of sources — including light detection and ranging (lidar), radar and high-resolution visible and near-infrared sensors — become more readily available[7]. Satellite-derived high-resolution data on tree canopy size and density could contribute to the inventory and management of forests and woodland, deforestation monitoring, and assessment of the carbon sequestered in biomass, timber, fuel wood and tree crops. The ability to map the size and location of individual tree canopies using such satellite data will complement information available from other instruments that provide data for tree height, vertical canopy profiles and above-ground wood biomass. Continuing research will be needed to develop more-efficient canopy-classification algorithms. In the meantime, Brandt and colleagues have clearly demonstrated the potential for future global mapping of tree canopies at submetre scales.

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