LETTERS
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Conservation policy and the measurement of forests

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Deforestation is a major driver of climate change[1] and the major driver of biodiversity loss[1,2]. Yet the essential baseline for monitoring forest cover—the global area of forests—remains uncertain despite rapid technological advances and international consensus on conserving target extents of ecosystems[3]. Previous satellite-based estimates[4,5] of global forest area range from 32.1 x 10^6 km^2 to 41.4 x 10^6 km^2. Here, we show that the major reason underlying this discrepancy is ambiguity in the term 'forest'. Each of the >800 official definitions[6] that are capable of satellite measurement relies on a criterion of percentage tree cover. This criterion may range from >10% to >30% cover under the United Nations Framework Convention on Climate Change[7]. Applying the range to the first global, high-resolution map of percentage tree cover[8] reveals a discrepancy of 19.3 x 10^6 km^2, some 13% of Earth's land area. The discrepancy within the tropics alone involves a difference of 45.2 Gt C of biomass, valued at US$1 trillion. To more effectively link science and policy to ecosystems, we must now refine forest monitoring, reporting and verification to focus on ecological measurements that are more directly relevant to ecosystem function, to biomass and carbon, and to climate and biodiversity.

Forests are the focus of efforts to mitigate harmful ecological and social impacts of land use, including agreements to reduce carbon dioxide emissions from deforestation and forest degradation (REDD+; refs 9–11). The goals are both scientific—to balance regional and global carbon budgets—as well as political, to reduce carbon emissions and stop species extinctions by defining national baselines and managing future anthropogenic change[12].

The Forest Resources Assessments (FRAs) of the United Nations Food and Agriculture Organization (FAO)—the authority for national and global accounting—recorded 40.8 × 10^6 km^2 of forest in 2000, equalling 31% of Earth's land area[13]. The FRAs rely on self-reporting by participating countries, raising concerns about subjectivity and consistency[14–16]. Although estimates from satellite images should provide a more objective base[9], even these disagree significantly over the amount and distribution of forests worldwide. Figure 1 maps the consensus among eight global satellite data sets over the class 'forest' in or near the year 2000 (Methods). The densely canopied biomes of the tropical, temperate and boreal zones, and the treeless deserts, prairies and tundra show near-perfect agreement across all sources on the presence or absence of forests. Yet the data disagree over the planet's semi-arid savannahs, shrublands and woodlands, and over the northern limits of the boreal forest. Although 102.2 × 10^6 km^2 show perfect consensus among the eight data sets on either the presence or absence of forests, 9.4 × 10^6 km^2 were identified as forest by four out of the eight sources. These sparsely forested regions are the areas of greatest remaining uncertainty.

There are two reasons for the uncertainty: technology and semantics. Among the remotely sensed estimates, the discrepancies are partially due to the imprecision of empirical models relating forest cover to optical measurements in challenging environments. Clouds frequently obscure the land surface in the most humid regions. Dense vegetation, water, and shadows are confused with tree canopies in herbaceous wetlands and agricultural areas. In semi-arid savannahs and woodlands, structural variation and understory seasonality reduce precision[8,17,18]. Limited presently by technological constraints, these uncertainties will shrink with increases in the number and breadth of sensors, providing greater temporal frequency, more accurate reference measurements, and better penetration of clouds[18].

More fundamentally, the disagreement is due to the many definitions of the term 'forest'. Owing to different geographic and cultural backgrounds, even expert human interpreters disagree on the identification of forests *in situ* or in satellite images. The problem runs deep etymologically. The word 'forest' (from the French forêt, referring to uncultivated land outside city walls) has only circumstantial connection to trees, which happened to occupy the wilderness in medieval France. In contrast, the 'New Forest'—founded as a royal hunting preserve in 1079 in southern England—comprised mostly farms, pasture, and heathland.

Today, there are >800 official definitions of forest[6,19]. Each of these discriminates land either by vegetation cover or by human use. Whereas definitions based purely on land use (for example, forestry) require only administrative boundaries for mapping, definitions based on land cover are more directly relevant to carbon and are observable by satellite sensors. Forest-cover definitions vary along criteria of tree cover, tree height, and parcel size, as well as between the actual and potential height of vegetation. The FAO (ref. 13) defines forests by the criterion of tree cover >10%. The International Geosphere-Biosphere Programme (IGBP) uses a criterion of >60% tree cover for forest, specifying savannah as 10–30% and woody savannah as 30–60% cover[20]. Spanning the range of the FAO and IGBP definitions, the United Nations Framework Convention on Climate Change (UNFCCC) allows participating countries

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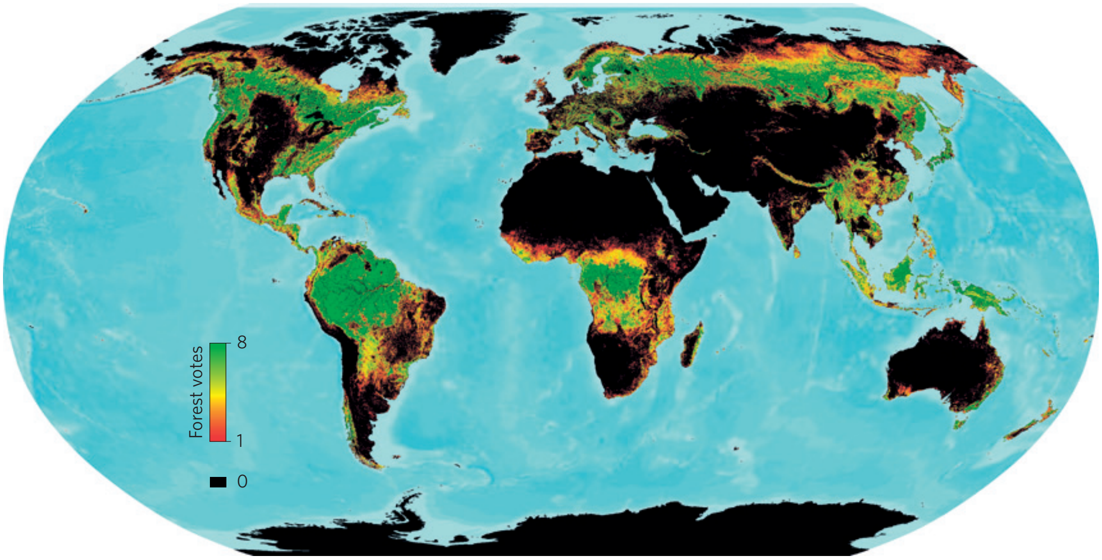

Figure 1 | Global distribution of consensus among eight satellite-based data sets[4,8,31–36] on the presence or absence of forest in or near the year 2000. Colours represent the number of times each pixel is identified as forest among the eight data sets—that is, the number of 'votes' (out of eight possible) for forest cover. Larger values (in green) show agreement on the presence of forest. Conversely, values near zero (in red and black) show agreement on its absence. Yellow values (near four) represent areas of maximum disagreement over both the presence or absence of forest.

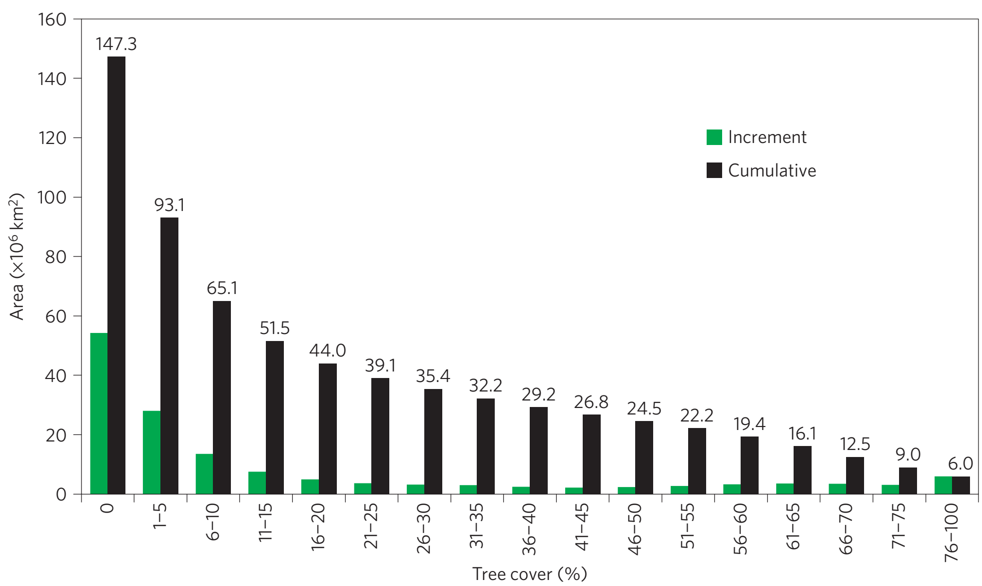

Figure 2 | Global area of forest cover as a function of the tree-cover criterion. Incremental values represent global area ($\times 10^6$ km^2) within each bin, and cumulative values refer to the global area with tree-cover values greater than or equal to that of the bin. Landsat-based tree-cover data[8] are publicly available at www.landcover.org. Global land area (147.3×10^6 km^2) reflects the extent of terrestrial ecoregion boundaries[21].

to select from a range of thresholds between >10 and >30% tree cover[7].

So, how much forest cover is there? The answer depends on the threshold of tree cover. When applied to the world's first high-resolution (30-m-resolution), global map of tree cover[8] (www.landcover.org), the official definitions yield large differences in the global area and distribution of forests. Figure 2 relates global forest area across the range of possible thresholds, and Fig. 3 maps the UNFCCC definitions and their differences. Given the more conservative UNFCCC threshold of >30% cover, there were 32.2×10^6 km^2 of forests in 2000. Given the FAO and lower UNFCCC threshold of >10% tree cover, there were 51.5×10^6 km^2. At the IGBP threshold of >60% tree cover, there were 16.1×10^6 km^2 of forests, with an additional 19.3×10^6 km^2 of savannah and 16.1×10^6 km^2 of woody savannah (10–30% and 30–60% cover, respectively). Discrepancies occur in all biomes, but the greatest differences are in regions of intermediate tree cover. Differences exceed 1×10^6 km^2 in boreal forests and taiga, in temperate broadleaf and mixed forests, and in tropical and subtropical grasslands, forests, savannahs and shrublands (Table 1). Differences exceeding 25% of biome area occur in boreal forests and taiga, flooded grasslands and savannahs, and tropical and subtropical dry broadleaf forests. Importantly, neither the geographic nor the statistical distribution of tree cover shows any clear breaks or inflections to discriminate a natural, a priori distinction between 'forest' and 'non-forest'. Thus, any definition must be arbitrary by nature.

The tree-cover discrepancy coincides precisely with the uncertainty among global satellite data sets. It also coincides with

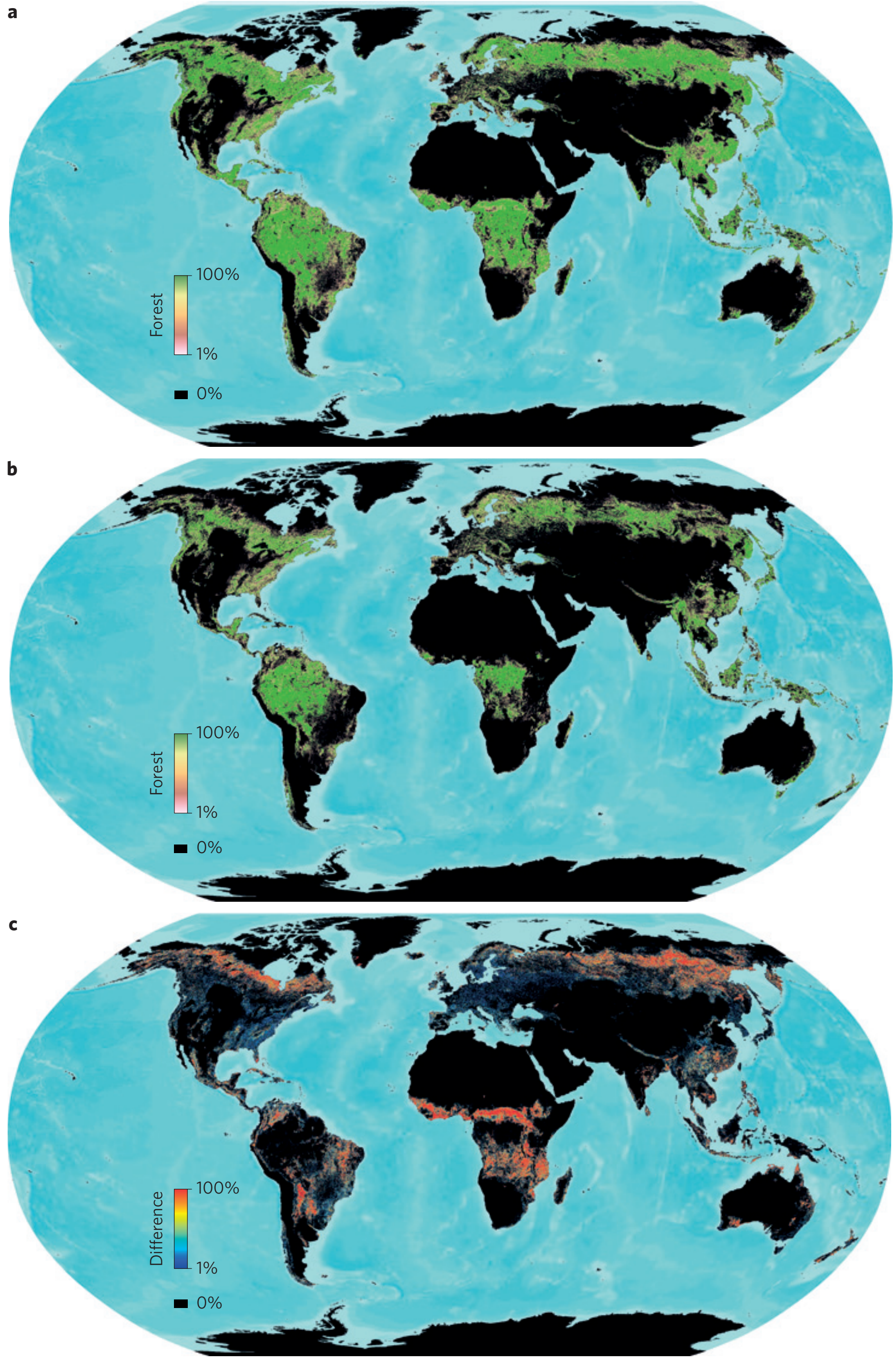

Figure 3 | Global distribution and discrepancy of forest cover based on United Nations Framework Convention on Climate Change (UNFCCC) definitions. **a**–**c**, Maps represent distributions of forest cover assuming criteria of 10% tree cover (**a**), 30% tree cover (**b**) and the difference in forest cover between the two definitions (**c**).

vast stores of biomass and many developing countries across the tropics (Supplementary Information). Overlain with pan-tropical estimates of biomass[22] at a social value of US$23/t C (Methods), the difference in forest cover coincides with 41.2 Gt C valued at US$1.0 trillion. Indonesia, Vietnam, Myanmar, Argentina, Bolivia, Colombia, Mexico, Côte d'Ivoire, Democratic Republic of the Congo, Nigeria, Tanzania, Zambia, Cameroon, Central African Republic, Ethiopia, Madagascar and South Sudan each could have forest-carbon assets changed by US$10 billion, depending on forest definition.

Finding a natural threshold of parcel area is equally challenging. Assuming the 30% tree-cover criterion, globally there were 1.59×10^5 km^2 of forests in 2000 with patch sizes between the FAO 0.5-ha threshold and 1 ha, and there were 1.98×10^5 km^2 of forest in patches between 1 and 100 ha in area (Fig. 4). Most patches meeting the 30% tree-cover criterion are smaller than the 0.5-ha size criterion. Again, the distribution offers no break or inflection as a natural distinction between forest and non-forest. The number of forest patches becomes intractable as the area criterion approaches zero, and 'forest' becomes immeasurable or even meaningless in

Table 1 | Global forest area by biome[21].

Biome	Area	Forest (>10% tree)		Forest (>30% tree)		Difference	
	km²	%	km²	%	km²	%	km²
Boreal forests/taiga	14,224,916	76.90	10,938,418	45.10	6,415,061	31.80	4,523,357
Deserts and xeric shrublands	27,752,829	2.34	650,180	0.46	126,774	1.89	523,406
Flooded grasslands and savannahs	1,036,966	45.21	468,838	10.60	109,913	34.61	358,925
Mangroves	293,404	80.23	235,402	57.19	167,793	23.04	67,609
Mediterranean forests	3,180,903	23.48	746,793	11.22	357,037	12.25	389,757
Montane grasslands and shrublands	5,120,243	9.91	507,643	4.43	226,628	5.49	281,016
Temperate broadleaf and mixed forests	12,466,617	59.80	7,455,587	40.73	5,077,288	19.08	2,378,300
Temperate conifer forests	4,010,340	69.88	2,802,276	53.26	2,135,870	16.62	666,406
Temperate grasslands	9,904,686	9.17	907,986	4.21	416,923	4.96	491,063
Tropical and subtropical coniferous forests	707,026	75.95	536,967	39.64	280,249	36.31	256,718
Tropical and subtropical dry broadleaf forests	2,969,433	47.59	1,413,112	23.96	711,398	23.63	701,714
Tropical and subtropical grasslands	20,089,822	34.52	6,934,566	10.68	2,146,591	23.83	4,787,975
Tropical and subtropical moist broadleaf forests	19,513,086	86.13	16,806,448	69.55	13,570,480	16.58	3,235,968
Tundra	7,449,513	12.76	950,209	4.39	326,854	8.37	623,355

Inland water, rock and ice, and deserts and xeric shrublands (each with <2.5% tree cover) are excluded.

high-resolution pixels. The paradox of imposing thresholds is that they place a large portion of Earth's forest carbon outside of 'forests'. Their practical implication is that refinements in satellite resolution will be unable to contribute directly to monitoring forest cover except through more scalable variables such as tree cover and height.

The challenge emerges to increase the ecological relevance of measurements while maintaining their practicality for policy. How can we increase precision without sacrificing the progress of REDD+ thus far? Two alternatives are apparent.

A single, unambiguous definition of forest, applied consistently across the globe, might resolve the confusion. Such a definition must incorporate attributes of forests that are both measurable and manageable. Moreover, to reduce emissions from the biosphere, the measurements must be relevant to biomass. An effective definition thus requires characteristics of the horizontal cover, vertical structure, and composition of vegetation—primarily trees. This solution is already implemented indirectly under the discretion of each country, through systems of tables relating forest cover to biomass stratified by country and biome[23]. Aside from the complexity and subjectivity of the stratification, the problem with such coarse tabulations is that the resulting conservation incentives do not vary with natural productivity or biomass gradients, nor do they discriminate primary natural forests from secondary forests or plantations[24].

Alternatively, a more transparent solution may be to shift the focus of monitoring from 'forest' onto the ecological characteristics used to define it. Global satellite estimates of tree cover, canopy height, and biomass are increasingly reliable and available[8,17,22,25–28], as are the methods to translate them into estimates of forest cover and change based on national definitions[29]. These more objective ecological variables—many of which are already recognized by the official definitions—comprise the volume and density of vegetation that are the fundamental components of biomass. They are also the characteristics managed by forestry and other land uses—including agriculture, wildlife management, and even urban planning. Given the growing technical capacity for monitoring, reporting and verification, science and policy may now refine their focus to communicate in terms of these more concrete characteristics of ecosystem structure, function and composition.

This challenge presents an opportunity for mutual advance. Mapping forest cover and its changes have contributed greatly to alerting the public to the global crisis of deforestation, and the political arena has matched this awareness with policy instruments such as the Kyoto Protocol[7], REDD+, and the Aichi Biodiversity Targets[3]. But although 'forest' is an intuitive label for general discussion, the intuition transcends neither cultures nor ecosystems, and the term is neither directly relevant to carbon nor directly measured from satellite or *in situ* observations. The resulting ambiguity blurs estimates of global area and distribution of forests, as well as the meaning of all logical derivatives of the term—for example, afforestation, reforestation, forest degradation, and deforestation[6,12,24,30]—up to and including the value of carbon.

Science and policy are working to reduce carbon emissions from the biosphere and to stem the loss of species. Satellite technologies now enable us to refine our focus from simply mapping forests to monitoring the dynamics of ecosystem structure, function and composition. Taking this step forward will improve the objectivity and precision of our measurements. It will also extend their scope to the entirety of the terrestrial biosphere and increase their relevance to biomass, climate change and biodiversity.

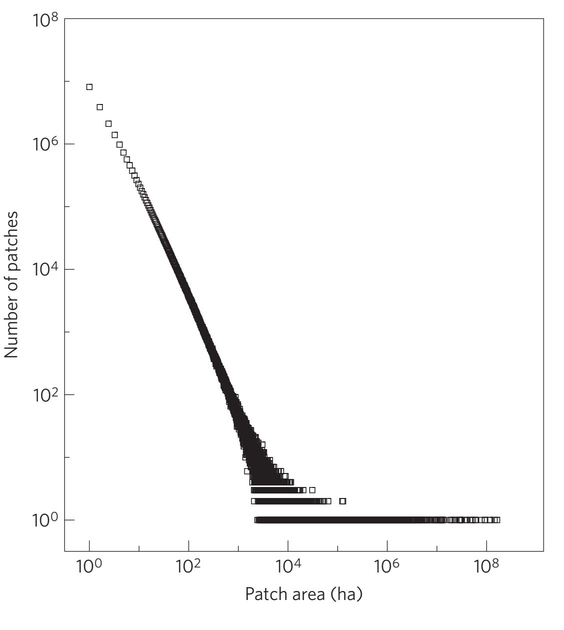

Figure 4 | Global frequency distribution of forest-patch size, assuming the 30% tree-cover criterion.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

J.O.S., P.N., X.-P.S., S.C., C.H. and J.R.T. conceived the study. P.N., D.-X.S., X.-P.S., M.F., A.A. and J.O.S. carried out the analyses. J.O.S. and S.L.P. wrote the manuscript with contributions from all authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.O.S.

Competing financial interests

The authors declare no competing financial interests.

Methods

To generate the forest-agreement map (Fig. 1), each of eight global land cover data products[4,8,31–36] was translated into a binary (forest versus non-forest) map and resampled to a common projection and 1-km resolution[37]. Percentage tree-cover data sets[4,8,38] were first spatially averaged to 1-km resolution and then translated to forest/non-forest by applying a 30% tree-cover threshold. We then evaluated each pixel as the number of times it was identified as forest by the eight maps, resulting in a score between zero and eight 'votes'. Larger values represent greater agreement between the products for the forest class, and smaller values represent greater agreement for the non-forest class. Values near four represent the greatest disagreement.

Maps of global forest cover (Fig. 3) and estimates of area were calculated by applying 10% and 30% thresholds to the global, Landsat-based data set[8] of circa-2000, percentage tree cover at 30-m resolution (data available at www.landcover.org). Gaps in the 2000 data were filled with Landsat-based estimates from circa 2005 (ref. 39) when available, or with estimates based on data from the MODerate-resolution Imaging Spectroradiometer (MODIS; ref. 38) otherwise. This produced two binary maps of forest cover. We subtracted the value in each pixel based on the 30% threshold from the value based on the 10% tree-cover threshold and spatially aggregated the result to a percentage for display.

To calculate affected area, biomass and carbon value, we aggregated the forest-cover data from 270-m resolution to match the 1-km resolution of the carbon density map[22]. We then calculated the difference in carbon stock for every 1-km grid cell by multiplying the forest-change percentage by the forest-carbon density in each cell and summed over area. The social cost of carbon (SCC) (US$23/t C, in 1995 US dollars) was adopted as the mean of Tol's (2008) survey of peer-reviewed SCC estimates[40] and adjusted for inflation to the year 2000 at an average rate of 2.37%/year.

The power-law model of the frequency distribution of forest-patch area:

$$n = 10^{7.22} a^{-1.84} \quad (1)$$

was estimated by ordinary least squares regression ($R^2 = 0.9485$). To minimize the effect of heteroscedasticity on model fit, the ordinate and abscissa were log-transformed, and the model was fitted based on the median patch area at each frequency level. We then evaluated the integral of equation (1) between thresholds to determine the effect of the patch-size criterion on forest area.

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