CARBON CYCLE

Tropical forests are a net carbon source based on aboveground measurements of gain and loss

A. Baccini,[1]* W. Walker,[1] L. Carvalho,[2] M. Farina,[1] D. Sulla-Menashe,[3] R. A. Houghton[1]

The carbon balance of tropical ecosystems remains uncertain, with top-down atmospheric studies suggesting an overall sink and bottom-up ecological approaches indicating a modest net source. Here we use 12 years (2003 to 2014) of MODIS pantropical satellite data to quantify net annual changes in the aboveground carbon density of tropical woody live vegetation, providing direct, measurement-based evidence that the world's tropical forests are a net carbon source of 425.2 ± 92.0 teragrams of carbon per year (Tg C $year^{-1}$). This net release of carbon consists of losses of 861.7 ± 80.2 Tg C $year^{-1}$ and gains of 436.5 ± 31.0 Tg C $year^{-1}$. Gains result from forest growth; losses result from deforestation and from reductions in carbon density within standing forests (degradation or disturbance), with the latter accounting for 68.9% of overall losses.

Tropical forests store large amounts of carbon, but agreement is lacking on their net contribution to the terrestrial carbon balance. Land-use and land-cover change (LULCC) are believed to release between 0.81 and 1.14 Pg C $year^{-1}$ (*1*–*4*), whereas intact native forests are thought to be a net carbon sink of approximately the same magnitude (*5*–*7*). Independent estimates based on atmospheric CO_2 concentration suggest an overall sink of 1.4 (±0.4) Pg C $year^{-1}$ (*8*). Reducing the uncertainty of these estimates is not only fundamental to advancing carbon cycle science, but is also of increasing relevance in the context of climate change mitigation policies designed to reduce atmospheric CO_2 emissions from deforestation and forest degradation (e.g., REDD+). Conventional approaches to estimating the net carbon balance of tropical forests rely on satellite-based estimates of forest area change between two time periods combined with information on biomass density (*1*, *7*, *9*–*13*). Alternative strategies based on a range of active (*14*–*20*) and passive (*21*) remote-sensing techniques have also been advanced; however, the majority of these are limited in terms of geographic scope, spatial resolution and/or data availability. Although all approaches are designed to capture losses in biomass due to land-use change (i.e., wholesale forest clearing or deforestation), most are limited in their sensitivity to forest degradation (e.g., selective logging and/or disturbance in forest that remains forest), which can account for additional biomass losses on the order of 47 to 75% of deforestation (*22*, *23*). Moreover, few of these applications include estimates of carbon sequestration rates in growing forest (*24*, *25*).

[1]The Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 04523, USA. [2]Department of Mathematics and Statistics, Boston University, Boston, MA, USA. [3]Department of Earth and Environment, Boston University, Boston, MA, USA.
*Corresponding author. Email: abaccini@whrc.org

Here we estimate changes in the aboveground carbon density (hereafter aboveground carbon) of woody live vegetation across tropical America, Africa, and Asia (between 23.45°N and 23.45°S, excluding Australia) for the period 2003 to 2014, including losses from land-use change and degradation or disturbance, as well as gains from growth. To do this, we build on methods developed by (*1*) for single-epoch mapping of aboveground carbon to generate a 12-year pantropical time series of carbon stock estimates at a spatial resolution of 463 m (21.4 ha). The approach combines field measurements with colocated NASA light detection and ranging (LIDAR) data to calibrate a machine learning algorithm (*1*, *26*) that generates annual carbon estimates from 12 years of NASA Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (fig. S4). The time-series data are then analyzed at the grid-cell level with a change-point fitting algorithm to quantify gains and losses in carbon storage through time (fig. S5). The algorithm identifies all possible change points in the time series based on the deviation from a simple linear regression function. An optimal segmentation of the time series is achieved with a Bayesian formulation to determines a best-fit linear trend model with which to assess changes in carbon storage over time contingent on an approximated *P* value (see supplementary materials). Summing losses and gains across all grid cells exhibiting a significant change ($P < 0.05$), we compute the total change (gain or loss) in aboveground carbon. By estimating changes in carbon storage directly rather than first determining changes in forest area, we eliminate the uncertainty associated with area-based estimation (*27*) and overcome the primary obstacle to quantifying carbon dynamics in degraded, disturbed, and growing forest. The results were evaluated with independent field data from (*28*, *29*) and spatially explicit data products from (*30*–*32*) (see supplementary materials).

The results indicate that carbon losses exceed gains on every continent (Fig. 1 and Table 1). The average net loss for the pantropics was 425.2 ± 92.0 Tg C $year^{-1}$ of which 59.8% of total losses are attributable to America, 23.8% to Africa, and 16.3% to Asia. Small changes in aboveground carbon dominate the frequency distribution of carbon dynamics (Fig. 2). Changes tend to be smaller in Africa, where the average carbon loss was 16.6 Mg C ha^{-1}. In tropical America and Asia, average losses were 23.6 and 26.6 Mg C ha^{-1}, respectively. Not surprisingly, average per-hectare gains across the three continents tend to be lower because annual losses from deforestation and forest degradation are larger than gains from growth.

The time-series approach allows for annual trajectories of gains and losses in carbon storage to be generated at scales ranging from pixel to pantropical (Fig. 3). At the continental level, patterns are generally characterized by decreasing loss or increasing gain early in the time series followed by a reversal late in the time series. Dynamics at the national level tend to be more complex, with each country displaying its own distinctive pattern of gain and loss (table S1). The largest countries in each region in terms of land area and forest cover (i.e., Brazil, Democratic Republic of Congo, and Indonesia) necessarily exert the greatest influence on continental trends (Fig. 3). In the case of Brazil, for which the body of research on forest loss trends is most extensive (*31*, *33*, *34*), decreasing losses in carbon density early in the time series reflect a documented deceleration in deforestation from 2004 to 2012 due to retractions in soy and cattle production, increases in monitoring and enforcement together with fines and embargos on illegal deforestation, and the creation of new protected areas (*35*). Increases in forest loss thereafter, increasingly attributable to forest degradation (*36*, *37*), are responsible for the upward trend in carbon density loss late in the time series (Fig. 3). Increases in gain are driven largely by prior losses, but with a time lag that in Brazil reflects increases in deforestation pre-2004 followed by the aforementioned deceleration. During this decline, conditions allowed for degraded and deforested lands left abandoned to rebound, resulting in the carbon gains observed late in the time series (Fig. 3).

This analysis of long-term trends derived from annual change estimates is more robust than that of conventional approaches based on just two points in time, even when the time interval is long, given that the uncertainty on all estimates is further constrained with each additional observation. At the scale of an individual grid cell (21.4 ha), annual estimates reflect positive (losses) or negative (gains) changes; however, because losses and gains can occur within the same cell, the estimated source or sink at the cell level is a net and, therefore, conservative value. Even so, the net change is considered unbiased as it is representative of the combined losses and gains occurring at the scale of individual grid cells. Hence, the summation of all grid cell observations of loss and gain yields

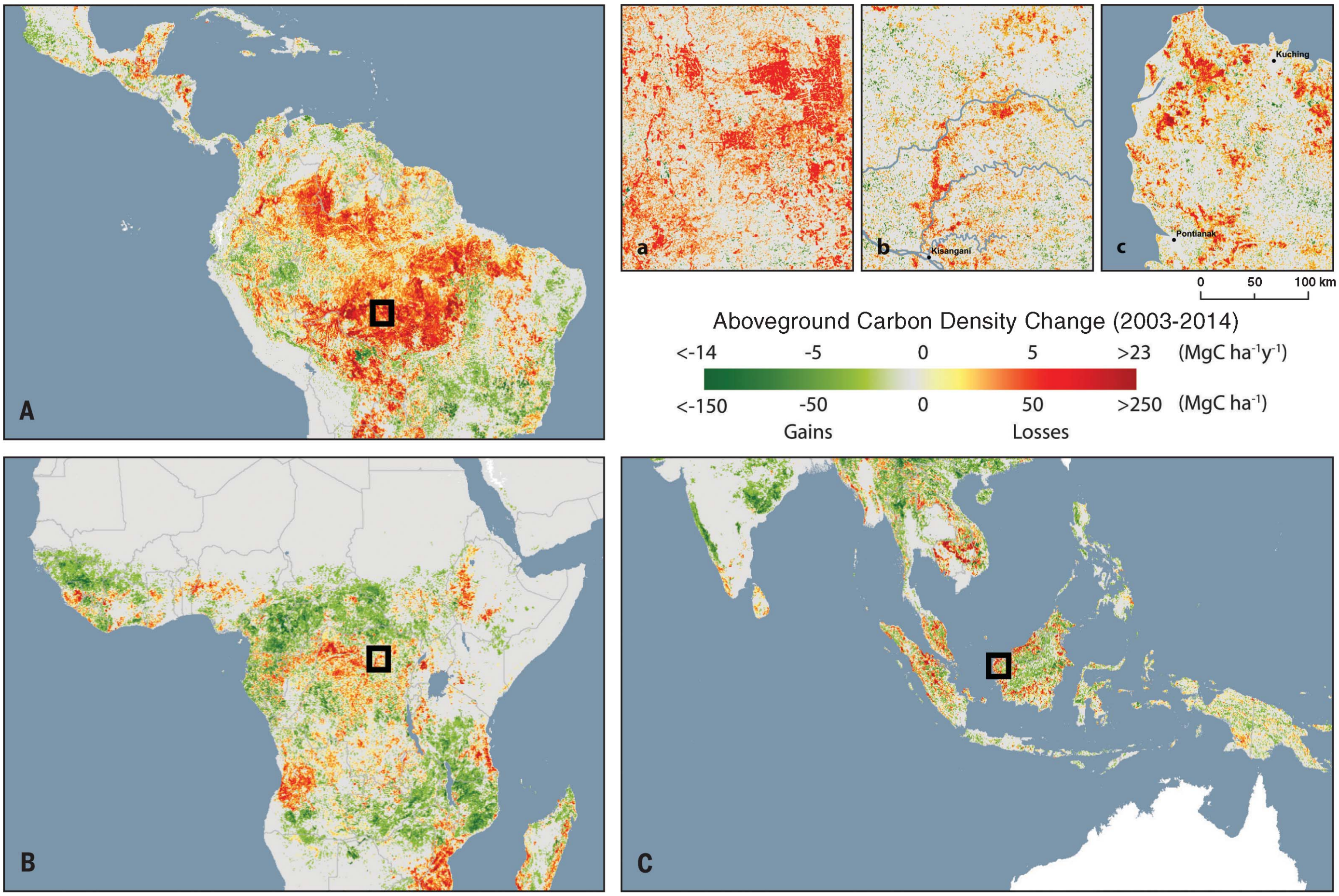

Fig. 1. Geography of carbon density change. (**A** to **C**) The figure depicts the spatial distribution of areas exhibiting gains, losses, and no change (stable). Values reported are the change from 2003 to 2014 within each 463 m by 463 m grid cell. Changes with a *P* value larger than 0.05 are identified as stable. Data in (A) to (C) have been aggregated to 5 km for display. Insets (a) to (c) are shown at full resolution and correspond to the black rectangles in (A) to (C), respectively.

a conservative estimate of gross loss and gain. We refer to these "gross" estimates as simply losses and gains, and refer to the sum of losses and gains at the grid cell level as net changes.

The vast majority of the land area (79%) across tropical America, Africa, and Asia exhibited no significant ($P > 0.05$) change in aboveground carbon over the 12-year period of study. Indeed, only 15% of the total area registered losses and only 6% registered gains. Tropical America exhibited the largest carbon losses (516.0 ± 69.5 Tg C year^{-1}) and a net change of 324.8 ± 73.5 Tg C year^{-1} (Table 1) (60% of the total change). By comparison, Africa accounted for 24% and Asia for 16% of the total change.

Analysis of those grid cells exhibiting gains (6% of grid cells) reveals that America had a net gain of 16.1 ± 2.0 Mg C ha^{-1} over the 12 years, while Africa gained 11.8 ± 1.8 Mg C ha^{-1} and Asia gained 19.0 ± 2.9 Mg C ha^{-1} (Fig. 2). Gains in forest area and/or associated carbon stocks have rarely been quantified across large areas, although the work of Baker *et al.* (*38*) and Phillips *et al.* (*28*) reveal a net accumulation of biomass in intact Amazon forests. Their analysis of 59 and 136 plots sampled across the Amazon Basin showed an average net uptake of 0.61 (±0.21) Mg C ha^{-1} year^{-1} and 0.73 (Mg C ha^{-1} year^{-1}), respectively, which are lower than the average uptake by tropical American forests observed in this study (1.1 ± 0.18 Mg C ha^{-1} year^{-1}). More recently, Brienen *et al.* (*6*) reported a reduction in the observed rate of carbon accumulation. Our study considers all aboveground woody vegetation, including intact, disturbed, and managed forests. Perhaps not surprisingly, natural secondary and managed forests have higher rates of gain than intact old-growth forests (*39*). When we limit our analysis to locations where the carbon stock at the beginning of the study period (i.e., 2003) is greater than 100 Mg C ha^{-1} [i.e., locations likely to be intact or old growth to be consistent with (*38*)], the average uptake is 0.78 (±0.23) Mg C ha^{-1} year^{-1}, consistent with the rate reported by Phillips *et al.* (*28*).

Quantifying carbon losses attributable to forest degradation or disturbance (D/D; i.e., losses in carbon density in a forest that remains forest), as opposed to stand-replacing forest cover loss (FCL), has proven challenging and is often ignored or overlooked in the estimation of carbon emissions. While distinguishing between FCL and D/D is technically unnecessary for carbon accounting (i.e., both represent varying degrees of biomass loss along a continuum), the distinction persists in the context of REDD+ and related policy frameworks. In response to the demand for estimates of these two widely accepted categories of forest carbon loss, we used existing 30-m spatial resolution data on FCL for the period 2000 to 2014 (*31*) and aboveground biomass data for the year 2000 (*40*) to separate carbon losses due to FCL from those due to D/D within those 21.4-ha grid cells exhibiting losses (15% of cells). Losses from FCL were computed as FCL area × carbon (See supplementary materials). Losses from D/D were calculated as the loss of carbon in excess of the loss attributable to FCL. Our analysis reveals that degradation and disturbance account for 70, 81, and 46% of carbon losses, respectively, across tropical America, Africa, and Asia. For the tropics as a whole, D/D accounts for ~69% of total

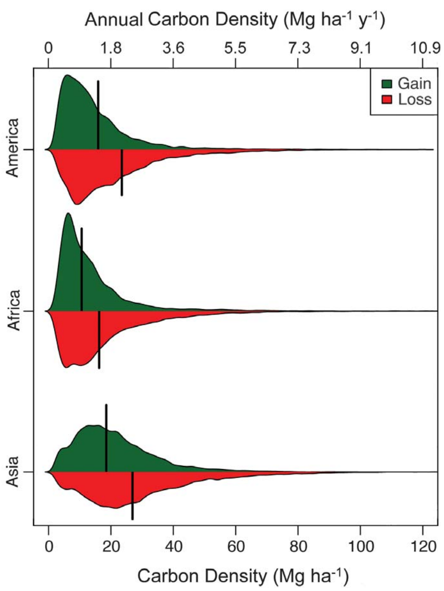

Fig. 2. Frequency distributions based on pixel counts of net carbon density gains and losses from 2003 to 2014 for tropical America, Africa, and Asia. Mean values of gain and loss are indicated with vertical black bars.

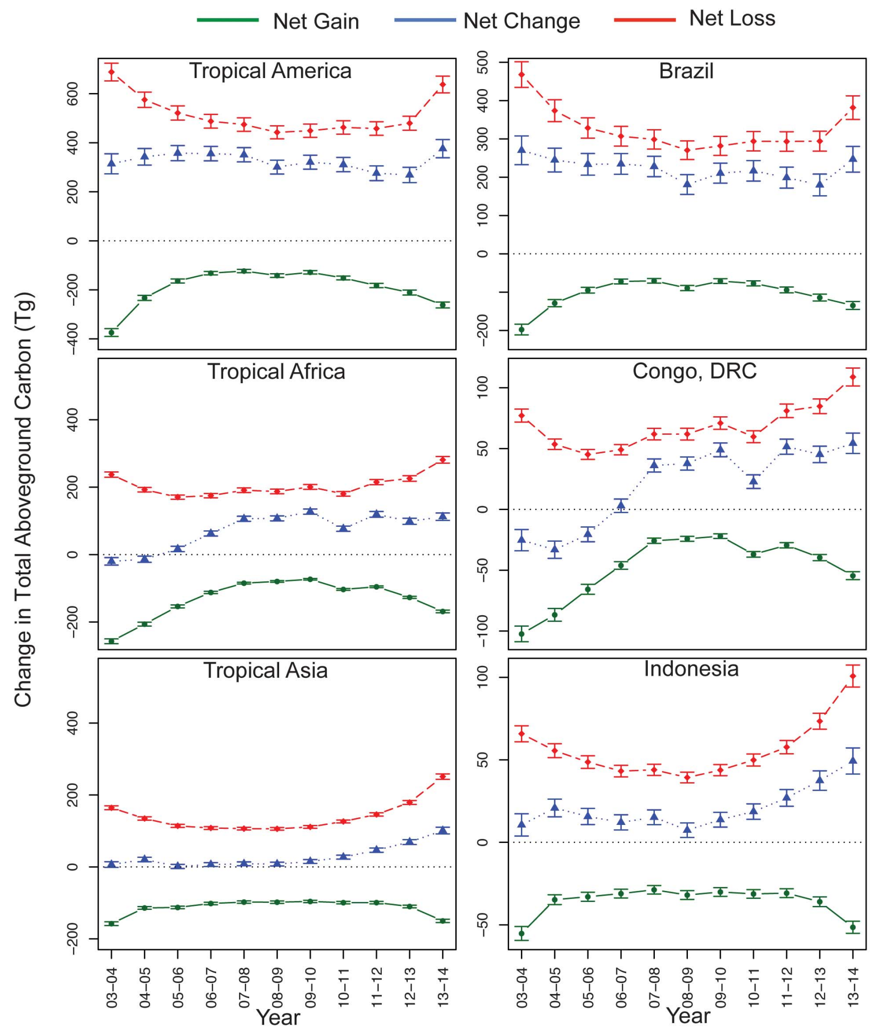

Fig. 3. Annual net change (95% confidence interval) in total carbon. Red lines indicate a loss in carbon; green lines indicate a gain. Blue lines reflect the difference between losses and gains. The vertical bars indicate the standard error of the change value. Trajectory plots are derived from data contained in table S1.

carbon losses. Although this percentage is higher than previous estimates (*22*, *23*), D/D are scale-dependent phenomena that can only be measured and interpreted relative to the resolution of the sample grid (i.e., 21.4 ha in this study; fig. S7).

The average net loss in aboveground carbon (425.2 ± 92.0 Tg C year^{-1}) reported here for tropical woody vegetation results from an approach designed to provide a complete accounting of aboveground sources and sinks, considering both natural and anthropogenic processes (Table 1), attributes that complicate like-for-like comparisons with most previous estimates (*1*, *2*, *7*, *25*). For example, the net loss is not an estimate of the emissions only from land-use and land-cover change (LULCC) (*1*, *2*, *3*, *25*) as it includes losses and gains of carbon from processes other than LULCC; that is, the effects of CO_2 fertilization, N deposition, climate change, windthrow, drought, and fires. The observed gain is also not directly comparable to the estimates of gain observed in intact forests (*5*, *41*), because it includes the effects of management, disturbance, (including degradation), and recovery. Nevertheless, our results are most directly comparable with those of Pan *et al.* (*7*) (Table 1), who estimated a net source of 80 Tg C year^{-1} based on the difference between emissions from LULCC (*1*, *3*) and accumulations in intact forests (*5*, *28*, *41*). Although the net source of Pan *et al.* (*7*) is an order of magnitude less than that reported in this study (425 Tg C year^{-1}), their results are strongly influenced by the indirect estimation and assignment of land area to the categories of intact, degraded, and managed forest. Our estimates, which result from direct measurements at the pixel level, are independent of ancillary data on forest area change and indicate that losses, particularly those associated with small but widespread natural and anthropogenic disturbances, are occurring in what was otherwise thought to be intact forest where previous practitioners considered only gains. Like Pan *et al.* (*7*), Achard *et al.* (*25*) also report a net source for the tropics; however, their estimate of 783 Tg C year^{-1} is higher than ours as their analysis considers only gains from regrowing forest (i.e., nonforest being converted to forest).

Most previous emissions estimates are limited to gross changes in forest cover, excluding losses from degradation and disturbance. Carbon loss in this analysis (861.7 Tg C year^{-1}) is larger than that estimated by Harris *et al.* (*2*); (810 Tg C year^{-1}). Although this difference is expected given our inclusion of losses from degradation, our estimate is admittedly conservative as a result of the moderate spatial resolution, which allows losses to offset gains at the pixel level. Our net estimate (425 Tg C year^{-1}), however, is not influenced by the resolution, and is indeed higher than, for example, Pan *et al.* (*7*) (80 Tg C year^{-1}). Carbon loss in this study is also somewhat larger than that estimated by Baccini *et al.* (*1*), who did account for emissions from LULCC, but does not include natural losses due to windthrow, wildfire, drought, and so forth. Although carbon loss in this analysis is smaller than that reported by Tyukavina *et al.* (*13*), their area of study extends well beyond the geographic tropics to include all of Mexico and parts of China.

Our finding that the tropics are a net source (0.425 Pg C year^{-1}) is counter to estimates of a net sink (1.4 Pg C year^{-1}) based on inverse analyses of atmospheric CO_2 (*8*, *42*), although the estimates are not strictly comparable. One important difference is that our approach does not consider herbaceous or nonwoody vegetation, nor does it consider soil carbon. Although year-to-year changes in leaf and grassland cover might account for short-term variations in atmospheric CO_2 increase, longer-term trends in carbon storage are unlikely to be attributable to deciduous,

Table 1. Changes in aboveground carbon storage (Tg C $year^{-1}$) in the world's tropical forests. Regional results from this study are included in columns 2 to 4; national-level results are reported in table S1 of the supplementary materials. The study area extent differs among all the studies referenced, with this study being the smallest (i.e., limited to the pantropical belt).

	Baccini *et al.* 2017—this study			Pan *et al.* 2011			Baccini *et al.* 2012	Harris *et al.* 2012	Achard *et al.* 2014			Tyukavina *et al.* 2015
	(2003–2014)			(2000–2007)			(2000–2010)	(2000–2005)	(2000–2010)			(2002–2012)
Region	**Loss**	**Gain**	**Net**	**Loss**	**Gain**	**Net**	**Loss**	**Loss**	**Loss**	**Gain**	**Net**	**Loss**
				(Gross)	(Gross)		(Gross)	(Gross; excludes degradation and disturbance)	(Gross; excludes degradation and disturbance)	(Regrowth only)		(Gross; excludes degradation and disturbance)
America	516.0 ±69.5	191.2±18.2	324.8±73.5	–	–	–	470 (560)*	440	464.8	62.4	402.4	442
Africa	205.0±24.7	132.9±19.3	72.1±32.9	–	–	–	230 (270)*	110	147.7	6.8	140.9	234
Asia	140.7±17.9	112.4±10.3	28.2±21.5	–	–	–	110 (130)*	260	267.1	27.5	239.6	346
Totals	861.7±80.2	436.5±31.0	425.2±92.0	(2820)*	2740	80	810 (960)*	810	880	97	783	1022

*Values in parentheses include losses from soils.

nonwoody tissues. Furthermore, changes in land use are unlikely to result in soil carbon storage if carbon is being lost aboveground. Another key difference between our approach and the inverse method is that the losses we observe in carbon storage do not necessarily reflect imminent atmospheric additions. Aboveground biomass may first transition to other carbon pools or be removed from the forest without release to the atmosphere, e.g., stored as wood products, which constitute 4 to 14% of losses. Although accounting for nonwoody tissues, soil carbon, and differences in the timing of emissions may well increase the interannual variability of emissions, it is unlikely to affect the trends reported here.

The results of this research also could be of operational value to land managers and policymakers as they facilitate annual monitoring of tropical forest carbon dynamics across the entire spectrum of change from wholesale removal to incremental growth with quantified uncertainty (fig. S6). With proper attribution of natural (disturbance) and anthropogenic (degradation) losses, the research has the potential to inform decision-making by governments across the tropics as well as affected stakeholders, including indigenous peoples and forest-dwelling communities, on how best to meet their emissions reductions targets under the Paris Agreement. More broadly, the approach provides for a consistent, synthetic, and independent global benchmark to which the international scientific and policy community can refer. Our observation that tropical forests are a net carbon source emphasizes the potential role of forests in stabilizing the concentration of CO_2 in the atmosphere. Ending tropical deforestation and forest degradation would reduce emissions by at least 862 Tg C $year^{-1}$, thus providing a bridge to a low–fossil fuel future (*43*).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/358/6360/230/suppl/DC1
Materials and Methods
Supplementary Text
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Tropical forests are a net carbon source based on aboveground measurements of gain and loss

A. Baccini, W. Walker, L. Carvalho, M. Farina, D. Sulla-Menashe and R. A. Houghton

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Forests out of balance

Are tropical forests a net source or net sink of atmospheric carbon dioxide? As fundamental a question as that is, there still is no agreement about the answer, with different studies suggesting that it is anything from a sizable sink to a modest source. Baccini *et al.* used 12 years of MODIS satellite data to determine how the aboveground carbon density of woody, live vegetation has changed throughout the entire tropics on an annual basis. They find that the tropics are a net carbon source, with losses owing to deforestation and reductions in carbon density within standing forests being double that of gains resulting from forest growth.

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