Supplementary Information for

Doubling of annual forest carbon loss over the tropics during the early 21st century

Yu Feng[1,2], Zhenzhong Zeng[1*], Timothy D. Searchinger[3,4], Alan D. Ziegler[5], Jie Wu[1,6], Dashan Wang[1], Xinyue He[1,7], Paul R. Elsen[8], Philippe Ciais[9], Rongrong Xu[1], Zhilin Guo[1], Liqing Peng[4], Yiheng Tao[10], Dominick V. Spracklen[7], Joseph Holden[11], Xiaoping Liu[12], Yi Zheng[1], Peng Xu[1], Ji Chen[2*], Xin Jiang[1], Xiao-Peng Song[13], Venkataraman Lakshmi[14], Eric F. Wood[10], Chunmiao Zheng[1*]

[1] State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China
[2] Department of Civil Engineering, The University of Hong Kong, Hong Kong, China
[3] Woodrow Wilson School, Princeton University, Princeton, NJ, USA
[4] World Resources Institute, Washington, DC, USA
[5] Faculty of Fisheries Technology and Aquatic Resources, Mae Jo University, Chiang Mai, Thailand
[6] Department of Geoscience and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark
[7] School of Earth and Environment, University of Leeds, Leeds, UK
[8] Wildlife Conservation Society, Global Conservation Program, Bronx, NY, USA
[9] Laboratoire des Sciences du Climat et de l'Environnement, UMR 1572 CEA-CNRS-UVSQ, Gif-sur-Yvette, France
[10] Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA
[11] School of Geography, University of Leeds, Leeds, UK
[12] School of Geography and Planning, Sun Yat-Sen University, Guangzhou, China
[13] Department of Geosciences, Texas Tech University, Lubbock, TX, USA
[14] Department of Engineering Systems and Environment, University of Virginia, Charlottesville, VA, USA
*Correspondence to: zengzz@sustech.edu.cn (Z. Zeng), zhengcm@sustech.edu.cn (C. Zheng), and jichen@hku.hk (J. Chen)

Manuscript for *Nature Sustainability*

Contents of this file

Tables S1 to S3

Figures S1 to S7

Table S1. Estimates of gross aboveground carbon loss (Pg C yr^{-1}) from tropical forest removal by several studies. The area extent of the tropics varies in these studies, with the largest study region included in Tyukavina *et al.*[1]. The area extents of our study (between 23.5°N and 23.5°S but excluding Australia) and Baccini *et al.*[2,3] are similar and the smallest among the referenced studies. All the studies exclude tropical Australia. The table is an update examining aboveground carbon loss from tropical forest conversion by Baccini *et al.*[3]. The aboveground values in this study are estimated using a stratified random sample approach from the four biomass maps (mean±s.d.).

Study period	By other studies		By this study for the same years
	Carbon loss	Sources	
2000–2005	0.81	Harris *et al.*, 2012 (ref.4)	0.70±0.12
2000–2010	0.81	Baccini *et al.*, 2012 (ref. 3)	0.77±0.12
2000–2010	0.88	Achard *et al.*, 2014 (ref. 5)	0.77±0.12
2000–2012	1.02	Tyukavina *et al.*, 2015 (ref. 1)	0.82±0.12
2001–2013	0.62	Zarin *et al.*, 2016 (ref. 6)	0.84±0.11
2003–2014	0.86	Baccini *et al.*, 2017 (ref. 3)	0.88±0.11

Table S2. Error matrix expressed as the proportion of area for different time periods.

	Period	Reference			
		Strata	Loss	No Loss	Total
Map	2001–2005	Loss	0.00544	0.00081	0.00625
		No Loss	0.00193	0.99182	0.99375
		Total	0.00737	0.99263	1
	2006–2010	Loss	0.00653	0.00087	0.00740
		No Loss	0.00203	0.99057	0.99260
		Total	0.00856	0.99144	1
	2011–2014	Loss	0.00642	0.00082	0.00724
		No Loss	0.00244	0.99032	0.99276
		Total	0.00886	0.99114	1
	2015–2019	Loss	0.01103	0.00131	0.01234
		No Loss	0.00323	0.98443	0.98766
		Total	0.01426	0.98574	1

Table S3. Mean relative changes in soil organic carbon (SOC) stocks at 0–30 cm soil depth for forest conversion to different land uses. SOC loss data resulting from forest (primary and secondary) loss to cropland (small-scale agriculture) and forest (forestry) are compiled from Fig. 2 in Don *et al.*[7]. The commodity-driven deforestation is usually a form of (large-scale) agriculture-driven deforestation, for example, row crop agriculture and cattle grazing in tropical America, and oil palm plantation in SEA. Thus, we consider that land uses following commodity-driven deforestation are overall mixed cropland (~20%), grassland (~11%), and forest (e.g., oil palm; ~9%), and the loss rate of SOC is assigned to be 15%, between minimum loss of 9% and maximum loss of 20%. Rates of SOC loss resulting from forest loss to other land uses (urbanization and wildfire, accounting for very small proportion of forest loss) are not available, so we simply assume the SOC loss rate to be 5% in this case. Negative values indicate loss of carbon from soil to atmosphere.

Land-use change type (Primary forest loss due to)	SOC loss (%)	Land-use change type (Secondary forest loss due to)	SOC loss (%)
Large-scale agriculture	-15.0	Large-scale agriculture	-15.0
Small-scale agriculture	-19.3	Small-scale agriculture	-21.3
Forestry	-8.8	Forestry	-8.8
Others	-5.0	Others	-5.0

Figure S1. Forest carbon stocks (including aboveground and belowground, excluding soil organic carbon) across the tropics and for three tropical continents. Bars and error bars represent the mean and s.d. estimated from four biomass maps (i.e., Baccini *et al.*[2], Saatchi *et al.*[8], Avitabile *et al.*[9], and Zarin *et al.*[6]), respectively. Lands within the mountain polygon defined by GMBA inventory data are classified as mountains and the remaining lands are classified as lowlands. 1 Mg C equals 10^{-6} Pg C.

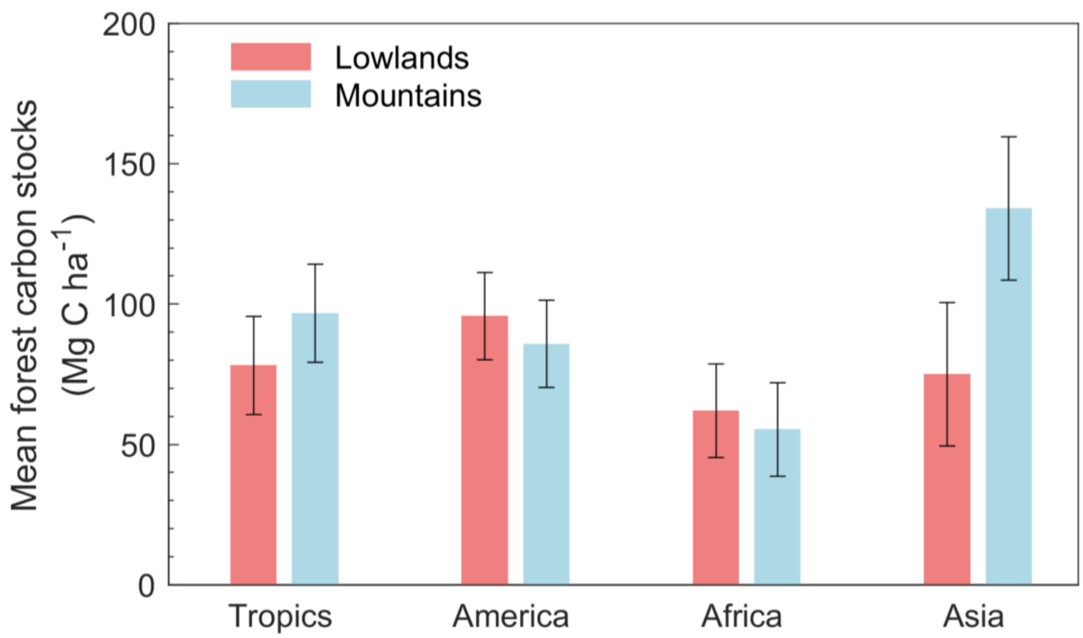


Figure S2. Time-series of gross carbon loss resulting from forest loss over the three tropical continents during 2001–2019. a, Total gross carbon loss, including aboveground, belowground, and soil carbon loss. **b**, Aboveground carbon loss. **c**, belowground carbon loss. **d**, Soil organic carbon loss. Shade area represents the s.d. estimated by four carbon density maps.

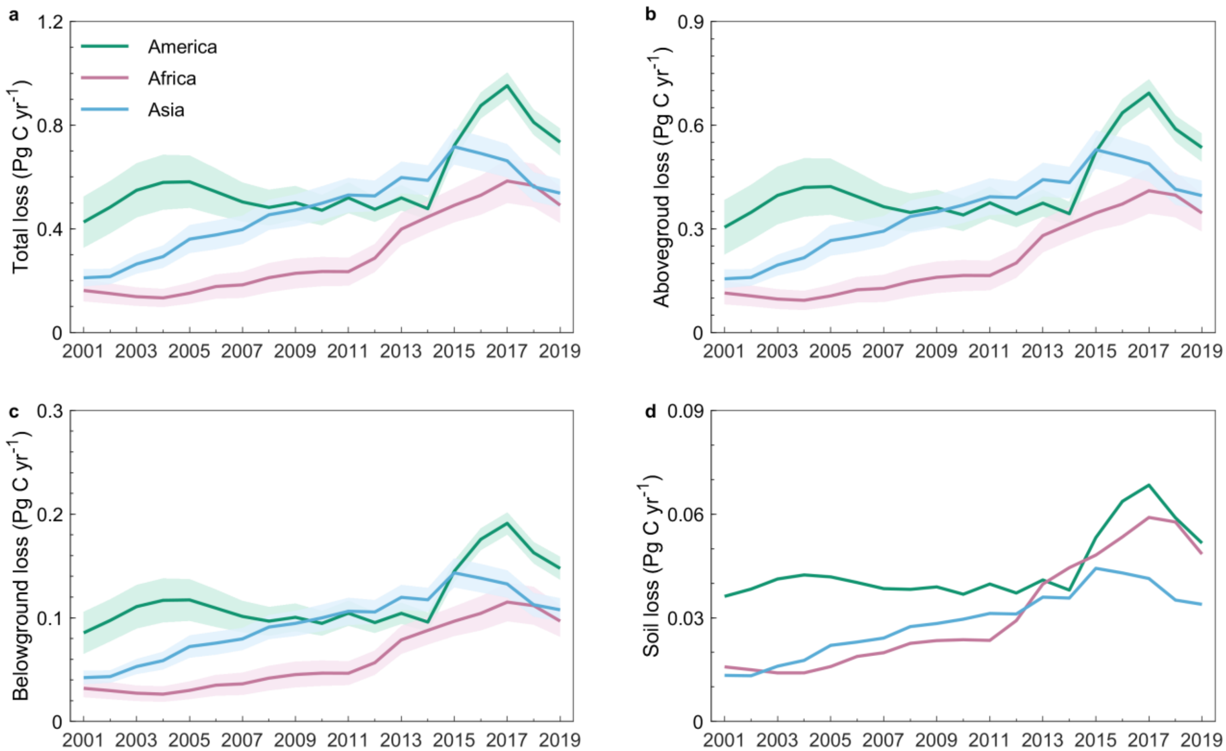


Figure S3. Spatial mapping of gross forest carbon loss (including aboveground, belowground, and soil carbon loss) over Brazil and the Democratic Republic of the Congo. a–b, Mean annual carbon loss during the period 2001–2015 (**a**) and 2016–2017 (**b**) in Brazil. **c**, Changes in mean annual carbon loss during 2016–2017 relative to the period 2001–2015 in Brazil. Grey lines are biome boundaries for Amazonia, Cerrado, Caatinga, Mata Atlântica, Pantanal and Pampa. Blue lines indicate major rivers over Amazonia. **d–e**, Mean annual carbon loss during the period 2001–2005 (**d**) and 2015–2019 (**e**) in the Democratic Republic of the Congo. **f**, Changes in mean annual carbon loss during 2015–2019 relative to the period 2001–2005 in the Democratic Republic of the Congo. Grey lines are country boundaries. Blue lines indicate major rivers over the Democratic Republic of the Congo. 1 Mg C equals 10^{-6} Pg C. The biome maps of Brazil were downloaded from the Global Forest Watch (https://data.globalforestwatch.org/). The country maps were downloaded from GADM website (https://gadm.org/).

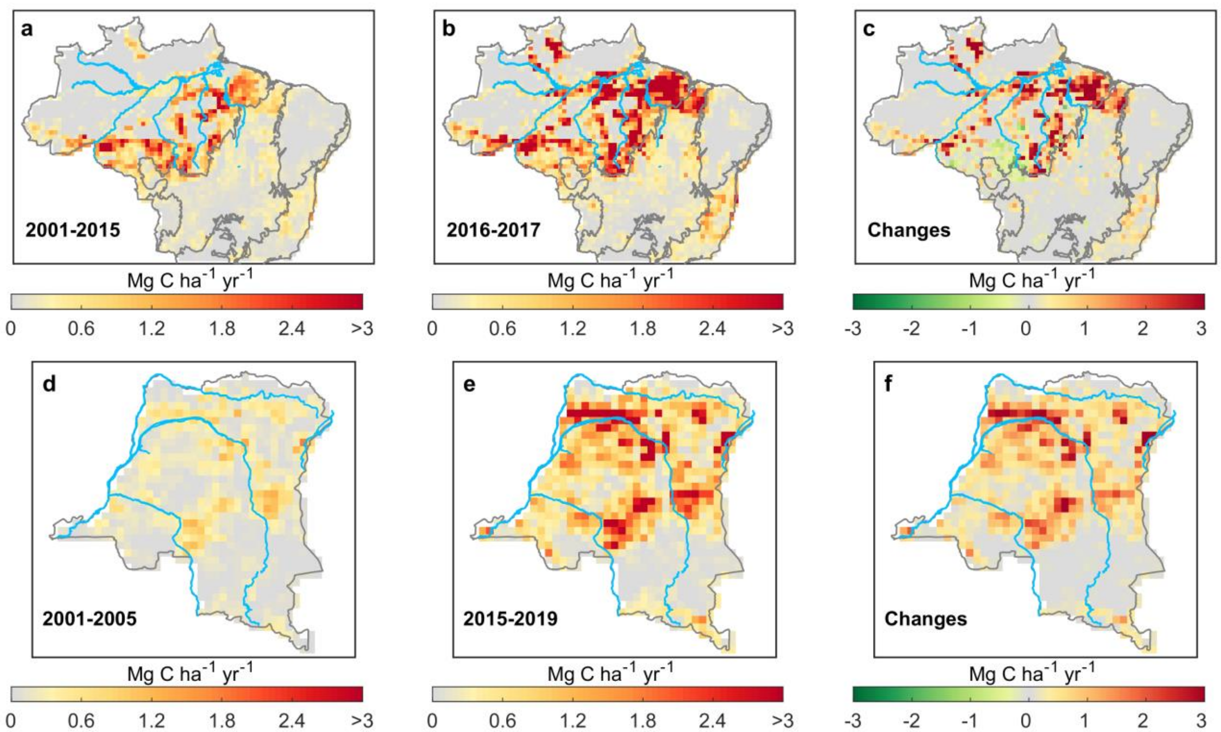


Figure S4. Land-cover information in 2020 in 1000 randomly-sampled pixels where forest was lost for agriculture in 2001–2005 and 2015–2019 across the tropics and three tropical continents. (**a**) Spatial distribution of the randomly-sampled pixels where forest was lost for agriculture in 2001–2005 (hollow points) and 2015–2019 (filled points). (**b**) Percentage of land-cover in 2020 in pixels with forest loss. The land-cover information in 2020 is visually interpreted from very-high-resolution satellite imagery from Planet.

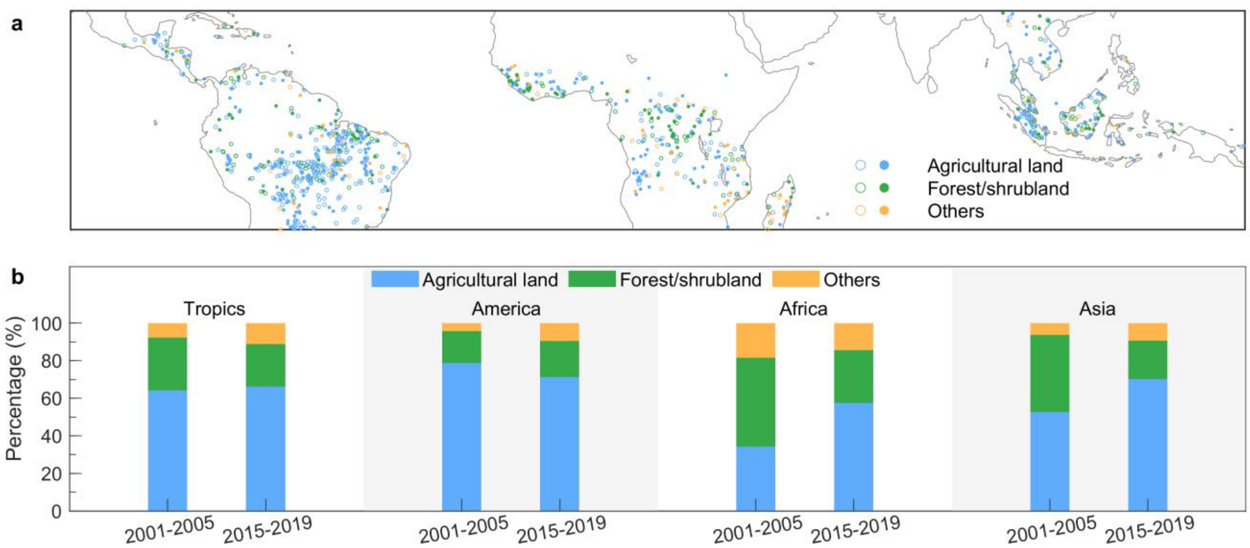


Figure S5. Time-series of gross forest carbon loss from different drivers over the three tropical continents during 2001–2019. Shade area represents the s.d. estimated by four carbon density maps.

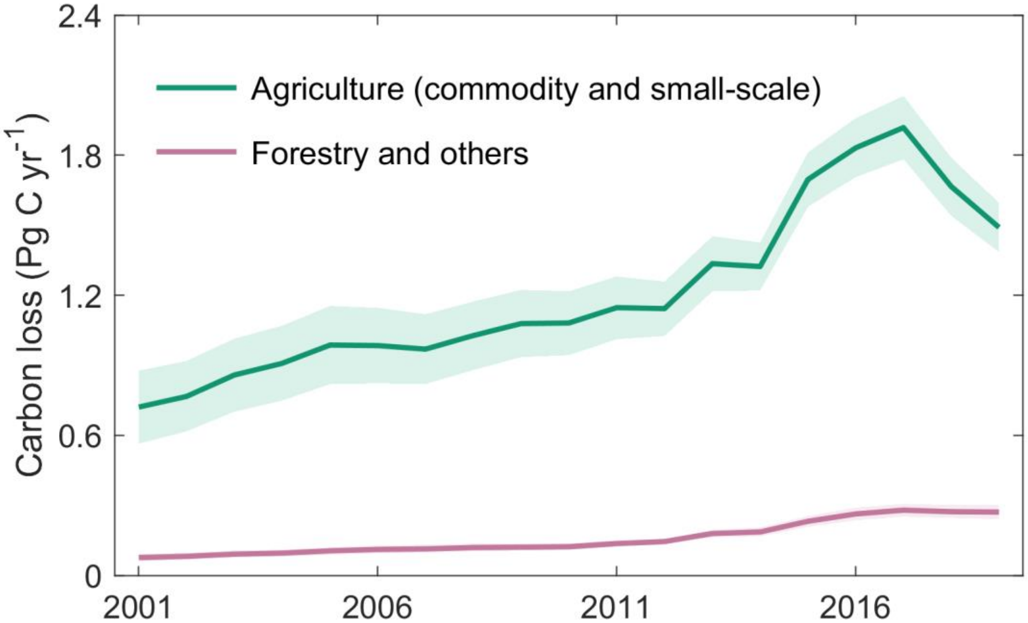


Figure S6. Selected Landsat path/row locations for visual interpretation of Global Forest Change data. We randomly sample 50 path/row locations in each tropical continent, with 150 path/row locations in total.

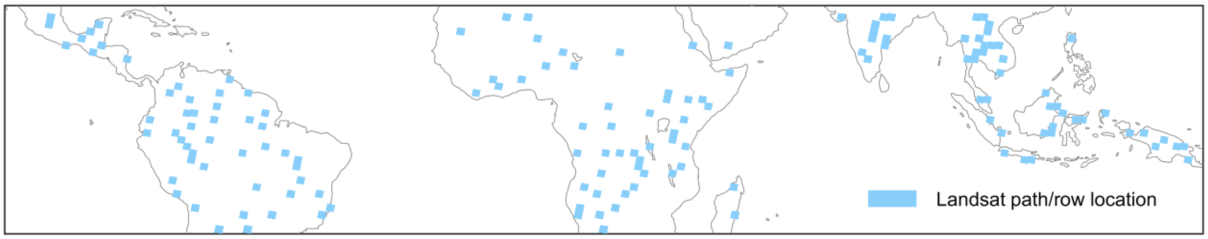
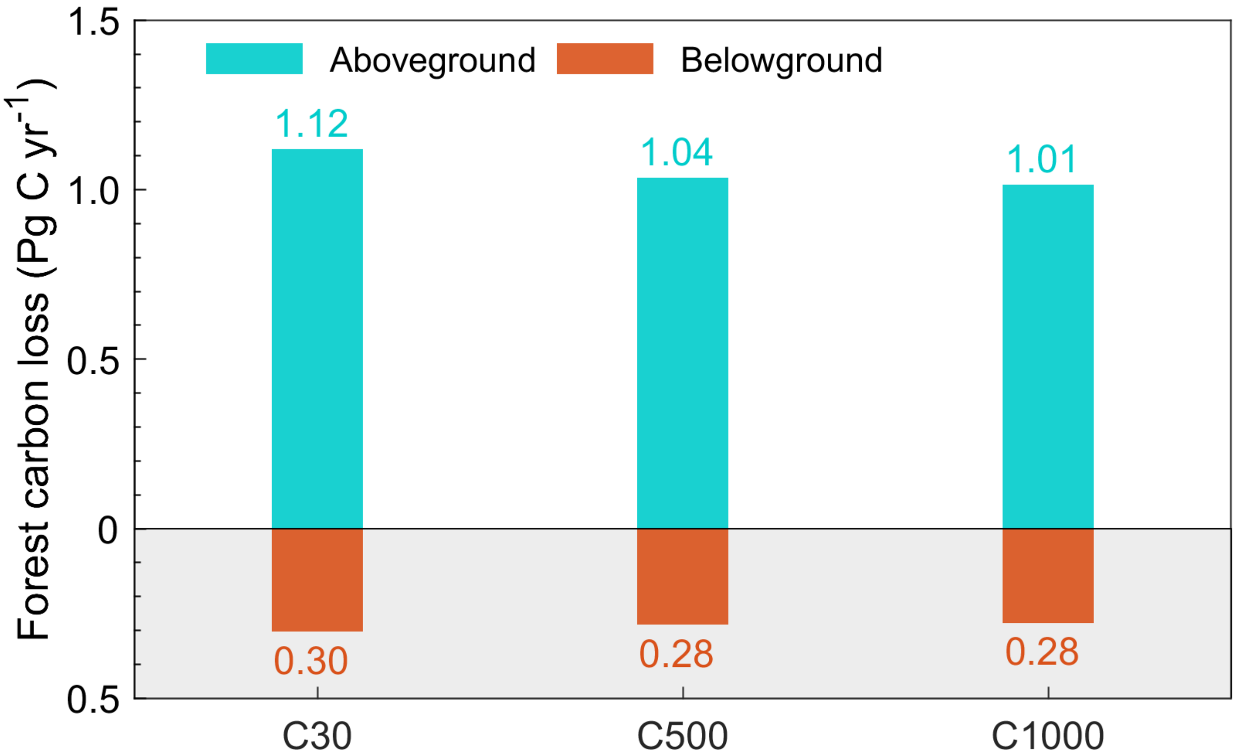


Figure S7. Resolution effects on the estimates of forest carbon loss across the tropics. C30 denotes forest (aboveground and belowground) carbon loss estimated from Zarin biomass map[6] (30 m spatial resolution); C500 and C1000 denote forest (aboveground and belowground) carbon loss estimated from resampled Zarin biomass map at 500 m and 1 km spatial resolution, respectively (see Methods).



References

1. Tyukavina, A. *et al.* Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environ. Res. Lett*. **10**, 074002 (2015).
2. Baccini, A. *et al.* Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Chang*. **2**, 182–185 (2012).
3. Baccini, A. *et al.* Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science* **358**, 230–234 (2017).
4. Harris, N. L. *et al.* Baseline Map of carbon emissions from deforestation in tropical regions. *Science* **336**, 1573–1576 (2012).
5. Achard, F. *et al.* Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. *Glob. Chang. Biol*. **20**, 2540–2554 (2014).
6. Zarin, D. J. *et al.* Can carbon emissions from tropical deforestation drop by 50% in 5 years? *Glob. Chang. Biol*. **22**, 1336–1347 (2016).
7. Don, A., Schumacher, J. & Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks–a meta-analysis. *Glob. Chang. Biol*. **17**, 1658-1670 (2011).
8. Saatchi, S. S. *et al.* Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl Acad. Sci. USA* **108**, 9899–9904 (2011).
9. Avitabile, V. *et al.* An integrated pan-tropical biomass map using multiple reference datasets. *Glob. Chang. Biol.* **22**, 1406–1420 (2016).