western Pacific[7]. The deepened thermocline in the western Pacific contributed to the record-setting super-typhoon Haiyan that devastated the Philippines in 2013[8].

As well as identifying the tropical Pacific cooling pattern, Meehl *et al.*[3] also pioneered an energy-based characterization of the hiatus. In their model, the net radiative imbalance that heats the planet shows little difference between hiatus and reference periods. As the surface layer of the ocean is not heating up, the deep layer beneath must take up more heat during a hiatus compared with reference periods. In search of this extra heat in the subsurface ocean, a growing body of literature has developed[5,9–11]. Upper-ocean adjustments in the tropical Indo-Pacific fit both the energy change and tropical Pacific SST patterns. The intensified equatorial trades during the hiatus steepen the east–west tilt of the thermocline[5] — the boundary between the warmer surface waters and the cooler deeper water — thereby increasing the warm water transport into the Indian Ocean via the Indonesian Throughflow[10–11] (Fig. 1b). The deepened thermocline in the western Indo-Pacific and the shallower one in the east create an apparent vertical dipole of temperature anomalies in the east–west mean, as is required by the energy view.

The concept of planetary energy budget is fundamental for understanding global warming. As the planet warms, it radiates more energy into space. The rate of the energy loss per degree GMST increase (namely climate feedback) determines the magnitude of temperature response to a change in radiative forcing. Existing theory predicts that the negative swing of internal variability would accelerate planetary energy uptake during the hiatus, but in observations, the global energy uptake has remained nearly constant since 2000[12]. This contradiction forced a re-evaluation of planetary energy budget theories. Climate feedback, as it turns out, differs between anthropogenic warming and internal cooling[13], and the difference is such that planetary energy uptake actually decreases during the surface warming hiatus. This conceptual shift has important implications for studying ocean heat uptake.

The hiatus spurred great interest in planetary energy uptake and redistribution in the ocean. A rigorous test of energy theory requires sustained global observations of planetary energy budget and ocean measurements beyond a depth of 2,000 m. A challenge is to reconcile ocean heat redistribution and the regional sea surface temperature modes that cause hiatus events. From the growing body of hiatus research, tropical Pacific decadal variability has emerged as an important pacemaker of global climate, but its mechanism remains to be elucidated. In the central equatorial Pacific, the surface cooling during the hiatus rides above a subsurface warming (Fig. 1b, at 100–250 m depth), highlighting the importance of ocean dynamics.

Much as weather forecasting improved over time through daily verification, the early-2000s hiatus provides a valuable case study to test our observations, understanding and models of the climate system. Climate models have withstood the test and scrutiny of the surge of research following the Meehl *et al.* study[3]. The La Niña-like pattern of tropical Pacific cooling not only proved to be a major driver for the early-2000s hiatus, but also explained regional anomalies — from the western Pacific sea level rise to California droughts. The need to track decadal changes in heat uptake provides a new impetus and raises the bar for ocean observations.

The early-2000s hiatus showed that we live in a special time in Earth's history, when anthropogenic warming and internal variability contribute equally to GMST change on timescales of a decade and longer. By exploiting the predictability from both initial conditions and radiative forcing, decadal prediction holds the promise of forecasting when the hiatus will end[14]. Stepping back in time, the first successful seasonal prediction of El Niño was made 30 years ago, using only a simple model of minimum essential physics[15]. It is clear that, to predict, we must first understand. ❐

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FOREST CARBON FLUXES

A satellite perspective

Reducing deforestation and forest degradation offers a quick win for climate mitigation. Using satellite data we are now able to better constrain pantropical estimates of forest loss, reshaping our understanding of the annual to decadal variability in land sources and sinks in the global carbon cycle.

Douglas C. Morton

Smoke plumes billowed from Borneo and Brazil in 2015, brought on by El Niño conditions that allowed fires to burn through tropical forests and peatlands. The damage from these fires, as measured by greenhouse gas emissions, depends on the amount of carbon stored in these tropical forest ecosystems. Writing in *Nature Climate Change* in 2012, Baccini *et al.*[1] used NASA satellite data to map tropical forest carbon stocks. Those data formed the foundation of a revised estimate of the net carbon fluxes from tropical forests, helping to shape the policy efforts to Reduce Emissions from Deforestation and Forest Degradation (REDD+), a core component of the Paris Agreement[2].

Using satellite data to estimate carbon stocks, rates of forest loss and degradation — and the fate of forest carbon following conversion — would provide the most transparent synthesis of carbon emissions from land-use change. The hybrid approach used by Baccini *et al.*[1] to combine satellite and survey data was an important milestone on the path towards constraining pantropical carbon emissions using satellite data alone. Moving beyond bookkeeping models[1,3,4] requires regular satellite data products on the carbon stocks in tropical forests[1,5,6] and the rates of forest loss[7,8]. New efforts to track the spatial and temporal variability in combustion completeness[9,10] and land abandonment to secondary forest (factors that together govern net carbon emissions from tropical forests)[4,10,11] are also needed. Many of these new satellite products can be obtained from Landsat data. Free and open access to the Landsat archive has already spurred scientific innovation and provided a foundation for REDD+ monitoring, reporting and verification. With 32 years' worth of data — and ongoing data collection — the Landsat data record (satellites 5, 7 and 8) captures the decadal and interannual variability in forest losses and gains needed to drive global carbon cycle models.

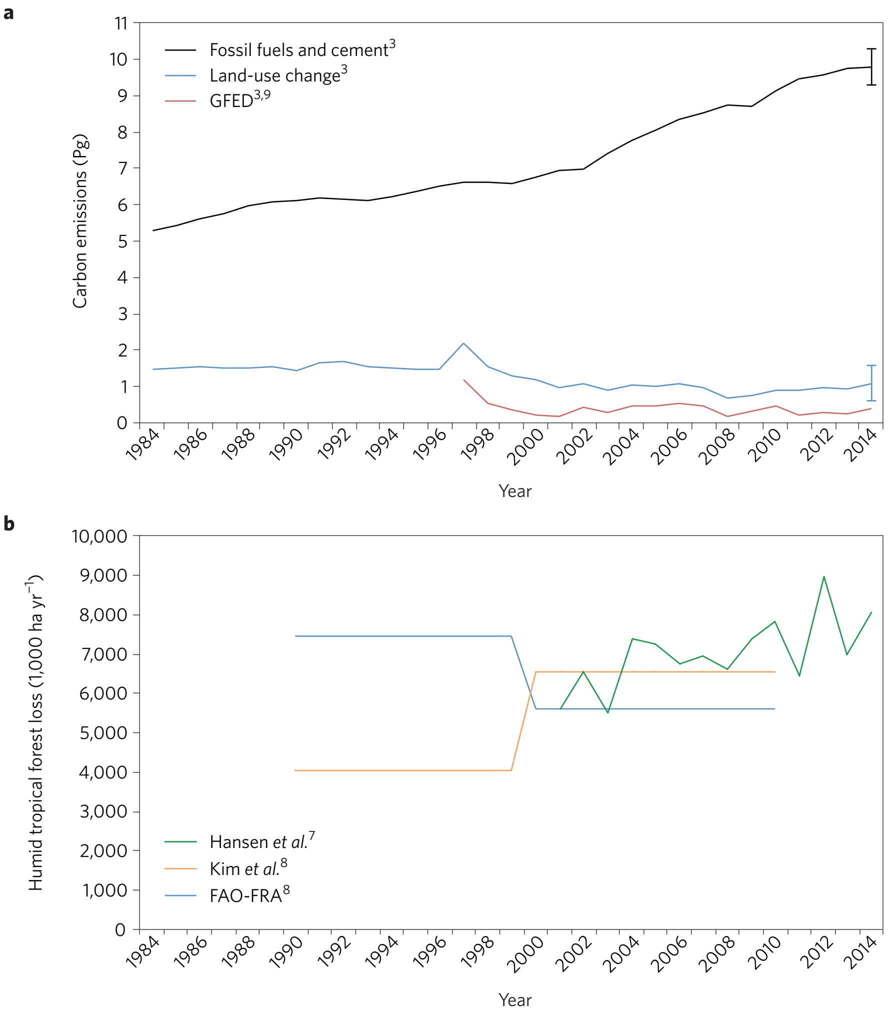

Figure 1 | Carbon emissions from human activity — including tropical deforestation — since the launch of Landsat 5 in 1984. **a**, Estimated carbon emissions from fossil fuels, land-use change, and fires[3]. Error bars indicate uncertainty in emissions estimates for 2014[3]. Land-use change emissions from 2011–2014 are preliminary estimates using the Global Fire Emissions Database (GFED) (red line)[9] to scale historic deforestation rates. **b**, Landsat data on humid tropical forest losses (34 countries)[8] contradict the decadal patterns in the survey data from the Food and Agriculture Organization (FAO) Global Forest Resources Assessment (FRA) used to estimate land-use carbon emissions (blue line in **a**).

The decadal differences between satellite and survey estimates of humid forest loss fundamentally alter our understanding of the land carbon sink from historic deforestation activity (Fig. 1). Wall-to-wall Landsat data show a clear increase in humid tropical forest loss between the 1990s and 2000s[8], contradicting the national survey data that are now used to model the global carbon cycle[3]. Lower deforestation in the 1990s would decrease emissions from land use and result in a smaller tropical land sink in subsequent years because deforestation rates propagate through global models by land abandonment to secondary forest[3,4].

New analyses of tropical forest loss on an annual basis capture the spatially heterogeneous, rapid responses of forest frontiers to markets, policies and climate variability. Annual Landsat estimates show an increase in gross losses of humid tropical forests between 2001–2014 (Fig. 1b). Although forest losses declined in South America during this period, that trend was more than offset by increasing forest conversion in Asia and Africa[7]. Year-to-year differences also reflect climate and market impacts because forest loss estimates include deforestation and forest degradation from logging and fires. Separating deforestation from degradation is a crucial step in improving the estimates of pantropical carbon emissions; carbon losses from forest degradation may be an order of magnitude smaller than from deforestation on a per-hectare basis. At present, global models use average deforestation by decade[3,12], adjusted on the basis of year-to-year variability in global fire emissions data[3,9], and do not account for degradation. Driving carbon cycle models with annual deforestation and degradation estimates could better constrain fast-acting processes in the Earth system, including how land and ocean sinks respond to interannual variability in climate.

Since 2012, progress on mapping tropical forest carbon stocks has largely come from forest inventories[13] and airborne lidar surveys[14]. At the deforestation frontier, first-generation pantropical biomass products[1,5,6] are limited by their coarse spatial resolution[15] and outdated satellite lidar measurements (2003–2007). Field and airborne remote sensing efforts can target data needs for REDD+, including the distribution of biomass in intact and degraded forests[13,14]. Expanding REDD+ readiness efforts to consider the residual forest carbon stocks in deforested lands and the trajectories of biomass recovery in degraded forests can further constrain these components of the net carbon emissions equation.

New satellite missions in the next five years will connect the dots between field and airborne studies to characterize three gradients in pantropical forest carbon stocks. First, the broad spatial patterns of biomass in intact tropical forests remain unclear[1,5,6]. Solidifying the relationships among carbon stocks, soils, climate and disturbance patterns is critical to advance contemporary estimates of the land carbon sink and improve the projections of tropical forest responses to climate change. Second, tropical forest frontiers probably exhibit a gradient in carbon stocks from the edge to the interior[13,15]; capturing the magnitude and distance of these forest edge effects is critical to support REDD+. Third, carbon mapping missions will characterize the biomass in the agricultural systems that replace tropical forest, including the growing influence of palm oil and plantation timber. In combination with field inventories and airborne lidar, second-generation forest carbon maps using data from the Ice, Cloud and Land Elevation Satellite-2 (ICESat-2), Global Ecosystem Dynamics Investigation Lidar (GEDI) and the European Space Agency's (ESA) Biomass missions will transform our understanding of the variability in vegetation carbon stocks in tropical forests and managed landscapes.

In absolute terms, fossil fuel emissions are now tenfold higher than those from land-use change[3], and the uncertainties in both estimates are equivalent (±0.5 PgC; see Fig. 1a). Declining relative contributions from land-use change reflect the rapid growth in fossil fuel emissions and early REDD+ successes. The goal of REDD+ to further reduce emissions from humid and dry tropical forests will require a concerted pantropical effort, including actions that target the drivers of deforestation and degradation[2] alongside mitigation strategies to counterbalance the increasing climate-driven risk of fires in tropical forests. Ongoing fire activity in tropical forests, amplified by the 2015–2016 El Niño event, underscores the vulnerability of the carbon stored in tropical forests and peatlands to climate variability. ❐

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