

LETTER

Evaluating the tropical forest carbon sink

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Less than half of anthropogenic carbon emissions are accumulating in the atmosphere, due to large net fluxes into both the oceans and the land (Le Quéré *et al.*, 2012). The land sink in particular has increased markedly, doubling in strength since the 1960s, to reach 26 petagrams of carbon in the latest decade. However, the location and drivers of this large terrestrial sink are still relatively poorly constrained by atmospheric measurements (Ciais *et al.*, 2013). Pan *et al.* (2011) recently utilized >1 million forest inventory plots to provide summaries of forest carbon stocks, and the first global bottom-up estimates of carbon fluxes for the world's forest biomes for the period 1990–2007. One key result was that almost all the residual global terrestrial carbon sink (i.e. carbon uptake after accounting for land-use change), some 2.4 ± 0.4 Pg of carbon per year, is located in the world's established forests (Pan *et al.*, 2011). The sink is distributed worldwide, with globally significant net fluxes into boreal and temperate forests, and a large sink in intact tropical forest, albeit with large uncertainty. Furthermore, Pan *et al.* (2011) showed that this tropical intact forest sink may have faded from an estimated annual 1.3 ± 0.4 Pg C in the 1990s to 1.0 ± 0.5 Pg C for 2000–2007. The tropical intact forest sink is offset by a net land-use emission [1.5 Pg C yr⁻¹ (1990–1999)] declining to [1.1 Pg C yr⁻¹ (2000–2007)], and as a consequence aircraft measurements and inverse modelling studies indicate the tropics to be close to neutral in terms of net carbon fluxes (reviewed by Ciais *et al.*, 2013). While the intact tropical forest sink values represent updates from similar values published previously (e.g. Lewis *et al.*, 2009), the fact that almost the entire residual terrestrial carbon sink is accounted for by the forests of the world was a notable discovery. Evidence from the ground now points to established forests being a net sink across almost every major forest region, including all extra-tropical forest regions analysed.

In a recent letter to this journal, Wright (2013) contested only the report of a sink in intact tropical forests.

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In so doing, he focused on only one aspect of the paper, ignoring the global result from Pan *et al.* (2011). Wright made three specific claims. Firstly, that the reported tropical forest sink is too large because of our definition of 'tropical forest'. Secondly, that we ignored vital data in our analyses. Finally, he devotes most space to arguing that carbon dioxide fertilization cannot be substantially responsible for the global forest sink. We briefly address each in turn.

Forest area and biomass

Wright argues that by using a globally consistent forest definition that includes more open forests (FAO, 2010), we overestimate the carbon sink. Pan *et al.* (2011) is a global-scale report, so we use the widely used global definition. Furthermore, there is no generally accepted single definition of tropical forest (see Torello-Raventos *et al.*, 2013). We agree the network of forest monitoring plots used in the analysis is certainly biased away from more open forests. The key question is therefore: will applying mean rates of increase in carbon storage from more closed forest to more open forest overestimate the total sink? Wright considers this to be the case, explaining that the 'changes in carbon stocks are potentially much larger in tall, closed canopy forests than those in stunted, open forests.' This is not necessarily so. There are numerous reports of significant closed forest advance and large biomass gains at the dry margins of forests in regions not captured by our networks [e.g., Bowman *et al.*, 2010 (Australia); Mitchard *et al.*, 2009 (central Africa); Buitenwerf *et al.*, 2012 (southern Africa)]. More fundamentally, if carbon dioxide is a driver of the increases in biomass then drier forests may well show greater sensitivity as they are more water limited and carbon dioxide increases water use efficiency (e.g., Keenan *et al.*, 2013).

How much is the undersampling of dry forests likely to matter for the total value of the pan-tropical intact forest sink? An alternative method that adopts a much more conservative assumption about dry-margin forest biomass increases (Malhi, 2010) produced a similar intact tropical forest sink estimate to ours, within our stated uncertainty in Pan *et al.* (2011). And like ours, Malhi's estimate ignores the well-documented

thickening and woody encroachment into savannas, and assumes zero net sink in tropical soils – in spite of the forest productivity increases. In sum, while the plot networks are of course not a stratified-random sample of all of today's undisturbed tropical forest, and therefore there is uncertainty as to the magnitude of the increase in carbon storage in more open intact tropical forests, there are clearly modest potential biases in both directions.

Datasets

We used 215 plots from across Amazonia and Africa to estimate the intact tropical forest carbon sink. Wright claims that our 'omission' of 12 forest plots from another inventory network reported by Chave *et al.* (2008) caused us to overestimate the carbon sink. Certainly data from other networks are valuable and alternative analyses possible. However, Wright may have misunderstood both the rationale of the analysis and the exact plots utilized. Thus, ours was a continental-scale analysis (rather than aimed at a single pan-tropical mean value as in Lewis *et al.*, 2009; which did include all the Chave *et al.* plots). Furthermore, in the Pan *et al.* paper the four African plots from Chave *et al.* (2008) were in fact all included. For the tropical Americas we already had 136 standardized plots from an Amazon-wide analysis based on tree-by-tree data (Phillips *et al.*, 2009), but lacked access to the additional tree-by-tree data analysed in Chave *et al.* (2008). Including those plots would have reduced the tropical American sink estimate by ~3%. Finally, for Southeast Asian forests we concluded that the six published plots in Chave *et al.* (2008) were insufficient to draw robust regional-scale conclusions. We therefore applied the mean rate of carbon storage increase measured from across Africa and Amazonia. This limitation was clearly stated ('we lack sufficient data in Southeast Asia to make robust estimates'). If tropical Asian forests turn out to have been behaving differently from other tropical forests it would be very interesting for ecologists to know why. However, it matters little for the global carbon balance: heavily deforested and fragmented, Asia only represents 9% of total intact tropical forest area. In Pan *et al.* they contributed 0.1 Pg C yr⁻¹ to the global forest sink, well within our stated uncertainty.

Mechanisms

Finally, Wright devotes most effort to denying the plausibility of atmospheric carbon dioxide as a significant driver of the forest sink. Yet, the possibility of carbon dioxide fertilization was not broached in Pan *et al.*

(2011). The important question of mechanism(s) was largely beyond the scope of that paper and is too complex to be treated in full here too. For brevity, we here focus on two points.

First, it is the rate of increase in a forest's woody production, together with the typical woody carbon residence time, that will determine the magnitude of the sink at any given time in an old-growth forest. Thus, other things being equal, and assuming CO₂ is the driver, the magnitude of the C sink should scale with the rate of increase in atmospheric CO₂ (averaged over the relevant woody biomass residence time), and *not* its absolute value as assumed by Wright in his calculations. Using first principles (Taylor & Lloyd, 1992; Lloyd & Farquhar, 1996), when the appropriate simulations are performed using Dynamic Global Vegetation Models, then the magnitude of the modelled residual terrestrial C sink is surprisingly close to that measured on the ground. The mean tropical forest sink (net biome productivity) across nine models was 1.1 ± 0.4 Pg C yr⁻¹ from 1980 to 2009 (Piao *et al.*, 2013), indistinguishable from the 1.2 ± 0.4 Pg C yr⁻¹ from 1990 to 2007 reported in Pan *et al.* (2011). Furthermore, the response of land vegetation to carbon dioxide fertilization is considered by vegetation modellers to be greatest in tropical forests (Ciais *et al.*, 2013; fig. 6.22). Of course, there are significant uncertainties and simplifications in these models, such as the lack of accounting for phosphorus. However, when simulations are run against experiments elevating CO₂ in (temperate) forest stands, the results are similar: Piao *et al.* (2013) report a 16% increase in net primary productivity per 100 ppm CO₂ in simulations, vs. 13% in experiments. We conclude that it is highly likely that a substantial fraction of the long-term large-scale increases in established forest carbon density is driven by rising atmospheric carbon dioxide concentrations.

Wright's second line of argument is that the rise in atmospheric carbon dioxide has been so large over the past two centuries that the implied increases in above-ground biomass and/or numbers of trees per hectare over such a timescale are simply implausible. Unfortunately, of course, we lack direct measurements of the preindustrial ecology of tropical forests, but we do have a rapidly improving understanding of present-day variation with the biome. Even humid forests today vary greatly, beyond the differences Wright suggests are implausible. For example, both Asian (Slik *et al.*, 2010) and African (Lewis *et al.*, 2013) forests, on average, store >30% more biomass per hectare than 'typical' Amazon forests, whereas Amazon forests themselves vary enormously across resource gradients (e.g. Quesada *et al.*, 2012). Asian and Amazon forests also have a ca. 40% greater density of trees >10 cm diameter

than African forests (Lewis *et al.*, 2013). Thus, differing environmental conditions across space coincide with large differences in forest structure, so the possibility that tropical forest biomass has increased markedly in response to global environmental changes is reasonable. These drivers of biomass increases could of course extend beyond the biological effects of carbon dioxide. Additional global mechanisms may include the effect of higher air temperatures that decrease water viscosity (Roderick & Berry, 2001), so benefiting tropical species with higher wood density (Lloyd, personal communication). Notably, wood density increases with temperature across contemporary thermal gradients in Amazonia (Quesada *et al.*, 2012) and Africa (Lewis *et al.*, 2013).

Elsewhere, Wright and colleagues recently also concluded that a plot-based annual increase in tropical biomass of 0.6 Mg C ha⁻¹ is indeed consistent with the recent carbon balance of the Earth system (Cernusak *et al.*, 2013). Similarly, a substantial intact forest sink is required to obtain a net balance of near zero for the tropics given known land-use emissions (Ciais *et al.*, 2013). So, while the precise contributions of the drivers of this increase in intact forest carbon stocks remain to be quantified, perhaps the long-running debate about the existence of a significant sink is now over (c.f. Wright, 2006). We do agree with Wright (2013) that there remains significant uncertainty as to how large the sink is, particularly (i) as no ground-based monitoring programme is fully randomized at continental and global scales; and (ii) changes belowground remain unassessed. We suggest that these uncertainties may result in either overestimating or underestimating the tropical forest carbon sink. Nevertheless the key points from Pan *et al.* (2011) bear repeating: atmospheric and other records show a very large amount of carbon being sequestered on the Earth's land surface, and ground measurements independently show that almost all forest regions – tropical forests included – have contributed to this remarkable multidecadal terrestrial carbon sink.

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