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The carbon balance of tropical forest regions, 1990–2005

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Global awareness of the significance of the role that tropical forests play in the global carbon cycle has never been greater, but much uncertainty still exists as to the exact magnitude of this role. Here I review and attempt to synthesise the latest evidence of both the carbon source from tropical forest conversion, and the carbon sink in tropical vegetation. Tropical biome conversion is estimated to be a source of 1.3 ± 0.2 Pg C year^{-1} to the atmosphere in both periods 1990–1999 and 2000–2005, whereas intact tropical biomes were estimated to be a net carbon sink of 1.1 ± 0.3 Pg C year^{-1}. The ratios of carbon source to carbon sink are very different for the different tropical continents, reflecting different rates of conversion and different area of forest cover, with tropical Asia probably a strong net carbon source and tropical Africa probably a strong net sink. The net balance of the tropical forest biomes is estimated to be +0.2 ± 0.4 Pg C year^{-1} (not significantly different from zero) over both periods 1990–1999 and 2000–2005; this result is consistent with that from atmospheric inversion models that better represent vertical CO_2 profiles (+0.1 ± 0.3 Pg C year^{-1}).

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Introduction

In this paper I present a brief overview of the state of knowledge of the carbon balance of the tropical biosphere, looking at both CO_2 emissions from land use change, and uptake by natural ecosystems. The tropical biosphere is often associated with rainforests, but encompasses many other biomes, ranging from flooded forests to dry forests, woody savannas and scrublands, grasslands, and desert systems. I focus here on humid and drier forests and woody savannas, principally because they contain the more substantial biomass carbon stocks, but also because so few data exist for other tropical systems. Total tropical land area is about 56 million km^2, divided between three main continents: South and Central America (32% of land area), Africa (52%) and South and South-East Asia (17%). According to the Global Land Cover (2000) classification [1], 24% of this tropical land area is covered by humid forests, 11% by deciduous woodlands, 27% by shrubs and grasslands, 15% by bare areas, and 20% by agricultural, managed or mosaic landscapes. These proportions vary by continent. The tropical Americas are dominated by humid forest (47%), followed by agricultural, managed or mosaic landscapes (25%), and herbaceous or sparse vegetation (15%). In contrast, tropical Africa is much drier, with 27% bare land, 29% shrublands and grasslands, 16% agricultural, managed and mosaic lands, 16% deciduous forest, and only 10% humid forests. Tropical Asia is different again, fairly evenly split between humid forest (24%), agricultural, managed or mosaic landscapes (23%), herbaceous or sparse vegetation (22%) and shrub cover (18%).

Direct anthropogenic effects

It is well established that the degradation and conversion of tropical biomes accounts for almost all current anthropogenic emissions from the biosphere to the atmosphere, through the combustion and decomposition of vegetation biomass. The exact magnitude of this emission has remained elusive to calculate. Uncertainty arises at a number of stages [2]. These include estimation of rates of deforestation, of vegetation and soil carbon stocks in both intact and converted forests, the mode of clearing and the fate of cleared carbon, the response of soil carbon to deforestation, and lag effects from historical land cover change.

Some estimates of carbon emissions from tropical forest conversion are summarised in Table 1. In several cases estimates have been updated over time as datasets have been revised; in these cases I focus on the most recent update only.

There have been four approaches taken to estimate carbon emissions. The longest-running approach has been to use country survey data on changes of forest cover reported to the Food and Agriculture Organisation (FAO), and then employ a carbon 'book-keeping' model to track the fate of logged, deforested and regrowing forests [3]. This approach has attracted criticism because the FAO country surveys have no consistent methodology across countries, and detail individual country studies have found very different patterns and rates from the country surveys. In 2006 the FAO revised downwards its estimates for global deforestation in the 1990s, and the

Table 1

Estimates of carbon emissions from land use change in tropical forest areas. All carbon flux units are Pg C year^{-1}.

Number	Source	Time period	Biome	Americas Pg C year^{-1}	Africa Pg C year^{-1}	Asia Pg C year^{-1}	Pantropics Pg C year^{-1}
1	Houghton (2008) [4]	1990–1999	Humid and dry forests	0.76	0.24	0.52	1.52
2	Achard *et al.* (2004) [7]	1990–1999	Humid forests	0.35 ± 0.23	0.10 ± 0.04	0.47 ± 0.20	0.92 ± 0.28
3	Achard *et al.* (2004) [7]	1990–1999	Humid and dry forests	0.44 ± 0.24	0.16 ± 0.05	0.47 ± 0.20	1.07 ± 0.31
4	DeFries *et al.* (2004) [8]	1990–1999	Humid and dry forests	0.43 ± 0.10	0.12 ± 0.02	0.35 ± 0.10	0.91 ± 0.22
5	Derived from Hansen *et al.* (2008) [9]	2000–2005	Humid forests	0.44 ± 0.11	0.09 ± 0.01	0.32 ± 0.09	0.89 ± 0.21
6	This study	2000–2005	Humid and dry forests	0.53 ± 0.12	0.15 ± 0.02	0.32 ± 0.09	1.01 ± 0.22
7	Houghton (2008) [4]	2000–2005	Humid and dry forests	0.63	0.25	0.60	1.47
8	Van der Werf *et al.* (2009) [5••]	2000–2005	Humid forests	0.42	0.19	0.42	1.03
9	Van der Werf *et al.* (2009) [5••]	1997–2006	SE Asia peat fires and oxidation			0.30 ± 0.09	
10	Best estimate (this study)	1990–1999	Humid and dry forests	0.44 ± 0.13	0.14 ± 0.02	0.71 ± 0.15	1.29 ± 0.20
11	Best estimate (this study)	2000–2005	Humid and dry forests	0.53 ± 0.12	0.15 ± 0.02	0.62 ± 0.13	1.30 ± 0.24

values presented in Table 1 (row 1 for 1990s, row 7 for 2000–2005) reflect these revised estimates [3,4], not the original estimates presented in publications prior to 2006. The revised estimates result in 30% lower CO_2 emissions than the original estimates using the same FAO methodology, or 23% lower than the original estimates using IPCC methodology applied here [5••].

Alternative approaches have employed satellite remote sensing in various forms. The FAO reported their own remote sensing survey for humid and drier tropical biomes, with subsampling with Landsat imagery of 10% of the sample area. The TREES project [6] employed a similar approach for the humid tropical forests alone, using Landsat satellite data for the period 1990–1997 (Table 1, row 2). Achard *et al.* [7] integrated these two approaches (Table 1, row 3), using TREES estimates for the humid tropics and assuming that the difference from FAO remote sensing estimates was accounted for by land use change in drier tropical biomes. In extrapolating to the whole 1990s, they also added 0.087 Pg C year^{-1} to the total for humid Asia because of the large Indonesian fire event of 1997/1998 (averaged over the 1990s; the amount released during the actual fire year was 10 times that amount); this is included in the Asian emissions in rows 2 and 3.

A different remote sensing approach was employed by DeFries *et al.* [8], who conducted a wall-to-wall pantropical analysis employing the lower resolution (8 km) Advanced Very High Resolution Radiometer (AVHRR) data, and then used a subset of higher resolution Landsat imagery to derive continent-specific correction factors to account for deforestation too fine to see in the 8 km imagery. A bookkeeping approach almost identical to that above was employed to convert deforestation and regrowth estimates into net carbon emissions (Table 1, row 4).

Hansen *et al.* [9] refined this approach with a more planned design for high resolution sampling for the period 2000–2005, where MODIS (Moderate Resolution Imaging Spectroradiometer) data are used to identify deforestation hotspots where high resolution analysis is targeted. As their approach (and rates of deforestation) are broadly similar to those of DeFries *et al.* [8], I use the continent-specific ratios of carbon emission to net forest loss from [8] to estimate carbon emissions for the period 2000–2005. They only calculated forest cover change estimates for the humid tropics; to include emissions for the drier forests I add the Achard/FAO estimate for the 1990s (row 2–row 1), resulting in row 6. A very different remote sensing approach has been to look at fire emissions from the humid tropics [5,10], and assume that 50% of the carbon dioxide emitted from deforestation is through detectable fires (the remainder being through decomposition of leftover material). These emissions are reported in the Global Fire Emissions Database (GFED version 2 [5,11]), and for 2000–2005 are given for the humid tropics in Table 1, row 8.

The above approaches all largely focus on carbon dioxide emissions through loss of live biomass (although some also incorporate changes in soil carbon stocks after land use change). There is at least one large additional source of CO_2 in the tropical biosphere that has increasingly been recognised: the loss of soil carbon from conversion of tropical peatlands, through both oxidation (triggered by human-caused drainage and lowering of the water table) and combustion. These peatlands are estimated to store 70–80 Pg C, with most of this on Borneo and Sumatra. Recent estimates based on fire emissions constrained by satellite-derived atmospheric concentrations of carbon monoxide suggest that peatland fires in SE Asia emitted 0.12 ± 0.06 Pg C year^{-1} over the period 1997–2006 [12]. Peatland drainage and oxidation (not counting fires) in SE Asia are estimated to have emitted a further 0.17 ± 0.07 Pg C year^{-1} over the period 1997–2006 [13••]. Combining these two estimates suggest mean tropical peatland CO_2 emission rates of 0.30 ± 0.09 Pg C year^{-1} ([5••]; Table 1 row 9), with substantially higher values during drought periods.

In Table 1 I distil this information to arrive at a CO_2 emissions estimate for each tropical continent. The IPCC Working Group I approach [14] was to take the mid-point between the FRA (Forest Resource Assessment/FAO) country survey-derived estimates and the satellite-derived estimates; this approach was also employed by Van der Werf *et al.* [5••]. However, here I argue that the country survey have repeatedly been shown to be problematic and inconsistent between countries. There are convincing arguments for applying only the satellite-based estimates (including those of the FAO), which have the advantage of consistent methodology across regions, and broad agreement between different methodologies. Hence, I average only the satellite-based estimates to arrive at a best estimate (rows 3 and 4 for the 1990s, and row 6 for the 2000s). I also add 0.30 ± 0.09 Pg C year^{-1} for peatland fires and oxidation in SE Asia. The fire-based emission estimates for the humid tropics (row 8 + 9) are broadly similar to those from land cover change analysis (row 11), with a similar distribution between continents.

This proposed 'best estimate' for all the tropics (humid and non-humid) suggests that CO_2 emissions from land cover change in the tropics were broadly similar in the 1990s (1.29 ± 0.20 Pg C ha^{-1} year^{-1}) and over the period 2000–2005 (1.30 ± 0.24 Pg C ha^{-1} year^{-1}). 41% of these emissions were from the tropical Americas, 47% from tropical Asia (where 23% of the global total, and almost half of the Asian total, was from peatlands) and only 11% from tropical Africa.

These estimates focus on emissions from deforestation as detected by satellites, but do try to incorporate estimates of degradation (either from logging or small-scale clearance), either from what degradation can be observed in Landsat or SPOT imagery [7] or else as a crude 7% correction based on a logging degradation study in the Brazilian Amazon [8,15]. It is conceivable that very small-scale degradation is more prevalent, especially in Africa and high population areas of Asia. Our satellite-only 'best estimate' for deforestation carbon emissions in Africa is 40% less than that indicated by the FAO country reports for Africa (Table 1), and part of this difference may be because of missing degradation (though quality of the country reports is also an issue). However, the importance of degradation emissions is intrinsically self-limiting — the harder the degradation is to detect, the smaller its likely influence on carbon stocks. It is likely that degradation would be at most only a small correction on our best estimates presented here, and substantially smaller than other uncertainties in the analysis.

Carbon sinks

Away from the zones of large direct human impacts on tropical biomes, another question is being asked of the carbon balance of intact tropical biomes: are they in carbon balance or net sinks of atmospheric CO_2?

Examination of the global atmospheric carbon budget makes it very clear that there is a carbon sink in the terrestrial biosphere. For example, in the period 2000–2008, only $45 \pm 4\%$ of emitted carbon dioxide was registered as an increase in atmospheric concentration (the 'airborne fraction'), with a further $26 \pm 5\%$ estimated to be going to the ocean, and $29 \pm 6\%$ going into the terrestrial biosphere [16••]. What proportion of this terrestrial carbon sink is in the tropical biosphere, however, is still a subject of active investigation.

Probably the most robust direct data on possible carbon uptake in tropical forests have come from long-term (multidecadal) forest inventory plots in South America (the RAINFOR network: [17–19,20••]) and Africa (the AfriTRON network: [21••]) and across the tropics (the Centre for Tropical Forest Science (CTFS) network: [22••]). From these plots it is possible to calculate changes in above-ground live biomass, admittedly only a partial picture of the overall changes in carbon stock (not measuring changes in below ground biomass and soil carbon, and in dead wood), but indicative nonetheless.

The estimated changes in forest biomass from these networks is summarised in Table 2.

Lewis *et al.* [21••] provided an integrated analysis of these various studies from across the tropics, weighted by plot size and estimated a mean tropical sink in humid forests of +0.49 (0.29–0.66; 95% C.I.) Mg C ha^{-1} year^{-1}. This synthesis incorporates 156 forest plots covering 562 ha in area and 1649 years of census interval, with the mean interval covering the period 1987–1997.

The forest plot approach was initially challenged on a variety of methodological issues [23,24]. In general, it has thus far proved robust to criticisms of field methodologies

Table 2

The carbon sink in tropical forests as estimated from forest inventory plot networks. All carbon flux units are Mg C ha^{-1} year^{-1}.

Region	Network	Study	No. of plots	Biomass carbon change Mg C ha^{-1} year^{-1}	Range Mg C ha^{-1} year^{-1}	Study period	Mean interval
Americas	RAINFOR	Phillips *et al.* (1998) [17]	40	+0.62	±0.30		
Americas	RAINFOR	Phillips *et al.* (2009) [20••]	123	+0.45	0.33–0.56	1975–2005	1990–2002
Americas	RAINFOR	Phillips *et al.* (2009) [20••]	123	+0.36		1975–2007	
Americas	RAINFOR	Baker *et al.* (2004) [19]	59	+0.62	±0.23		
Africa	AfriTRON	Lewis *et al.* (2009) [21••]	79	+0.63	0.22–0.94	1968–2007	1987–1996
Pantropics	CTFS	Chave *et al.* 2008 [22••]	10	+0.24	0.07–0.39	1982–2006	
Pantropical synthesis	RAINFOR/ AfriTRON/CTFS	Lewis *et al.* (2009) [29••]	156	+0.49	(0.29–0.66)		1987–1997

[19,25,26], as the forest plot monitoring network has gradually transformed towards one designed for purpose rather than inherited from previous botanical and forestry inventories. The most fundamental methodological concern has surrounded the extent to which relatively small plots on decadal timescales effectively sample a spatially heterogeneous matrix of occasional disturbance followed by slow recovery. A partial sampling of a landscape with such a skewed distribution of net carbon fluxes can lead to a biased mean favouring an apparent carbon sink [27]. As the dataset has grown both in temporal and spatial extent and still shown a consistent result, it seems increasingly unlikely that the increase in biomass is an artefact of inadequate sampling of the disturbance-recovery matrix [21••,28••].

There are two schools of thought regarding the cause of such a long-term and wide-ranging increase in biomass. One suggests that this might be recovery from a large-scale disturbance prior to the commencement of the sampling either caused by a natural drought event or previous human pressure on the forests (*e.g.* collapse of forest-using populations in Amazonia and Africa through disease and colonisation). The other suggests this is a response to ongoing atmospheric change, most likely the rise of atmospheric CO_2 but also perhaps other factors, such as warming temperatures increasing nutrient mineralisation rates and increased diffuse light from biomass burning increasing canopy photosynthetic efficiency. There are two features that challenge the disturbance hypothesis. The further back in time the disturbance, the large the disturbance needs to have been to explain current biomass accumulation rates, and any disturbance required in the early 20th century or earlier would have had to have been very large. Secondly, the increase in biomass seems to be accompanied by an increase of growth followed by an increase of mortality, whereas with recovery from disturbance the general long-term pattern would be expected to one of declining growth and increasing mortality [29••].

The analysis in Table 2 covers only relatively intact moist or humid tropical forests. The picture in drier tropical forests and woodlands is less clear, mainly because these biomes have a strong (natural and anthropogenic) cycle of fire disturbance and recovery, over which it is challenging to distinguish a signal of net long-term biomass change. One clue can come from long-term shifts in the ecotone between forests and savannas. In many tropical regions a phenomenon of encroachment appears to be occurring, with increasing woody biomass in savanna regions and an advance of trees at the expense of grasses. Such changes could be caused by decreasing fire regimes in some areas (driven perhaps by rural depopulation towards urban areas), or by global atmospheric drivers, in particular rising CO_2 favouring C3 photosynthetic pathways (overwhelmingly tropical trees) over C4 photosynthesis (overwhelmingly tropical grasses), and also increasing the water use efficiency and reducing drought stress in trees, or by local increases in rainfall.

Table 3

Scaled estimates of total carbon sink in tropical forests. All carbon flux units are Pg C year^{-1}.

Region	Units	Americas	Africa	Asia	Pantropics
Area (humid forest)	10^6 km^2	6.31	2.33	2.31	10.94
Area (total forest)	10^6 km^2	8.02	6.61	3.89	18.51
Biomass carbon sink[a] (humid forest)	Pg C year^{-1}	0.49 ± 0.07	0.16 ±0.03	0.16 ±0.03	0.82 ±0.11
Biomass carbon sink (humid and dry forest[b])[a]	Pg C year^{-1}	0.56 ± 0.07	0.31 ± 0.15	0.22 ± 0.06	1.09 ± 0.29

[a] Where the original study gives estimates of 95% confidence intervals, standard errors are estimates as CI/1.96, assuming a normal symmetric distribution.

[b] Assumes that dry forests have half the carbon sink per hectare of humid forests, with error bars of 100%.

Table 4

'Best estimates' of the net carbon balance of tropical biomes. All units are Pg C year^{-1}.

	Biome	Period	Americas	Africa	Asia	Pantropical
Deforestation carbon source[a]	Humid and dry forests	1990–1999	0.44 ± 0.13	0.14 ± 0.02	0.71 ± 0.15	1.29 ± 0.20
	Humid and dry forests	2000–2005	0.53 ± 0.12	0.15 ± 0.02	0.62 ± 0.13	1.30 ± 0.24
Biomass carbon sink[b]	Humid ± 50% dry forests		0.56 ± 0.10	0.31 ± 0.15	0.22 ± 0.06	1.09 ± 0.29
Net balance	All tropics	1990–1999	−0.12 ± 0.16	−0.17 ± 0.15	+0.49 ± 0.16	+0.20 ± 0.35
		2000–2005	−0.03 ± 0.15	−0.16 ± 0.15	+0.41 ± 0.15	+0.21 ± 0.38
Atmospheric inversion best estimate[c]	All tropics	1992–1996				+0.13 ± 0.32

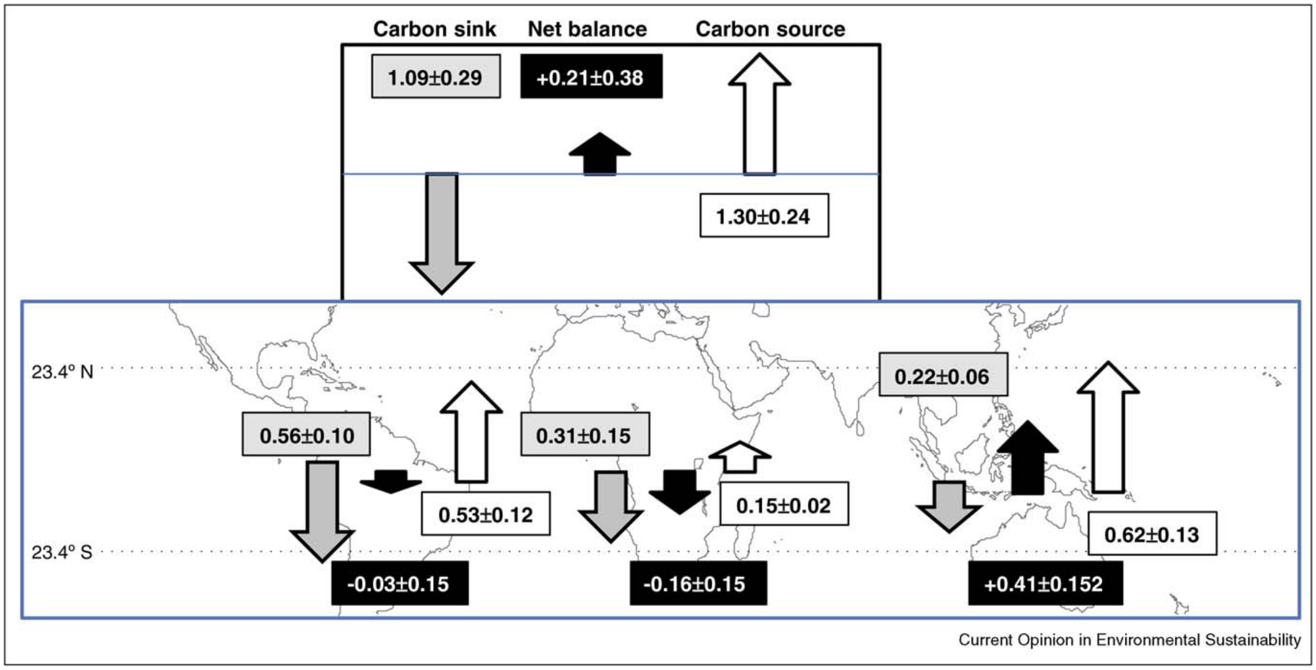
[a] From Table 1.
[b] From Table 3.
[c] From Stephens *et al.* (2007) [30].

In Table 3 I summarise estimated tropical forest carbon sinks in each continent based on the analysis of Lewis *et al.* [21••], where a global mean per hectare value (weighted by sampling intensity and extent) was multiplied by forest areas in each continent (here employing forest areas estimated from the Global Land Cover dataset). Strictly, this extrapolation should only be applied to the humid forest biome, where almost all the forest plots are located. However, it is reasonable to expect that such a carbon sink is also occurring in drier biomes, and indeed may be larger because the effects of increasing water use efficiency and CO_2-induced competitive exclusion of grasses. On the other hand, the biomass and productivity of drier forests is lower, and so the absolute carbon sink may be smaller. Hence I suggest an intermediate extrapolation with large uncertainty as a best estimate, where the carbon sink per hectare in the dry forests in 50 ± 50% of the carbon sink in humid forests.

This best estimate does not take into effect what may be happening in grassland-dominated biomes (including savannas), including woody encroachment. It also says nothing about any changes in soil carbon stocks, which may also be increasing in response to productivity increases, or decreasing because of warming, or showing little change.

The area estimates are from the GLC2000 dataset [1], which estimate a total tropical forest (humid and dry) area of 18.5 × 10^6 km^2. Other datasets suggest a total tropical

Figure 1



Estimates of carbon sources and sinks in tropical forest regions, 2000–2005. Arrow lengths are indicative of magnitude of fluxes, but not exact. Grey arrows indicate biomass carbon sink, white arrows deforestation net carbon source, and back arrows the net balance.

forest area between 15.7×10^6 km^2 (−15%) for FAO remote sensing analysis, 16.4×10^6 km^2 (−11%) for the World Conservation Monitoring Centre and 20.4×10^6 km^2 (+10%) for FAO country surveys. Estimates of total biomass carbon sink would scale similarly, though with smaller range since much of the uncertainty in forest area arises from drier forests.

The net carbon balance of tropical biomes

Above I have tried to generate best estimates of the CO_2 source from conversion of tropical forests, and the CO_2 sink from biomass increases, for both humid forests only and for all forests, and with specific values for each continent. In Table 4 I bring together these components to estimate the net carbon balance of each tropical continent (also illustrated for 2000–2005 in Figure 1).

This analysis suggests that South America forests are a moderate net sink of carbon, with very high rates of deforestation offset by a substantial sink across the vast expanses of Amazonian forest. The Asian tropics appear a large net source of carbon, both from direct deforestation and from oxidation and burning of peatlands, with the potential sink in limited and declining forest area unable to offset these large sources. African forest appears a large net sink, with low emissions, and a substantial net sink, particularly in the forest expanses of the Congo Basin.

Atmospheric data

An additional strand of empirical insight into the carbon balance of the tropical biome comes from the atmospheric budget of CO_2. As mentioned above, from global budget considerations there is strong evidence that there is a global land biosphere sink, of magnitude 2.7 ± 0.9 Pg C year^{-1} in the period 1990–2008 [16]. To partition this sink between tropical and temperate latitudes from an atmospheric perspective requires examination of the small-scale spatial variation and seasonal variations of CO_2 concentration. Such 'atmospheric inversion' approaches involve utilising worldwide observations of CO_2 concentrations, and then inverting an atmospheric transport model to predict surface sources and sinks of CO_2. Once the (relatively well described) fossil fuel associated sources are accounted for, the remaining inbalances can be attributed to biospheric and oceanic sources and sinks. In practice, these analyses are hampered by model difficulties in representing all relevant aspects of atmospheric dynamics, and by the sparseness of CO_2 observation data, particularly in the tropics where data are almost non-existent. The last feature means that the tropical carbon balance is often derived as a residual from the mass balance, after the northern temperate carbon balance is constrained by atmospheric observations in North America and Eurasia. Such approaches have yielded a broad range of results, with the full range of results in recent inverse model studies having tropical net land carbon balance spanning values of −1 (carbon sink) to +4 (carbon source) Pg C year^{-1}. The calculated northern temperate net carbon balance is strongly correlated with any particular atmospheric model's ability to represent vertical mixing of CO_2 between the near-surface and the upper troposphere. Stephens *et al.* [30] compared model-predicted vertical CO_2 profiles with worldwide observations from aircraft profiles. They found that only 3 models out of 12 came close to matching the observed atmospheric profiles. Over the period 1992–1996, these three models suggested a mean tropical land carbon balance (including deforestation emissions) of +0.13 ± 32 Pg C year^{-1} (*i.e.* no significant net imbalance), as compared to +1.79 ± 0.90 Pg C year^{-1} (a large net source) suggested by a simple average of all 12 models (the errors are standard errors calculated from data provided in [30]). Conversely, the temperate land carbon sink is −1.5 ± 0.2 Pg C year^{-1} for the 'best estimate' models, as opposed to −2.4 ± 0.4 Pg C year^{-1} averaged across all 12 models.

Conclusions and future pathways

In this paper, I have tried to summarise the most recent findings on the magnitude of CO_2 emissions from tropical land use change, and the magnitude of the carbon sink in intact tropical biomes. I have suggested that the best emissions estimates come from satellite analyses, and the best carbon sink estimates come from long-term forest plot inventories, though no approach is ideal or comprehensive in either case. When these two approaches are scaled and combined, the best estimate of the net carbon balance of tropical biomes suggests a near-balance between carbon sources and sinks, a finding that is consistent with results from those atmospheric inversion models that best capture vertical CO_2 gradients (Table 4). Hence four independent streams of data (satellite-derived land use change estimates, satellite-derived fire emissions, long-term forest inventories and gradient-evaluated atmospheric inversion models) point to a consistent picture of tropical forest sources and sinks. The case is far from closed in any of these estimates, and these numbers may be further refined or even potentially shift substantially as improved data sets and new insights are incorporated. A key focus for future research should be drier tropical biomes, which could be contributing significantly to carbon sources and sinks, but where thus far the carbon balance is particularly poorly quantified.

This paper presents a snapshot of suggested tropical carbon balance for the period 1990–2005. What are likely future pathways of this carbon budget? There appears to be no immediate upward trend in deforestation rates, and indeed substantial pressure for declining deforestation rates through schemes such as REDD+ (Reduced Emissions from Deforestation and Degradation). Of particular note is the reduction of deforestation rates in the Brazilian Amazon by 67% (by 2009) from 2000 to 2005 mean levels of 21,550 km^2 year^{-1} [31]. As Brazil contributed about

48% of global humid tropical deforestation over 2000–2005 [9], this suggests that emissions from Brazilian Amazonia have dropped by 0.29 Pg C $year^{-1}$ (Table 1, row 5). However, Loarie *et al.* [32••] noted that recent and imminent Brazilian deforestation was moving into higher biomass forests, which would increase carbon emissions per unit area converted, partially offsetting the beneficial consequences of reduced deforestation rates. Neglecting this complication, and if rates elsewhere have not changed, global deforestation emissions may have dropped from 1.3 to 1.0 Pg C $year^{-1}$. If REDD+ is effective, there may be substantial reductions in land use change emissions over the coming decades. On the other hand, there are substantial countervailing forces, such as increased global demand for food, timber, biofuels and other products from tropical forest lands.

The future of the biomass carbon sink is also unclear. We do not have a conclusive mechanistic explanation of its cause. If a transient response to CO_2 fertilisation is the most likely cause, it is likely that at some point this sink will saturate, either for ecophysiological (decreasing CO_2 sensitivity), structural (a limit to how much biomass forests can hold) or ecological reasons (negative feedbacks such as proliferation of lianas: [33]). If drought becomes more frequent in some tropical regions, the biomass sink may indeed flip into a source, as evidenced in Amazonia in 2005 [20••]. Rising temperatures may also affect plant photosynthesis and respiration rates, though whether this would negatively or positively affect vegetation carbon balance is not clear. The most likely global prospect is that the sink will persist, but perhaps gradually decrease in magnitude.

The size of this carbon sink is substantial when compared to existing forest biomass. For a typical tropical forest holding 150 Mg C ha^{-1} of live biomass, a sink of 0.5 Mg C ha $year^{-1}$ represents a 7% increase of biomass over 20 years. In terms of the impact of tropical forest protection on atmospheric CO_2, strictly it should be the most likely biomass at the end of any particular accounting period that is relevant, not the current biomass. A problem is that we cannot know the persistence and future magnitude of the tropical forest sink, but a risk-weighted accounting approach could take this into account.

Over the period 2000–2005 global fossil fuel and cement CO_2 emissions were 7.3 Pg C $year^{-1}$ [34]. Tropical deforestation contributed 1.30 ± 0.24 Pg C $year^{-1}$ (Table 1, row 11), 15 ± 3% of total CO_2 emissions, a proportion smaller than often quoted and continuing to decline as fossil fuel CO_2 emission rates continue to rise rapidly. If our estimate of the tropical carbon sink is correct, over the period 2000–2005 it absorbed 12 ± 3% of 2000–2005 total anthropogenic emissions, accounting for about 47% of the land carbon sink. If the tropical biomass carbon sink were not present and this excess carbon were instead allocated to ocean and atmospheric pools at the current fractions (but not to the remaining land pool), atmospheric carbon dioxide would be rising at a mean rate 17% higher than that currently observed, and oceans would absorb a further 0.4 Pg C $year^{-1}$, an additional cause of ocean acidification and coral reef decline. This is a substantial global ecosystem service that intact tropical biomes appear to be currently providing.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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The authors show the deforestation is a smaller component of global carbon emissions than usually cited, and a proportionally decreasing source as fossil fuel CO_2 emissions increase.

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