Tropical Forests and Atmospheric Carbon Dioxide: Current Knowledge & Potential Future Scenarios

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Abstract

Tropical forests affect atmospheric carbon dioxide concentrations, and hence are modulate the rate of climate change, by being both a source of carbon, from land-use change (deforestation), and a sink or source of carbon in remaining undisturbed forest. These fluxes are the least understood and most uncertain major fluxes within the global carbon cycle. We synthesis new data on the carbon balance and ecology of tropical forests, showing concerted changes consistent with undisturbed tropical forests presently functioning as a carbon sink of ~1 Pg C a^{-1}*. However, predictions suggest that this sink is unlikely to continue. Global Circulation Models including dynamic vegetation and an interactive carbon cycle show tropical forests may become a mega-source of carbon: under "business as usual" (IS92a) atmospheric carbon dioxide concentrations could reach 980 ppmv by 2100. Finally, we suggest that subtle biodiversity changes, not included in these models, could push projections to even more alarming levels.*

1. Introduction

The Earth is an integrated system: the atmosphere, oceans, terrestrial ecosystems and the dominant mammal – *Homo sapiens* - all interact in a highly complex way. Changes in one component affect the behaviour of the others. These changes are often characterised by non-linear responses, complex feedback mechanisms and threshold transitions. Understanding the links between these different components is therefore critical. Predicting the impacts of climate change requires a detailed understanding of the global carbon (C) cycle. This is because the positive radiative forcing of carbon dioxide (CO_2) in the atmosphere is the major cause of air temperature increases and other features of climate change [1].

This paper reviews and synthesises the latest research concerning one important component of the global carbon cycle: tropical forests. Being relatively extensive, carbon dense and highly productive tropical forests play a pivotal role in the global carbon cycle. To illustrate: globally from 1750-2000 land-use change released ~180 Pg C (Pg C = billion tons of carbon) to the atmosphere, 60 % from the tropics [2, 3], alongside 283 Pg C released from fossil fuel use over the same time period [4]. Thus tropical forest conversion has released ~108 Pg C. Further major carbon additions are possible, with 553 Pg C residing within remaining tropical forests and soils [1, 5], the equivalent of over 80 years of fossil fuel use at current rates.

The total carbon release from land-use change and fossil fuel use from 1750-2000 has been estimated at 463 Pg C, but the increase in atmospheric CO_2 concentrations has been only 174 Pg C [5]. The remainder has been absorbed into the oceans (129 Pg C; [6]) and terrestrial ecosystems (160 Pg C), half of which is thought to have gone into the tropics. This 160 Pg C is a potentially transient sink. And importantly, what if this sink becomes a source? This would radically increase atmospheric CO_2 concentrations, accelerating the rate and magnitude of climate change.

Inter-annual variability in the rate of increase in atmospheric CO_2 concentrations can be partially explained by large and rapid changes across the tropical CO_2 fluxes. Since direct measurements of atmospheric CO_2 began in 1957, the lowest rate of increase was in 1992, 1.9 Pg C a^{-1}, and the highest in was 1998 (6.0 Pg C a^{-1}). Statistically, El Niño years have shown the highest rates of increase in atmospheric CO_2 concentrations, apparently largely driven by higher deforestation rates, and increased mortality and decreased growth in intact tropical forest [7, 8, 23]. Such warmer and dryer conditions are projected to occur more frequently, with potentially severe implications for both climate change and tropical forests [9].

Understanding the role of the terrestrial tropics as an accelerator or buffer of the rate of climate change via additions and subtractions to the atmospheric CO_2 pool is essential. However, tropical forests are the least understood and quantified major source (from deforestation) *and* sink (from undisturbed forest uptake) of CO_2. This new synthesis aims to reduce that uncertainty, and sketch a range of future possible scenarios for this important biome.

2. Tropical Forests and the Global Carbon Cycle over the 1990's

2.1 Estimating and partitioning the terrestrial carbon sink

Accounting for known annual global carbon fluxes from fossil fuel use and known land-use change, the known additions of carbon to the atmosphere, and the known oceanic uptake of carbon, show that there must be a terrestrial carbon sink. As the simple mass balance equation below shows, (i) the net increase in atmospheric CO_2 must equal the source terms minus the sink terms, and (ii) an under- or over-estimate of one parameter implies a corresponding error in one or more other parameters:

$$E_{fossilfuels} + E_{tropicaldeforestation} = \Delta_{atmosphericCO2} + \Delta_{oceans} + \left(\Delta_{tropics} + \Delta_{other} \right),$$

6.3 1.7 3.2 2.1 2.7
±0.4 ±0.8 ±0.1 ±0.7 ±1.1

where E is emissions, and Δ is change, with all units as Pg C a^{-1}.

The change in atmospheric CO_2 and emissions from fossil fuel use are known with reasonable precision (3.2 ± 0.1 Pg C a^{-1} & 6.3 ± 0.4 Pg C a^{-1} respectively [5]). Partitioning of the terrestrial and oceanic fluxes using simultaneous atmospheric measurements of CO_2 and O_2 give the net terrestrial flux as a sink of ~1.0±0.8 Pg C a^{-1}, (and an oceanic sink of ~2.1±0.7 Pg C a^{-1}, [10]). Using $C0_2$ and $^{13}\delta C$ (inverse models) the net terrestrial flux estimates ranges from a sink of 0.8 to 1.4 Pg C a^{-1} (Prentice et al. 2001). Thus terrestrial ecosystems are estimated to be a net sink for carbon, using two independent methods. Assuming land-use change contributes 1.7 ± 0.8 Pg C a^{-1} [5], the residual term, the 'terrestrial' sink is therefore 2.7±1.1 Pg C a^{-1}.

Partitioning this global terrestrial sink between northern-extratropical and tropical lands, using atmospheric transport models, show that while the terrestrial land-mass as a whole is a sink, tropical regions may be neutral, or a source of C (1.5±1.2 Pg C a^{-1} [11, 12]). Meanwhile, studies of tropical land-use change (deforestation) show this is a source of between 1.1 ± 0.3 Pg C a^{-1} [13], and 2.2 ± 0.8 Pg C a^{-1} [12].

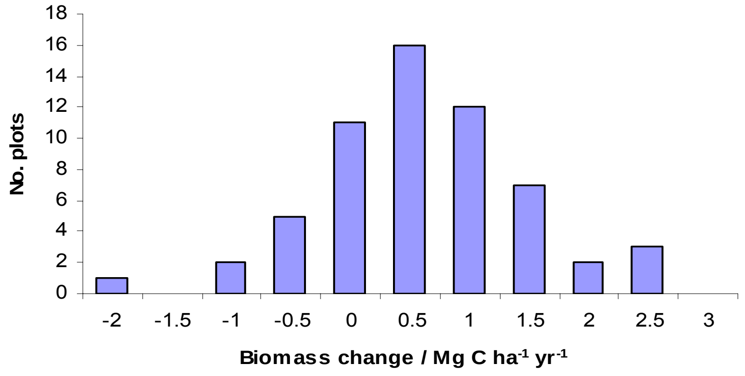
2.2 Large or small changes across the tropics?

The fluxes of carbon from the tropics are very poorly constrained due to a lack of data and methodological limitations. Current evidence, summarised above, suggests two possibilities for the tropics: (1) A large release of carbon from deforestation, partially offset by a large sink in undisturbed forest. (2) Smaller release of C from deforestation, with little, if any sink in undisturbed forest [10, 12].

Differences in carbon flux estimates from deforestation are largely due to contrasting estimates of the rate of deforestation, and decisions regarding the average carbon content of a tropical forest (as forest biomass varies widely across the biome). These are controversial at present [14-16].

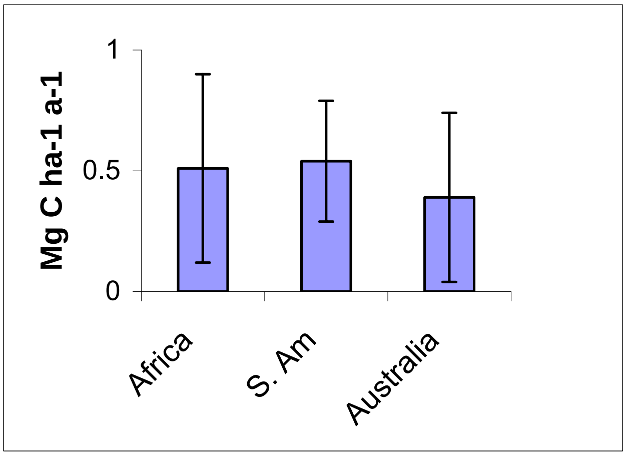
Two methods have been used to detect whether tropical forests are a major sink, forest inventories and micrometeorological techniques (eddy-covariance). Both show sinks [17,18], but have attracted considerable controversy [19, 20]. New results from forest inventories across Amazonia, taking explicit account of highlighted methodological concerns, confirm the sink, with C stocks increasing by ~0.5 % a^{-1} (Fig. 1, [21]). New, as yet unpublished data, from inventory plots in Africa and Australia also suggest a sink, which when scaled to the biome indicates a total sink within undisturbed tropical forests of ~1 Pg C a^{-1} (Fig. 2; Lewis & 55 others, *in prep.*).

Fig. 1. Frequency distribution of biomass change, from 59 x 1 ha plots, corrected for wood density, from across Amazonia [21]. Includes corrections for lianas, plants smaller than 10cm diameter, and for below-ground biomass. The distribution is normal and shifted to the right of zero. The average increase is significantly greater than zero (0.61±0.,22 Mg C ha^{-1} a^{-1}).



Two interpretations of the new inventory data have been suggested. (1) the sink is an artefact of the sampling, as most forests increase in biomass, and carbon, most of the time, as forests are naturally affected by rare major disturbances in which they rapidly lose carbon: they then accrue biomass and carbon slowly over long periods of time. (2) the sink is caused by an increase in net primary productivity, most likely caused by rising atmospheric CO_2 (see [22]). However, if the sink is an artefact of disturbance, then growth fluxes must exceed mortality fluxes within intact forest plots, but, on average, there should be no large change in these fluxes over time. By contrast, if the sink is caused by an increase in net primary productivity then the growth flux should increase markedly through time [23].

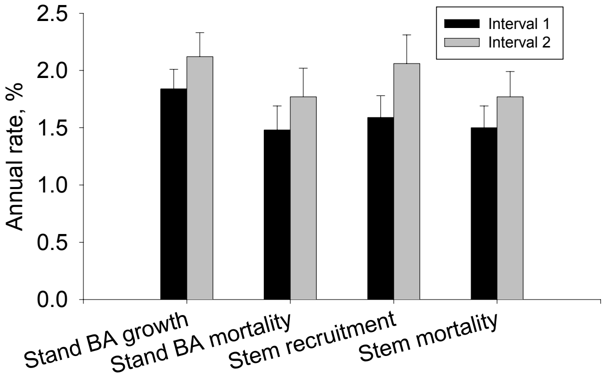
Figure 2. Mean estimated change in aboveground carbon from South American (n = 50), African (n = 50) and Australian (n = 17) forest plots, with 95% CIs. Conversions from basal area to biomass to carbon, without adjusting for wood specific gravity, from Ref 21. With total forest area and multiplier for belowground biomass increases as Ref. 17, and assuming Asian forests increase is equivalent to the mean increase from African, Asia and S. America, gives an estimate of the net carbon sink from undisturbed tropical forest of ~1 Pg C a^{-1}.



Inventory data from across South America show that the growth flux is rapidly increasing (Fig. 3 [22]). Furthermore, the mortality flux is increasing at a similar rate, as are fluxes on a per stem basis (which exclude most potential measurement errors) but lagging growth and recruitment. These suggest a continent-wide increase in resource availability, increasing net primary productivity, and altering forest dynamics. Time-lag analyses suggest losses from a forest are ~10-15 years behind the gains, implicating long-term change in plant resources [24]. The most obvious candidate increasing resource availability is rising atmospheric CO_2 concentrations, consistent with theoretical and model results [39].

Long-term forest plot data not only show that widespread and concerted changes are occurring in the structure of undisturbed tropical forests, but that the dynamic and functional composition are changing markedly [25, 26, 27]. This provides evidence that intact tropical forests are a large sink, and hence that the higher estimates of C release from deforestation are more likely (possibility 1 above). Overall, this suggests that tropical forests were a highly dynamic component of the global carbon cycle over the 1990s, in terms of being a major source from deforestation and a major sink in undisturbed forest.

Fig. 3. Annualised rates of stand-level basal area growth, stand-level basal area mortality (correlated with biomass and C), stem recruitment and stem mortality from two consecutive census intervals, each giving the mean from 50 plots from across South America, with 95 % CIs. The average mid-year of the first and second censuses was 1989 and 1996 respectively. All four parameters show significant increases (*P*<0.05).



3. Future Scenarios

To make predictions about the future, we must understand the drivers of change and how these then percolate through and alter the Earth System. There is great uncertainty at all stages of this predictive process. Here we focus solely on interactions and feedbacks between the tropics and changes expected from climate change.

3.1 Land Use Change

The drivers of land-use change, in particular deforestation, are a complex mix of political, economic and climatic factors. In short, the demand for land that is currently tropical forest to be converted to other uses is expected to remain high, keeping carbon emissions high. In terms of climatic interactions, the flammability of a given forest is a key attribute. The hot and dry conditions from El Niño years compared to non-El Niño years explains the high incidence of forest burning, and hence higher than average atmospheric CO_2 concentrations. [7, 8]. One-third of Amazonia was susceptible to fire from increased flammability during the 2001 ENSO period [28]. If droughts, temperatures and ENSO events increase in frequency and severity - as seems to have been the case over the past 200 years [29] - then the carbon flux from the tropics could rise rapidly in the future, creating a dangerous feedback loop via the impacts of deforestation.

3.2 Undisturbed Tropical Forest

Undisturbed forests will remain a sink while carbon uptake associated with photosynthesis exceeds the carbon efflux from respiration. Under the simplest scenario of a steady rise in forest productivity over time, it is predicted that forests would remain a carbon sink for decades [30, 31, 39]. However, the current increases in productivity, apparently caused by continuously improving conditions for tree growth, cannot continue indefinitely, as if CO_2 is the cause, trees are likely to become CO_2 saturated (limited by another resource) at some point in the future. More generally, whatever these 'better conditions for growth' are, forest productivity will not increase indefinitely, as other factors, e.g. soil nutrients, will limit productivity.

Rising temperatures may also cause a reduction in the undisturbed tropical forest sink, or cause forests to become a source in the future. Warmer temperatures increase the rates of virtually all chemical and biological processes in plants and soils, until temperatures reach points where enzymes and membranes become denatured. There is some evidence that the temperatures of leaves at the top of the canopy, on warm days, may be at the bottom of this range around midday at some locations [23]. Canopy-to-air vapour deficits and stomatal feedback effects may also be paramount in any response of tropical forest photosynthesis to future climate change [40, 41].

The relationship between temperature changes and respiration is critical [32]. The global circulation model (GCM) of Cox *et al.* [9, 33], was the first to include dynamic vegetation and a carbon cycle that is responsive to these dynamic changes, and shows very large differences in atmospheric CO_2 concentrations over the 21st century compared to previous models. Under the 'business as usual' scenarios of emissions, IS92a, the previous GCM models predicted that atmospheric CO_2 would be ~700 ppmv (parts per million by volume) in 2100, while the Cox et al. [33] predictions are much larger, at 980 ppmv. These concentrations depend critically on (1) the alarming dieback of the Eastern Amazon rainforests, caused by climate change-induced drought, and (2) the subsequent release of C from soils. The release of C from soils is critically dependent on the assumed response of respiration to temperature.

Additional mechanisms may also come into play in the near future such as subtle biodiversity, or functional composition changes, and these could plausibly even reverse the current carbon sequestration that we think is currently occurring in undisturbed tropical forests. Firstly, a shift to faster growing species may be occurring as tree mortality rates have increased by ~3 % a^{-1} in recent decades [24, 34], causing an increase in the frequency of tree-fall gaps. This suggests a shift towards light- demanding species with high growth rates at the expense of more shade-tolerant species [23, 35]. Such fast-growing species are associated with lower wood specific gravity, and hence lower volumetric carbon content ([36]). A decrease in mean wood specific gravity across Amazonia of just 0.4 % a^{-1} would be enough remove the carbon sink effect of 0.62 Mg C a^{-1}. As mean stand-level wood specific gravity values differ by >20% among Amazonian forests and species values vary 5-fold [37] it is possible that changes in species composition alone could remove or reverse the current sink contribution of tropical forests [35]. Secondly, lianas are structural parasites that decrease tree growth and increase mortality, and are disturbance adapted [38]. Thus the rapid rise in large lianas across Amazonia, could also turn some surviving forests into a C source over time [25].

While there is considerable uncertainty concerning the future trajectory of the tropical forest biome, (1) continued deforestation will undoubtedly lead to major C additions to the atmosphere, (2) the C sink contribution of remaining undisturbed tropical forests, currently ~15 % of global fossil fuel emissions, appears unlikely to continue for the rest of this century, and (3) plausible mechanisms have been identified which may turn this biome to a modest or even mega-source of C. Mechanisms not currently incorporated into GCM models indicate that projected atmospheric CO_2 concentrations of 700-980 ppmv by 2100 under 'business as usual' scenarios (IS92a) may be conservative. Efforts to limit atmospheric concentrations of CO_2 cannot ignore the danger of substantial net carbon emissions from tropical forests in a globally changing world.

4. References

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