ENVIRONMENTAL RESEARCH LETTERS

PERSPECTIVE • OPEN ACCESS

The enigma of the Amazonian carbon balance

To cite this article: A J Dolman and T A J Janssen 2018 *Environ. Res. Lett.* **13** 061002

Environmental Research Letters

OPEN ACCESS

RECEIVED
1 May 2018

REVISED
22 May 2018

ACCEPTED FOR PUBLICATION
24 May 2018

PUBLISHED
20 June 2018

PERSPECTIVE

The enigma of the Amazonian carbon balance

A J Dolman[1,2] and T A J Janssen[1]

[1] Vrije Universiteit Amsterdam, Department of Earth Sciences, Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
[2] Author to whom any correspondence should be addressed.

E-mail: han.dolman@vu.nl

Keywords: Amazon, carbon dioxide, future climate, tree, models, soil nutrients

Abstract

The carbon balance of the Amazon depends on a complex interplay between climate, soil and tree behaviour. Land surface models have difficulty in reproducing the observed biomass distribution and relationships between net productivity and biomass. A new model representing in more detail the effect of different succession stages is capable of observing this relationship (Rödig *et al* 2018 *Environ. Res. Lett.* 1–40). The key question for future models is how to incorporate more realistically the nutrient influences on growth and that of a future climate enriched with carbon dioxide.

The Amazon basin contains the largest contiguous tropical humid forest on the planet. It stretches from the Atlantic to the Andes and it spans more than five and a half million square kilometres. The forest harbours most of the world's biodiversity while its river systems contribute 20% of the global fresh water resources (Davidson *et al* 2012). The carbon that is stored in biomass equals roughly ten times the current annual fossil fuel emissions (Davidson *et al* 2012). Ground observations suggest that, through tree growth, the Amazon forest acts as a net carbon sink to the atmosphere (Brienen *et al* 2015), which is confirmed by atmospheric studies (Gatti *et al* 2015). However, the sink strength appears to have been declining since the 1990s and recent drought events in 2005, 2010 and 2015 might have temporarily reversed the Amazon carbon sink into a source (Feldpausch *et al* 2016, Gatti *et al* 2015).

Land surface models (LSMs) generally experience difficulties in reproducing the observed spatial variability in above-ground biomass (AGB) across the Amazon basin (Johnson *et al* 2016). This is highly relevant, as we expect standing biomass, forest productivity and biomass turnover to drive the fluxes of water and carbon from the biosphere to the atmosphere. Importantly, in LSMs, biomass gain through above-ground net primary productivity (ANPP) and biomass turnover tend to follow the climatological moisture gradient in the basin, creating a gradient that runs counter to the observed biomass gradient. (Johnson *et al* 2016) showed that the models consistently overestimate ANPP and fail to represent the spatial patterns of both AGB and ANPP when compared to inventory data from 167 plots in the Amazon forest.

So, what is happening in the Amazon? Quesada *et al* (2012) show that edaphic conditions related to soil chemical composition and physical structure drive a basin-wide gradient of forest productivity, tree mortality and AGB. In the geologically younger western Amazon, the soils are still rich in nutrients, most importantly phosphorus, which results in relatively fast forest growth (figure 1). Furthermore, the soils are also shallow and limited rooting depth likely contributes to a high tree mortality and fast biomass turnover in the west of the basin. In the east, the forest grows on very deep but less fertile soils and shows a relatively low growth and a low mortality rate, resulting in a less dynamic forest with a higher AGB. To our knowledge, no LSM is currently able to model this curious feature.

While Quesada *et al* (2012) showed the importance of soil phosphorus as a control on spatial variations in AGB, it is worth emphasizing that this contributes to about 20% of the observed variability in AGB. In their multiple regression, that took into account spatial correlation between observations, almost 50% of the variance remained unexplained with the other 30% was linked to several correlated environmental factors, such as precipitation and temperature. These findings suggest that the Amazon carbon balance emerges from the subtle interplay between climate, soil characteristics and the response of individual trees, with the importance of each contribution relatively unknown. Resolving how these interactions work out will require incorporating tree demography, forest

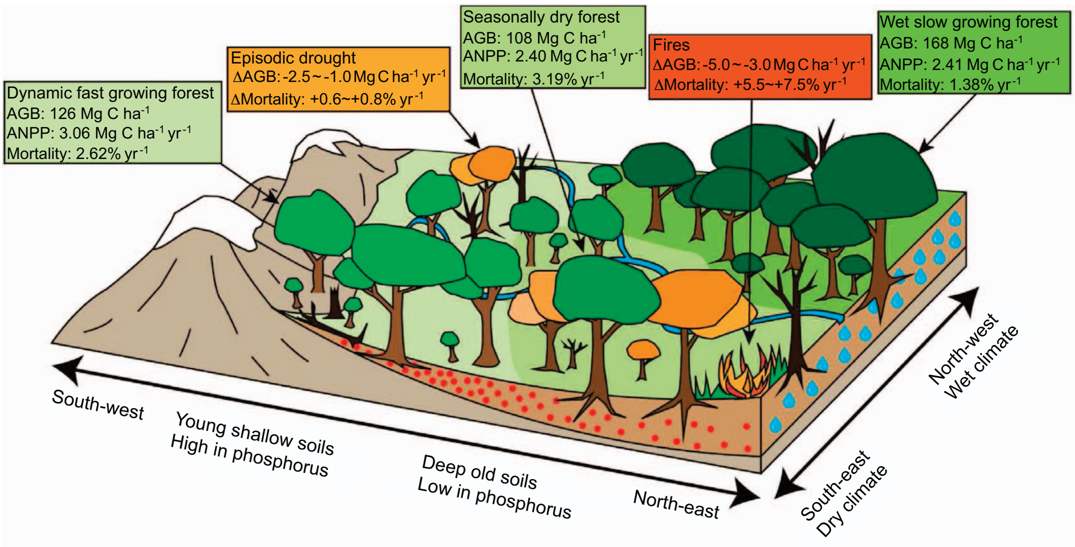

Figure 1. Two perpendicular environmental gradients in the Amazon basin drive the spatial variations in above-ground biomass, forest productivity and tree mortality. Above-ground biomass (AGB, Mg C ha^{-1}), above-ground net primary productivity (ANPP, Mg C ha^{-1} yr^{-1}) and tree mortality (% yr^{-1}) are retrieved from Johnson *et al* (2016). Change in AGB (ΔAGB, Mg C ha^{-1} yr^{-1}) and tree mortality (Δ Mortality, percentage point, % yr^{-1}) for episodic droughts from Feldpausch *et al* (2016), Williamson *et al* (2000) and Phillips *et al* (2009) and for fires from Brando *et al* (2014). Dynamic and highly productive forests are found on fertile and shallow soils in the west of the basin. Seasonally dry forests are found on the Brazilian shield in the south-east of the basin where seasonal drought and recurrent fires limit forest growth and enhance tree mortality resulting in relatively low AGB. In the wet east-central part of the basin, soils are deep and low in phosphorus resulting in relatively low productivity and mortality and high AGB.

structure and plant functional traits into LSMs (Johnson *et al* 2016). Furthermore, other mechanisms that influence tree growth and survival such as soil phosphorus acquisition, storm damage, droughts, fires and deforestation, all deserve a place in future LSMs but have also proven to be notoriously difficult to incorporate into predictive models.

This is the point where Rödig *et al* (2018) enter the stage. The authors incorporated a LIDAR derived canopy height map of the entire Amazon basin into a numerical model that simulates individual tree growth. This allows the model to capture basin-wide differences in forest structure and successional stages at a very high spatial resolution (40 m). Furthermore, the model is able to simulate dynamic forest gaps and individual tree mortality rates, instead of biomass turnover, to estimate standing biomass and carbon fluxes. The major advantage of using an individual tree-based model is that it allows for a dynamic interaction between the environment, forest structure and tree demography. As a consequence, their results differ from previous LSM simulations in one key aspect: the relationship between AGB and NPP. In most existing LSMs, a strong positive linear relation between NPP and AGB emerges in the forest of the Amazon basin that is not observed in the inventory plots (Johnson *et al* 2016). Rödig *et al* (2018) show that when successional stages and individual tree mortality from, for example self-thinning, are incorporated, the model is able to simulate a bell-shaped relation between ANPP and AGB with an optimum of potential ANPP at an AGB of 250 Mg C ha^{-1}, similar to what is observed in inventory plots.

The future of the Amazon basin as a carbon sink is highly uncertain, as the forest remains under threat of expected climate warming and drying, deforestation and a likely increase of episodic drought frequency. Due to its peculiar structure, bounded by the Atlantic Ocean on one side and the Andes mountain range at the other, several amplifying effects and feedbacks operate that can strengthen initial disturbances, shifting precipitation regimes and forest loss far downwind of the original disturbance area (Zemp *et al* 2017). It is therefore essential that LSMs accurately represent the Amazon forest sensitivity to climatic changes, including responses of growth and mortality.

However, in the model of Rödig *et al* (2018), as in other models (Johnson *et al* 2016), ANPP is overestimated. This is especially the case in the slow growing forest of the east-central Amazon (4.3 Mg C ha^{-1} yr^{-1} vs. 2.41 Mg C ha^{-1} yr^{-1} for modelled and observed plot data respectively) and the seasonally dry forests on the Brazilian shield (4.6 Mg C ha^{-1} yr^{-1} vs. 2.40 Mg C ha^{-1} yr^{-1} for modelled and observed plot data respectively)). This suggests that factors limiting forest growth in the east-central Amazon (phosphorus availability) and on the Brazilian shield (seasonal drought) are still not accurately incorporated in current models, leading to overestimations of ANNP and the forest carbon sink. Progress in our understanding of the key mechanisms that drive forest productivity and tree mortality in the Amazon basin under future climate must therefore come from a variety of disciplines. These should include both modellers and experimentalist, that focus on the interactions between edaphic conditions, water availability, forest structure and plant functional traits. The planned Amazon FACE experiment will provide the first testbed for such research (e.g. Hofhansl *et al* 2016).

Acknowledgments

AJD and TAJ are supported by the Netherlands Earth System Science Centre (NESSC), financially supported by the Ministry of Education, Culture and Science (OCW) (grant 024.002.001).

ORCID iDs

A J Dolman https://orcid.org/0000-0003-0099-0457

References

Brienen R J W *et al* 2015 Long-term decline of the Amazon carbon sink *Nature* **519** 344–8

Brando P M *et al* 2014 Abrupt increases in Amazonian tree mortality due to drought-fire interactions *Proc. Natl Acad. Sci.* **111** 6347–52

Davidson E A *et al* 2012 The Amazon basin in transition *Nature* **481** 321–8

Feldpausch T R *et al* 2016 Amazon forest response to repeated droughts *Glob. Biogeochem. Cycles* **30** 964–82

Gatti L V *et al* 2015 Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements *Nature* **506** 76–80

Hofhansl F, Andersen K M, Fleischer K, Fuchslueger L, Rammig A, Schaap K J, Valverde-Barrantes O J and Lapola D M 2016 Amazon forest ecosystem responses to elevated atmospheric CO_2 and alterations in nutrient availability: filling the gaps with model-experiment integration *Front. Earth Sci.* **4** 19

Johnson M O *et al* 2016 Variation in stem mortality rates determines patterns of above-ground biomass in Amazonian forests: implications for dynamic global vegetation models *Glob. Change Biol.* **22** 3996–4013

Phillips O L *et al* 2009 Drought sensitivity of the Amazon rainforest *Science* **323** 1344–7

Quesada C A *et al* 2012 Basin-wide variations in Amazon forest structure and function are mediated by both soils and climate *Biogeosciences* **9** 2203–46

Rödig E, Cuntz M, Rammig A, Fischer R, Taubert F and Huth A 2018 The importance of forest structure for carbon flux estimates in the Amazon rainforest *Environ. Res. Lett.* 1–40

Williamson G B, Laurance W F, Oliveira A A, Delamônica P, Gascon C, Lovejoy T E and Pohl L 2000 Amazonian tree mortality during the 1997 El Nino drought *Conserv. Biol.* **14** 1538–42

Zemp D C *et al* 2017 Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks *Nat. Commun.* **8** 14681