Nutrient constraints on the Amazon carbon sink: from field measurements to model projections

Katrin Fleischer¹, Beto Quesada², David Lapola³, Lucia Fuchslueger⁴, Laynara Lugli², Tatiana Reichert¹, Anja Rammig¹

1 Technical University of Munich, TUM School of Life Sciences Weihenstephan, Freising, Germany
2 National Institute for Amazonian Research, Manaus, Brazil
3 CEPAGRI, University of Campinas, Brazil
4 Centre for Microbiology and Environmental Systems Science, University of Vienna, Austria
The Amazon rainforest provides numerous, globally significant ecosystem services; its contribution to carbon storage in its biomass and continuous sequestration from the atmosphere, is only one of them.

One key question is: How much carbon is the Amazon rainforest storing and sequestering from the atmosphere? And how will this change in response to future climate and elevated atmospheric CO$_2$?

Will the Amazon rainforest continue to sequester carbon from the atmosphere?
The Amazon carbon sink: plot measurements

- **Biomass accumulates carbon worldwide** but decreasing sink strength in the tropics 1990s to 2000s\(^1\) – Are we witnessing increasing limitations (e.g. nutrients, water, light) to the CO\(_2\) fertilization effect?

- **Amazon C sink in strongest decline, continued throughout 2010s and predicted to reach zero by 2030** – But net C sink reductions are mainly due to increases in turnover/mortality, not lowering off productivity.\(^2\)

\(^1\)Pan et al. 2011 Science; \(^2\)Brienen et al. Nature; Hubau et al. 2020 Nature
The Amazon carbon sink: CO₂ experiments

- Free Air CO₂ enrichment (FACE) experiments can assess CO₂ effect at ecosystem scale – Young and temperate forests are sequestering C in response to eCO₂, but experiments from mature forests show no sign of increased carbon storage so far.¹

- No FACE experiment has ever been conducted in mature and highly diverse tropical rainforests – preventing us from reliably foreseeing the eCO₂ effect from a large contributor to the land C sink²*


*Alternating hypothesis: CO₂ treatment (as grey bar) induces higher biomass C accumulation (blue) or accelerates initial growth but does not lead to higher biomass accumulation (red) in young forests (a) and in mature forests (b)
The Amazon carbon sink: CO$_2$ experiments

- Extrapolation in space and time of existing CO$_2$ experiments indicates largest (but moderate) biomass C sink in the tropics$^1$ – but tropical estimate also associated to the greatest uncertainty since experimental evidence is scarce.

- The actual future Amazon carbon sink induced by eCO$_2$ may be overestimated with such extrapolations – Upscaling to the Amazon assumes that responses and feedbacks observed in other FACE experiments are representative for mature and highly diverse forests in the Amazon.

$^1$Terrer et al. Nature Climate Change 2019
Vegetation models project that CO₂ fertilization of plant growth will continue to induce terrestrial C sink – the CMIP5 Earth System Model ensemble predicted a 63% increase in global NPP over the 21st century¹, however this is mainly based on C-only simulations.

CO₂ fertilization effect may by impeded by lack of rock-derived nutrients (e.g. phosphorus) in the tropics – while vegetation models progressively include the P cycle, our lack of understanding has prevented them from being consistently considered in ESM simulations.

¹Kolby Smith et al. Nature Geoscience 2016
The Amazon carbon sink: Vegetation models

• **The status**: Field measurements indicate a declining biomass carbon sink strength, C-only model simulations predict a continuing CO$_2$-induced carbon sink, and experimental evidence (albeit from non-representative systems) points to a moderate sink in the Amazon.

• **The question remains**: Will the Amazon rainforest sequester more carbon in its biomass when exposed to elevated CO$_2$ in the future?

• We performed a model-ensemble (14 vegetation models) to simulate the planned AmazonFACE experiment and derive model-based hypotheses for the experiment (6 models considered P control on productivity, growth and nutrient dynamics)
The Amazon carbon sink: Vegetation models

• Models considering CNP feedbacks projected a lower CO2-induced biomass C sink than models considering C-only or CN interactions¹

• Low soil P availability in the Central Amazon reduces the carbon sink strength, however the response varied across CNP models, inducing 0 - 2 kg C m⁻² after 15 years of eCO₂

• What caused these differences among the CNP models?

¹Fleischer et al. Nature Geoscience 2019
The Amazon carbon sink: vegetation models II

- CNP models represented varying degrees of flexibility in alleviating soil P shortages under eCO₂

- Stoichiometric flexibility and greater carbon allocation to wood aided in increasing P use efficiency (PUE) in some models

- Plant acquisition of less-available P forms was upregulated in some models (e.g. phosphatase-based biochemical mineralization or desorption)

¹Fleischer et al. Nature Geoscience 2019
The Amazon carbon sink: hypotheses

H1. **Low soil P availability will strongly constrain future plant biomass growth response to eCO$_2$** either by downregulating photosynthesis or limiting plant growth directly, or a combination thereof.

H2. Despite the limited soil P supply, **plasticity in vegetation stoichiometry and allocation patterns will allow for some biomass growth** under eCO$_2$.

→ Question whether phenological plasticity alone can result in improved PUE or whether a community shift to better adapted species may improve PUE?

H3. **Plants will increase investments in P acquisition** to increase P supply and allow biomass growth under eCO$_2$ either via greater P interception through fine root production or via greater P liberation from P desorption or biochemical mineralization of P.

→ Question whether these is further room for upregulation of P acquisition mechanisms, on these millennia old ecosystems?
The Amazon carbon sink: further considerations

- The model ensemble encapsulates a range of plausible hypotheses and represents a potential range of biomass C responses to eCO\textsubscript{2} under low soil P availability in the Central Amazon.

- Community response to eCO\textsubscript{2} will depend on species-specific responses in this highly diverse ecosystem\textsuperscript{1}, some species may, other may not further respond to eCO\textsubscript{2}.

- Interactions of eCO\textsubscript{2}-nutrient feedbacks with climatic conditions, drought, and atmospheric moisture circulation need further consideration.

\textsuperscript{1}Turner et al. Nature 2018
The Amazon carbon sink: what we need next

- Research on plant phosphorus acquisition in the Amazon is urgently needed to estimate coverage and governing processes, C costs, etc.¹ – see also Reichert et al. in this session

- Phosphorus controls ecosystem functioning, not necessary limits, but controls functioning in terms of carbon storage and cycling² – models that neglect C-P feedbacks likely overestimate C sink strength (and underestimate adverse climate impacts)

- Exact constrains of soil P availability on the future C sink remain uncertain, also due to varying edaphic, climatic and biogeographical conditions in the Amazon basin³

The Amazon carbon sink: the diverse basin

- The model ensemble of the AmazonFACE project simulated vegetation on impoverished weathered old soils, which are representative of ~32% of Amazon forest (Ferralsol)\(^1\)

- The control of P on forest functioning, and thus its response to environmental change, is expected to vary along the soil fertility gradient in the Amazon\(^2\)

\(^{1}\)Quesada et al. Biogeosciences 2011; \(^{2}\)Quesada & Lloyd, 2016
The Amazon carbon sink: the next step

- Conduct AmazonFACE... see: https://amazonface.inpa.gov.br/

- Conduct **basin-wide model simulations with CNP models** that adequately capture C-P feedbacks, the control of the soil fertility gradient on carbon cycling, and climate interactions

- **Assess simulated resilience of the intact Amazon forest to climate change** and carbon sequestration potential for various scenarios of future atmospheric CO$_2$ and climate conditions
References


