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

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The Amazon rainforest

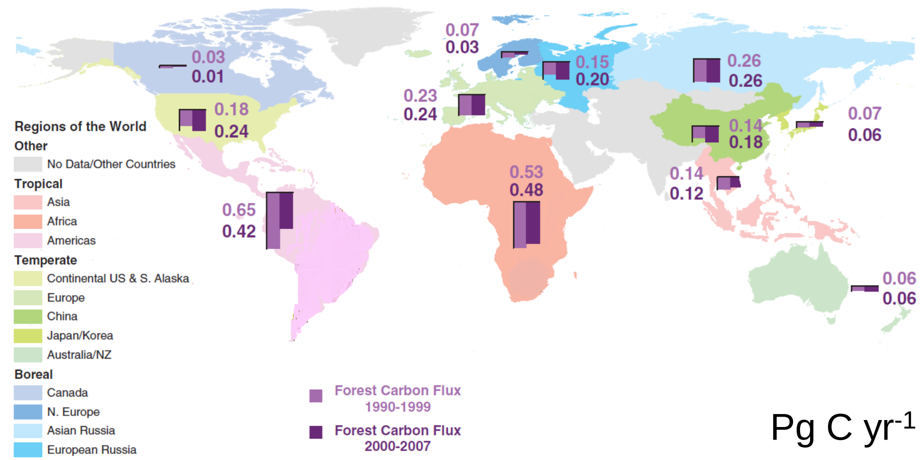
The Amazon rainforest provides numerous, globally significant ecosystem services; it's contribution to carbon storage in its biomass and continuous sequestration from the atmosphere, is only one of them.

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 in the future?

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?



Pg C yr^{-1}

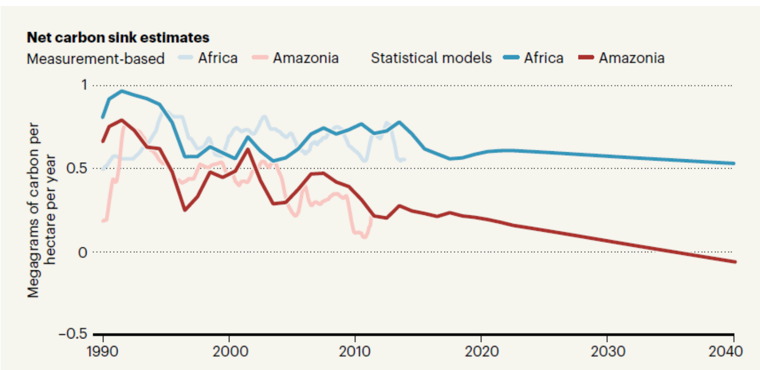


Figure 2 | Estimates and projections of tropical carbon sinks. Hubau *et al.*[4] have estimated the net amount of carbon that was absorbed from the atmosphere by tropical forests – the tropical carbon sinks – in Africa and Amazonia for the period from 1968 to 2015, using measurements of tree establishment, growth and mortality; only estimates from 1990 onwards are shown. The data show that the sink in Amazonia has declined since the 1990s, whereas the African sink was stable for the 30 years up to 2015. The authors also estimated the carbon sinks using statistical models, which they extrapolated to 2040. The extrapolations suggest that, by 2030, the carbon sink in Africa will be 14% lower than in 2010–15, whereas the Amazonian carbon sink will reach zero by 2035. Data shown are mean values; see Fig. 3 of ref. 4 for confidence intervals.

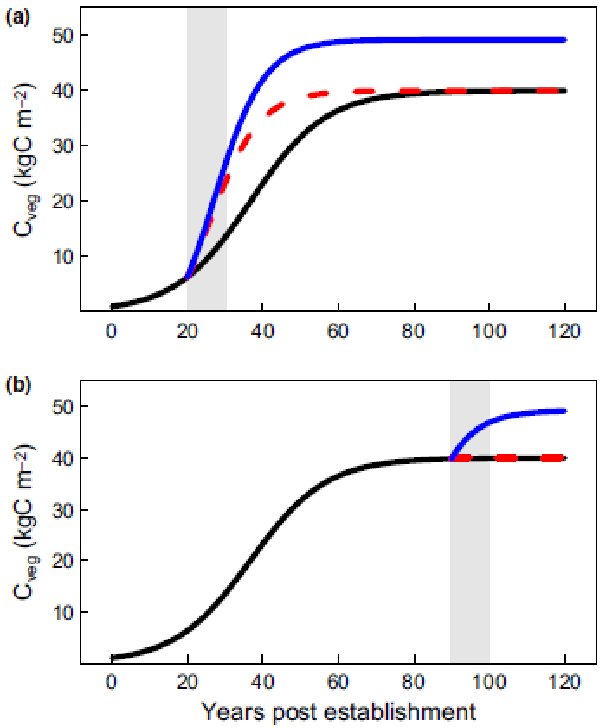
- **Amazon C sink in strongest decline, continued throughout 2010s and** predicted to reach zero by 2030 – But net C sink reductions are mainly due to increases in turnover/mortality, not lowering off productivity.[2]

[1]Pan et al. 2011 Science; [2]Brienen et al. Nature; Hubau et al. 2020 Nature

The Amazon carbon sink: CO_2 experiments

- **Free Air CO_2 enrichment (FACE) experiments can assess CO_2 effect at ecosystem scale** – Young and temperate forests are sequestering C in response to eCO_2, 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 eCO_2 effect from a large contributor to the land C sink[2]*



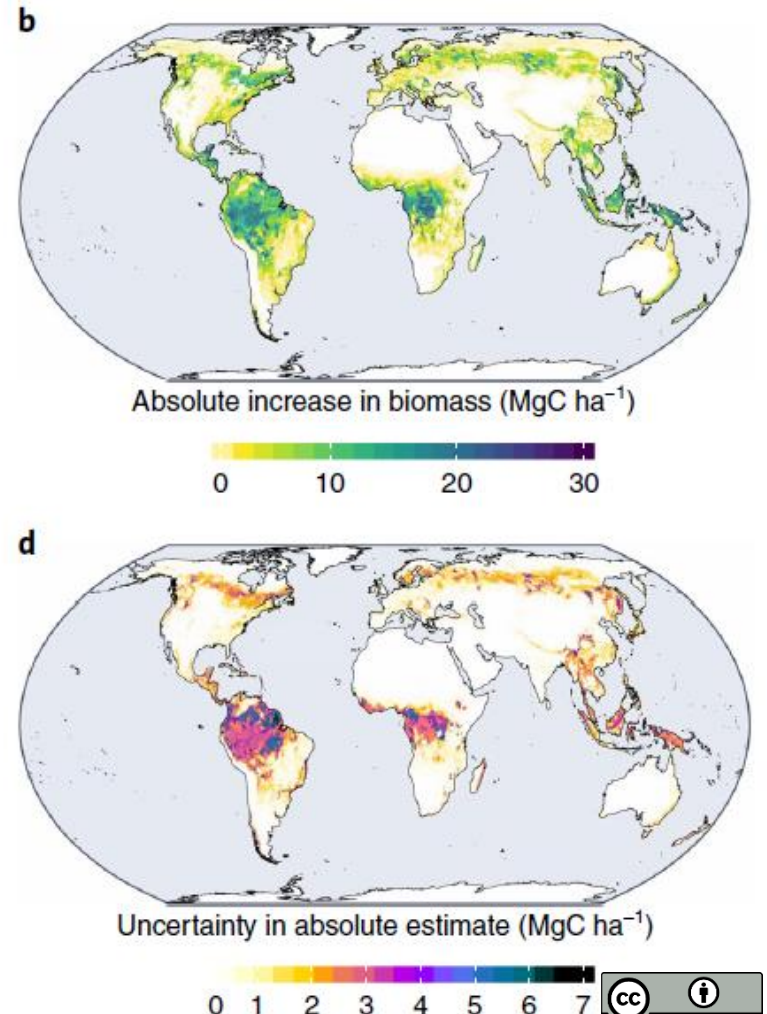
*Alternating hypothesis: CO_2 treatment (as grey bar) induces higher biomass C accumulation (blue) or accelerates initial growth but does not lead to higher biomass accumulation (red) in young forests (a) and in mature forests (b)

[1]Jiang et al. Nature 2020; [2]Norby et al. New Phytologist 2016

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.

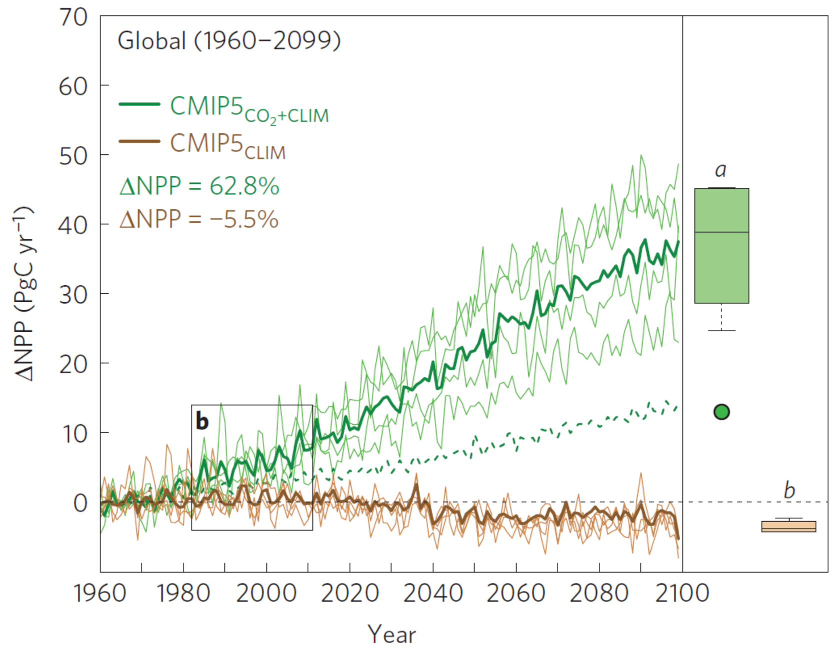


[1]Terrer et al. Nature Climate Change 2019

The Amazon carbon sink: Earth system models

- **Vegetation models project that CO_2 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 century[1], however this is mainly based on C-only simulations

- **CO_2 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



[1]Kolby Smith et al. Nature Geoscience 2016

The Amazon carbon sink: Vegetation models

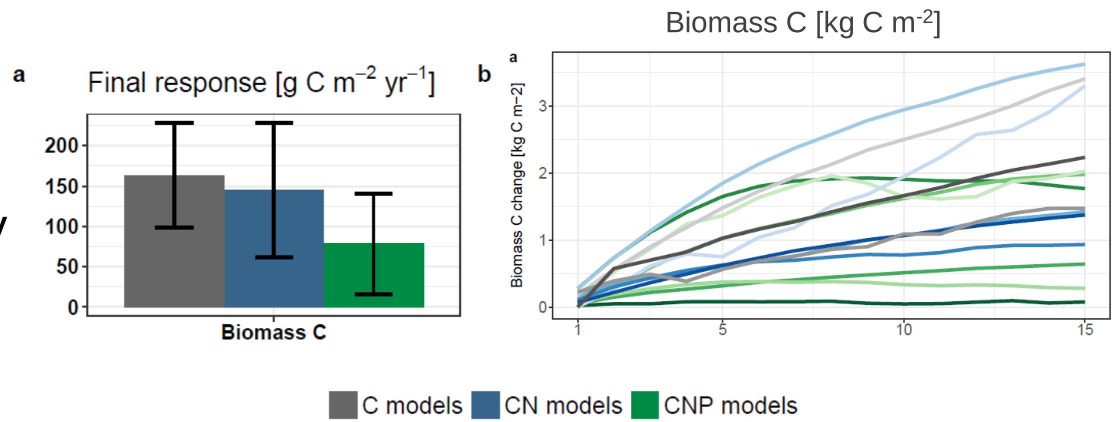
- **The status**: Field measurements indicate a declining biomass carbon sink strength, C-only model simulations predict a continuing CO_2-induced carbon sink, and experimental evidence (albeit from non-representative systems) points to a moderate sink in the Amazon.

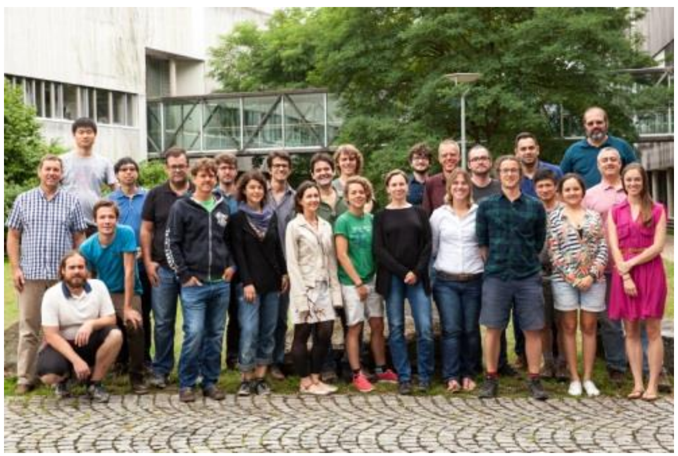
- **The question remains**: **Will the Amazon rainforest sequester more carbon in it's biomass when exposed to elevated CO_2 in the future?**

- 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 CO_2-induced biomass C sink** than models considering C-only or CN interactions[1]





- 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 eCO_2
- **What caused these differences among the CNP models?**

[1]Fleischer et al. Nature Geoscience 2019

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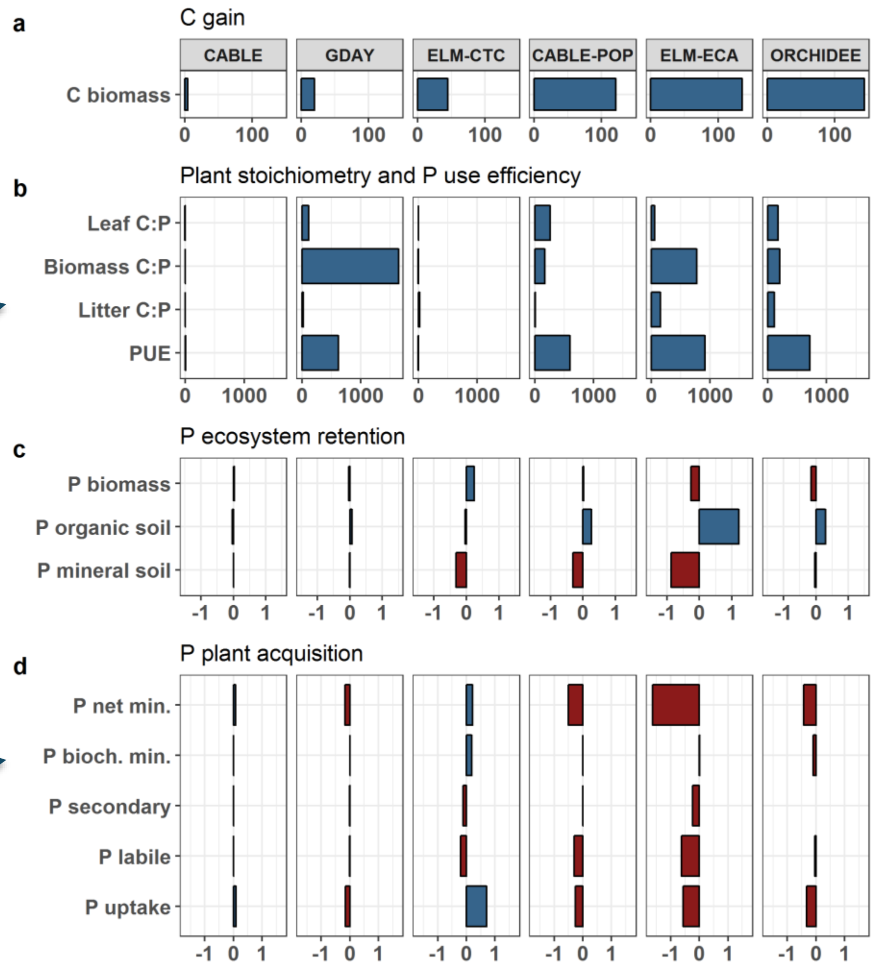
The Amazon carbon sink: vegetation models II

- **CNP models represented varying degrees of flexibility in alleviating soil P shortages under eCO_2**
- 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)



[1]Fleischer 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 there 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_2 under low soil P availability in the Central Amazon

- **Community response to eCO2 will depend on species-specific responses** in this highly diverse ecosystem[1], some species may, other may not further respond to eCO_2

- Interactions of eCO_2-nutrient feedbacks with climatic conditions, drought, and atmospheric moisture circulation need further consideration.

[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 cycling[2] – 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 basin[3]

[1]Lugli et al. Plant and Soil 2019; [2]Quesada et al. Biogeosciences 2012
[3]Esquivel-Muelbert et al. Global Change Biology 2019

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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 it‘s reponse to environmental change, **is expected to vary along the soil fertility gradient in the Amazon**[2]

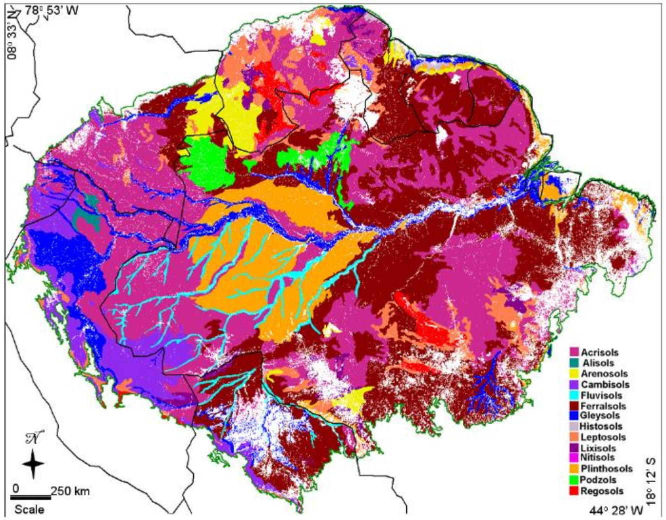
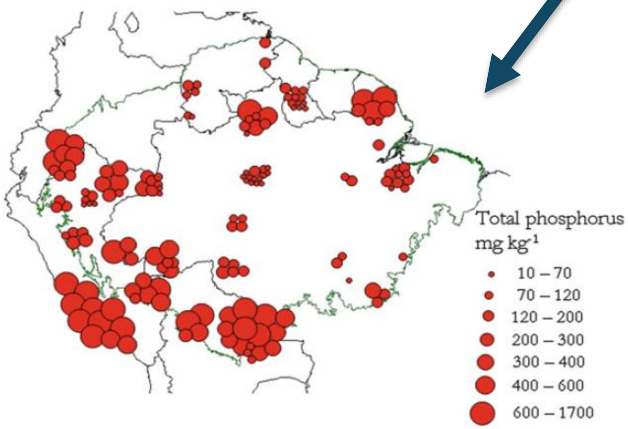


Fig. 4. Basin wide distributions of soils under forest vegetation. Map based on the SOTERLAC–ISRIC soil database (version 2.0, 1:5 million scale) and the vegetation database of Saatchi et al. (2008) for South America.

~60% of soil = Ferralsols, Acrisols
~30% of soil = Plinthosols, Gleysols, Cambisols, Leptosols
~10% of soil = all others (n>8)



[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/
  or watch the MOVIE!
  https://www.youtube.com/watch?v=9dgFl4S-7QE

- 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

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