After the *Long Bloody Arguments* *(LBA)*: An Earth-System perspective on unresolved questions about the Amazon Biome

Michael Keller

USDA Forest Service, International Institute of Tropical Forestry

Jet Propulsion Laboratory, California Institute of Technology

EMBRAPA, Agricultural Informatics

Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)

- The Large-scale Biosphere–Atmosphere Experiment in Amazonia (LBA) is a multinational, interdisciplinary research program led by Brazil. NASA was an active co-sponsor of the first Phase of LBA.

- For Phase I of LBA, the driving scientific questions were,

1. How does Amazonia currently function as a regional entity?
2. How will changes in land use and climate affect the biological, chemical and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate?

In the beginning … scientific themes at the outset of LBA

- <u>Carbon cycling in old-growth forests</u>
  - Eddy covariance was still immature
  - Very few long term forest inventory studies, most oriented towards forestry
- <u>Anthropogenic forest disturbance</u>
  - Clear-cut deforestation extent was already well-quantified and its effects on surface-energy and water budgets had been investigated by ABRACOS
  - Other anthropogenic disturbances including logging, understory fires, and fragmentation were poorly understood
- <u>Regional and global influence of Amazonia</u>
  - Potential effects of Amazon deforestation explored in numerical models considering water and energy budget influences. Carbon not yet modeled at the global scale.

Three key papers …

Carbon Dioxide Uptake by an Undisturbed Tropical Rain Forest in Southwest Amazonia, 1992 to 1993

John Grace,* Jon Lloyd, John McIntyre, Antonio C. Miranda, Patrick Meir, Heloisa S. Miranda, Carlos Nobre, John Moncrieff, Jon Massheder, Yadvinder Malhi, Ivan Wright, John Gash

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Most of the world's tropical forest is mature and undisturbed, and little is known about its carbon balance. Ecologists consider that in an unvarying environment, undisturbed ecosystems are in a steady state such that photosynthetic gains are balanced by respiratory losses due to death and decomposition. However, the terrestrial biosphere may be undergoing fertilization as a result of increasing concentrations of CO_2 coupled with higher deposition rates of nitrogen (*1*, *2*). If this is the case, undisturbed tropical forest may be a large sink of CO_2 because of its huge area (3), 10×10^{12} m^2. Now we report direct measurements of CO_2 flux over tropical rain forest in the Brazilian Amazon, to test the hypothesis that virgin forest sequesters carbon from the atmosphere.

We measured fluxes of CO_2, water vapor, and sensible heat over undisturbed forest (*4*) at Reserva Jaru, Rondonia, Brazil (10°04.84'S, 61°56.60'W), during the dry and wet seasons (September 1992 and April to June 1993, respectively). An eddy co-

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Large-scale impoverishment of Amazonian forests by logging and fire

Daniel C. Nepstad*†, Adalberto Verissimo‡, Ane Alencar†, Carlos Nobre§, Eirivelthon Lima†, Paul Lefebvre*†, Peter Schlesinger*, Christopher Potter‖, Paulo Moutinho†, Elsa Mendoza†¶, Mark Cochrane*† & Vanessa Brooks‖

Amazonian deforestation rates are used to determine human effects on the global carbon cycle[1–3] and to measure Brazil's progress in curbing forest impoverishment[1,4,5]. But this widely used measure of tropical land use tells only part of the story. Here we present field surveys of wood mills and forest burning across Brazilian Amazonia which show that logging crews severely damage 10,000 to 15,000 km^2 yr^{-1} of forest that are not included in deforestation mapping programmes. Moreover, we find that surface fires burn additional large areas of standing forest, the destruction of which is normally not documented. Forest impoverishment due to such fires may increase dramatically when severe droughts provoke forest leaf-shedding and greater flammability; our regional water-balance model indicates that an estimated 270,000 km^2 of forest became vulnerable to fire in the 1998 dry season. Overall, we find that present estimates of annual deforestation for Brazilian Amazonia capture less than half of the forest area that is impoverished each year, and even less during years of severe drought. Both logging and fire increase forest vulnerability to future burning[6,7] and release forest carbon stocks to the atmosphere, potentially doubling net carbon emissions from regional land-use during severe El Niño episodes. If this forest impoverishment is to be controlled, then logging activities need to be restricted or replaced with low-impact timber harvest techniques, and more effective strategies to prevent accidental forest fires need to be implemented.

Human uses of tropical forests vary greatly in their ecological impacts. Ranchers and farmers 'deforest' land in preparation for cattle pasture and crops by clear-cutting and burning patches of forest. Loggers do not clear-cut and burn, but perforate forests by harvesting or damaging many trees. Rubber tapping and similar activities use the forest at very low intensity through the harvest of animals, fruits, latex and other "non-timber products"[8–11]. Deforestation by ranchers and farmers has a greater effect on forest carbon content, forest hydrology, and the diversity of native plant and animal species than other forest uses[8–14] and has become the main parameter by which human effects on tropical forests are measured. Part of the appeal of this forest versus non-forest approach to assessing human effects on tropical forests is its tractability. Forest conversion to agriculture is readily monitored from space using imagery from the Landsat Thematic Mapper (TM) satellites, permitting the development of deforestation maps of large regions at a reasonable cost and speed[4,5].

This binary approach to the analysis of human effects on tropical forests neglects those forest alterations that reduce tree cover, but do not eliminate it, such as logging and surface fires in standing forests. The forest openings created by logging and accidental surface fires are visible in Landsat TM images, but they are covered over by regrowing vegetation within 1 to 5 years, and are easily misclassified in the absence of accompanying field data[15]. Although logging and forest surface fires usually do not kill all trees, they severely damage forests. Logging companies in Amazonia kill or damage 10–40% of the living biomass of forests through the harvest process[9,13,16]. Logging also increases forest flammability by reducing forest leaf canopy coverage by 14–50%[7,9,16,18,17], allowing sunlight to penetrate to the forest floor, where it dries out the organic debris created by the logging. Fires ignited on agricultural lands can penetrate logged forests[6,7,18], killing 10–80% of the living biomass[6,27] and greatly increasing the vulnerability of these forests to future burning[6,18]. Fires from agricultural lands can also penetrate those undisturbed forests that have lost portions of their leaf canopies because of severe seasonal drought[19].

We estimated the area of Brazilian Amazonian forest that is impoverished each year through logging by interviewing 1,393 wood mill operators, representing more than half of the mills located in 75 logging centres (Table 1); these logging centres are responsible for >90% of Amazonian timber production. In each interview, we obtained the mill's harvest records of roundwood (tree trunks) for 1996 and 1997 and the harvest rate (m^3 of timber per ha of forest), thereby calculating the forest area required to supply each centre's timber production. The accuracy of the roundwood harvest rates reported by mill operators was tested by comparing these interview data with direct measurements of roundwood harvest in

Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model

Peter M. Cox*, Richard A. Betts*, Chris D. Jones*, Steven A. Spall* & Ian J. Totterdell†

* Hadley Centre, The Met Office, Bracknell, Berkshire RG12 2SY, UK
† Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK

The continued increase in the atmospheric concentration of carbon dioxide due to anthropogenic emissions is predicted to lead to significant changes in climate[1]. About half of the current emissions are being absorbed by the ocean and by land ecosystems[2], but this absorption is sensitive to climate[3,4] as well as to atmospheric carbon dioxide concentrations[5], creating a feedback loop. General circulation models have generally excluded the feedback between climate and the biosphere, using static vegetation distributions and CO_2 concentrations from simple carbon-cycle models that do not include climate change[6]. Here we present results from a fully coupled, three-dimensional carbon–climate model, indicating that carbon-cycle feedbacks could significantly accelerate climate change over the twenty-first century. We find that under a 'business as usual' scenario, the terrestrial biosphere acts as an overall carbon sink until about 2050, but turns into a source thereafter. By 2100, the ocean uptake rate of 5 Gt C yr^{-1} is balanced by the terrestrial carbon source, and atmospheric CO_2 concentrations are 250 p.p.m.v. higher in our fully coupled simulation than in uncoupled carbon models[2], resulting in a global-mean warming of 5.5 K, as compared to 4 K without the carbon-cycle feedback.

The general circulation model (GCM) that we used is based on the third Hadley Centre coupled ocean–atmosphere model, HadCM3[7], which we have coupled to an ocean carbon-cycle model (HadOCC) and a dynamic global vegetation model (TRIFFID). The atmospheric physics and dynamics of our GCM are identical to those used in HadCM3, but the additional computational expense of including an interactive carbon cycle made it necessary to reduce the ocean resolution to $2.5° \times 3.75°$, necessitating the use of flux adjustments in the ocean component to counteract climate drift. HadOCC accounts for the atmosphere–ocean exchange of CO_2, and the transfer of CO_2 to depth through both the solubility pump and the biological pump[8]. TRIFFID models the state of the biosphere in terms of the soil carbon, and the structure and coverage of five functional types of plant within each model gridbox (broadleaf tree, needleleaf tree, C_3 grass, C_4 grass and shrub). Further details on HadOCC and TRIFFID are given in Methods.

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Three key papers

- **Carbon balance of old growth forests**
  - Grace et al. (1995) Carbon dioxide uptake by an undisturbed tropical rain forest in Southwest Amazonia, 1992 to 1993. *Science* 270: 778-780.
- **Forest degradation by logging and fire**
  - Nepstad et al. (1999) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398: 505-508.
- **Regional influences of Amazonia and Earth system feedbacks**
  - Cox et al. (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408: 184-187.

Carbon cycling in old growth forests …

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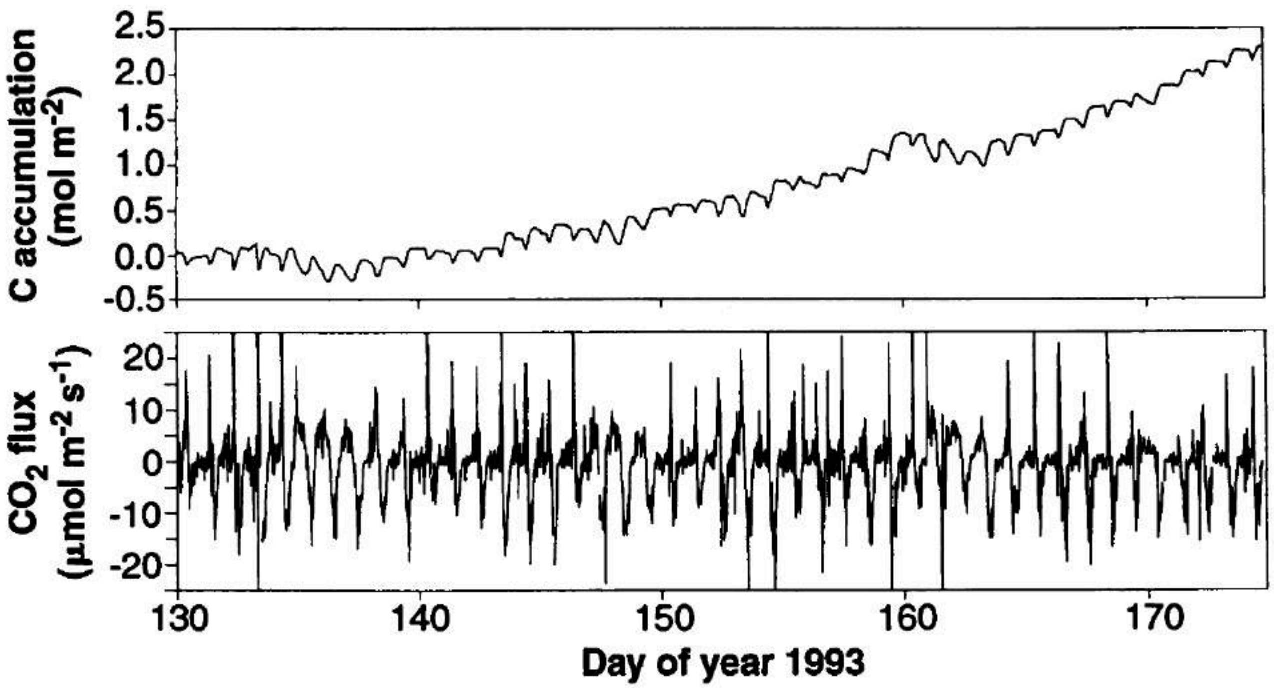


Challenge to dogma…

- ”Grace et al. have now called into question the steady-state assumption for *undisturbed* tropical forests. Determining whether or not tropical forest ecosystems are indeed important global carbon sinks will require an understanding of their historical and spatial complexity” [Keller et al. 1996]
- Scientific concerns
  - Obviously, this was a study at a single site
  - Interannual variability (study in 1992-1993 followed mid-1991 Pinatubo eruption)
  - Recovery from the 1983 El Niño or even older drought disturbance
  - Anthropogenic disturbance at this riverine site

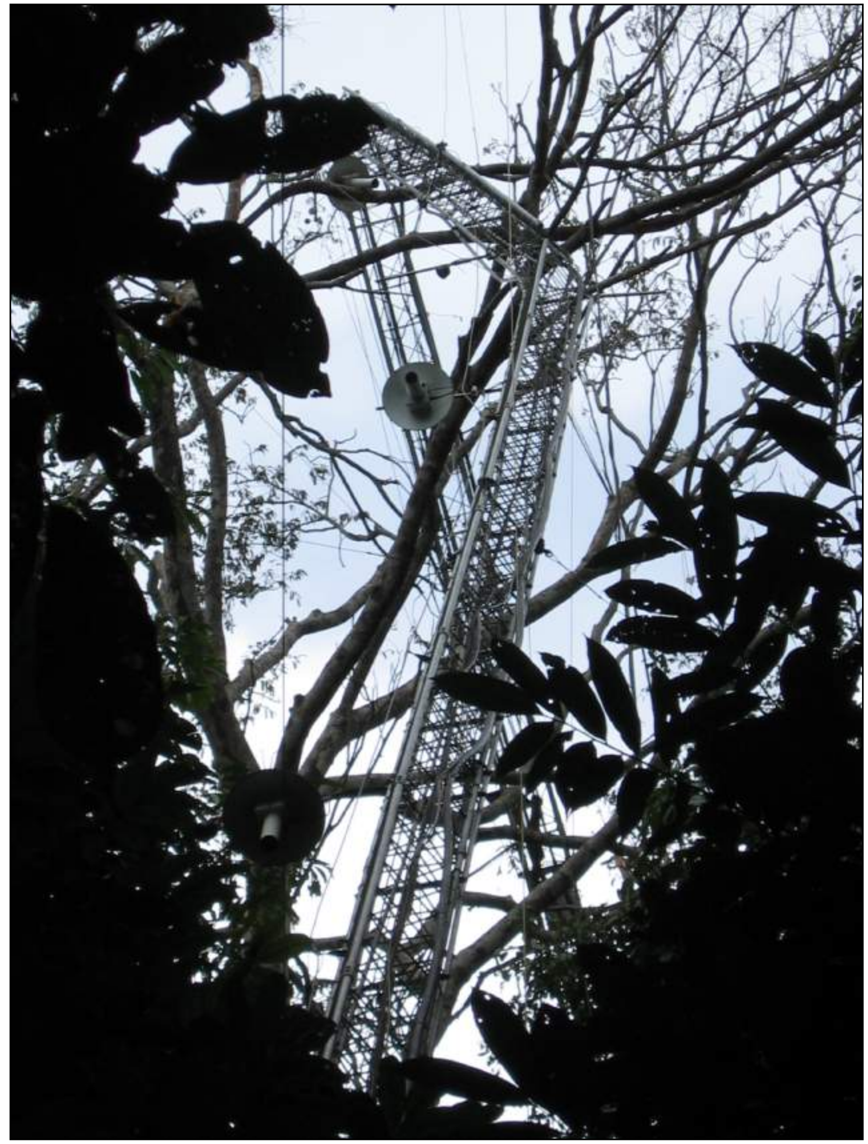
Methodological concerns …

“If a tree falls in the forest….”

“Who would risk siting a 45 m tower and $100,000 of delicate instrumentation near a senescent emergent?”

Keller et al. *Science,* 1996

Be careful what you ask for!



Forest inventory plots of the RAINFOR network also find carbon uptake

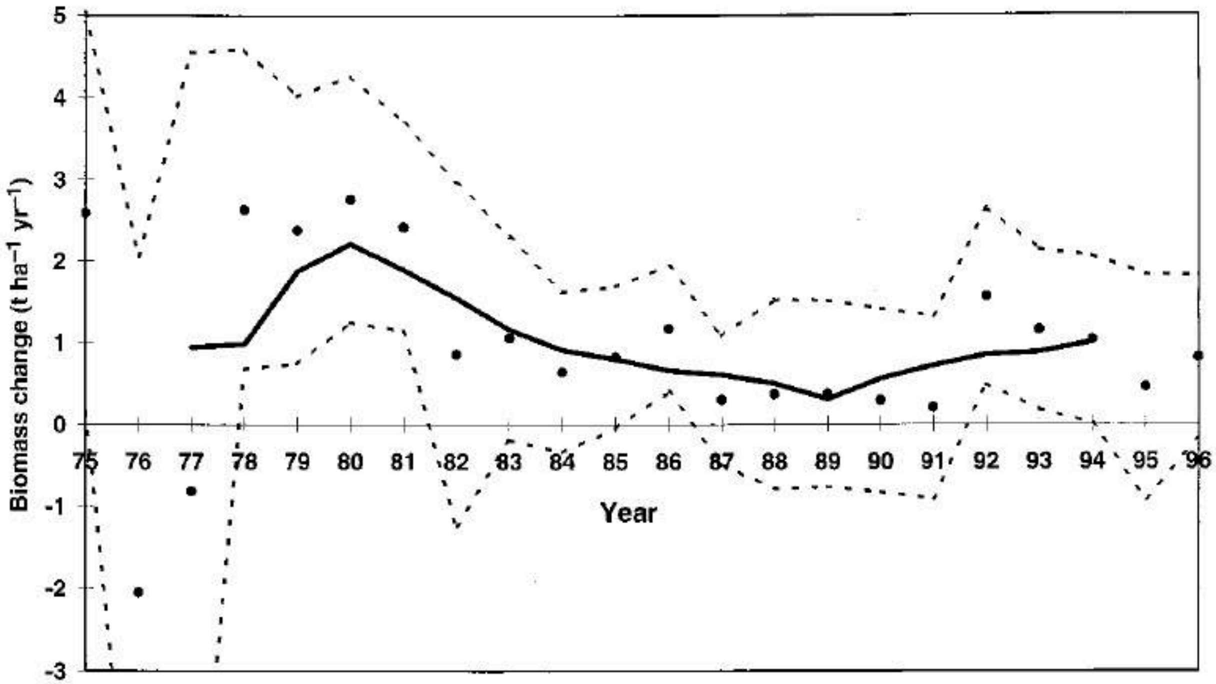
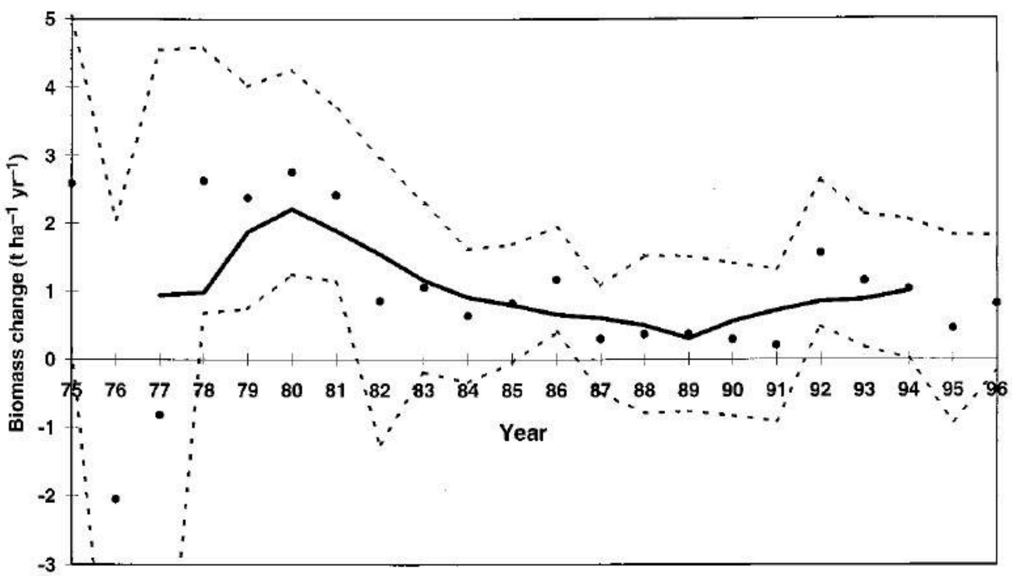


Fig. 1. Annual aboveground biomass change in Amazonian forests, 1975–96. Mean (solid circles), 95% confidence intervals (dotted line), and 5-year moving average (solid line) are shown.

Phillips et al. 1998

Forest inventory plots of the RAINFOR network also show carbon uptake ... Until they don't



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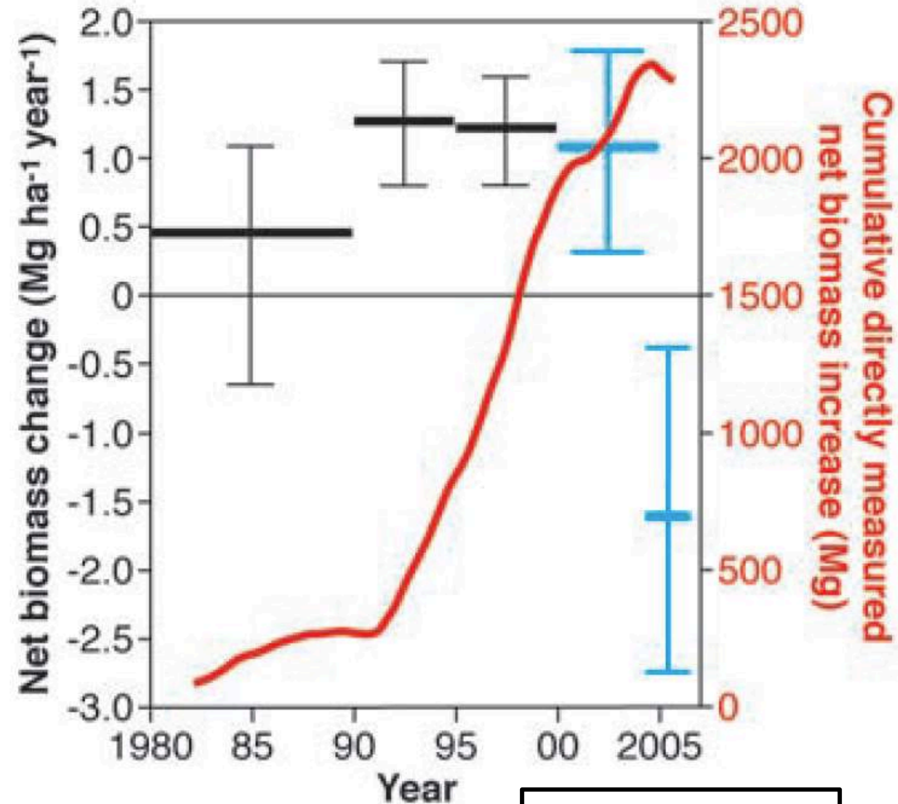
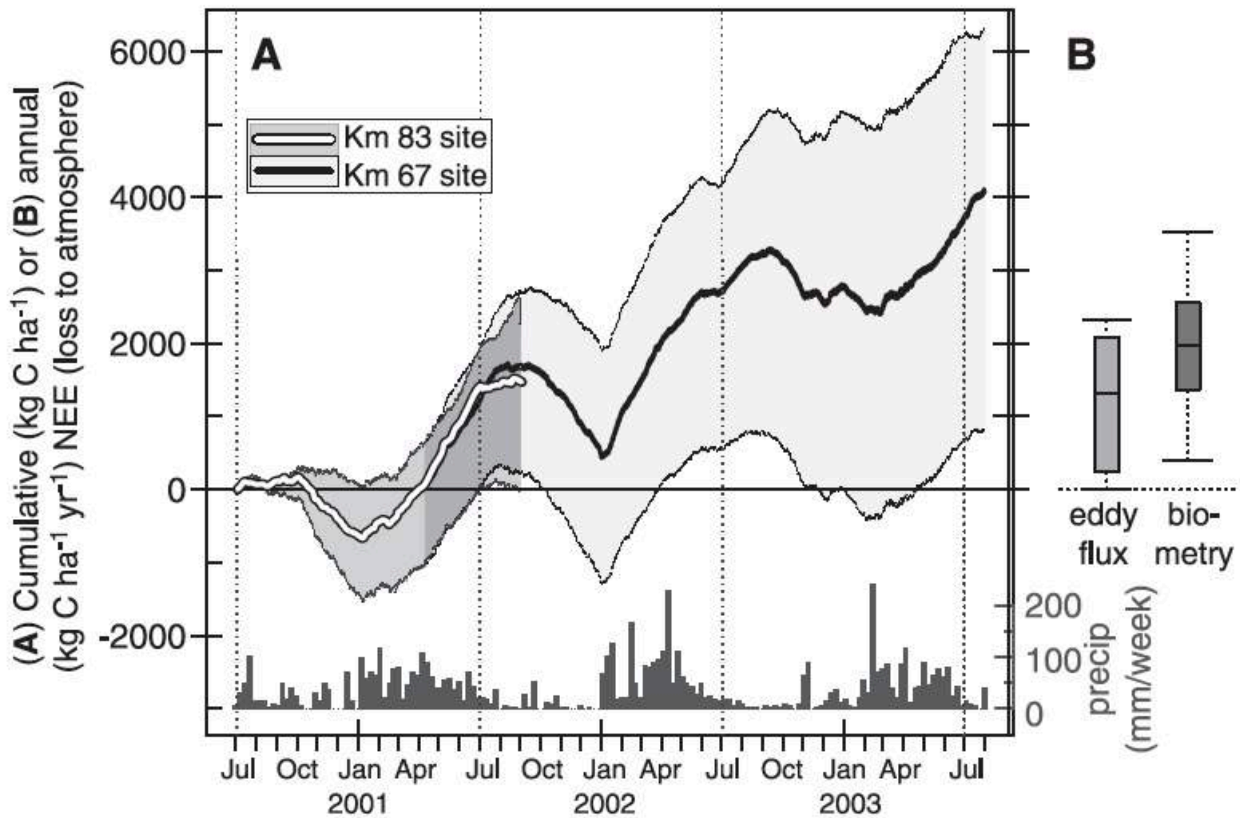


Phillips et al. 2009

Inevitably, an eddy covariance tower forest site also had to lose carbon

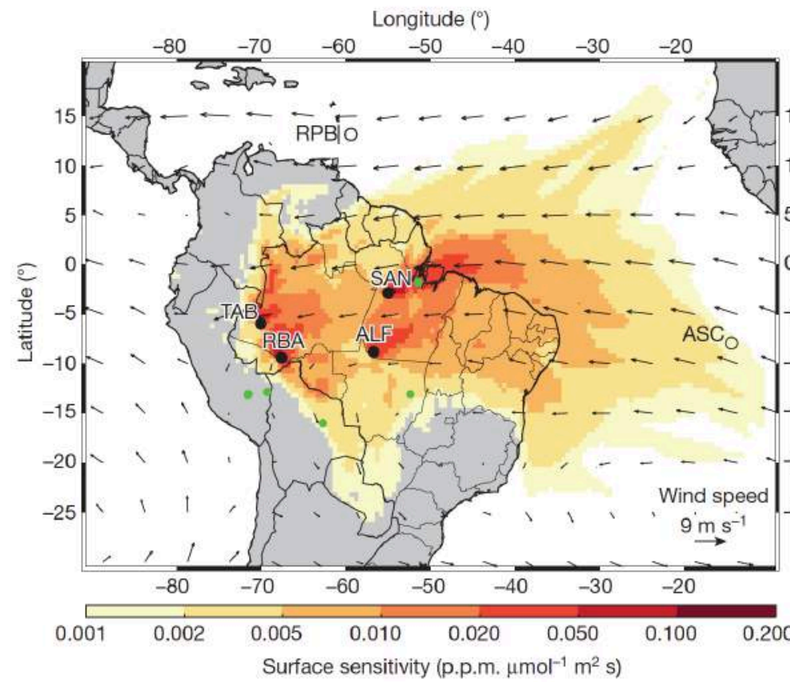
- Carbon loss to the atmosphere at the Tapajos National Forest eddy covariance tower sites was related to high rates of tree mortality prior to the start of observations possibly related to the 1997-1998 ENSO event. The sites had unusually large accumulations of woody debris.



Saleska et al. 2003

Carbon budgets from atmospheric observations

- Sampling from aircraft profiles
- Fluxes estimated from integrated mole fraction differences compared to coastal values divided by the air-mass travel time from the coast to the sampling site

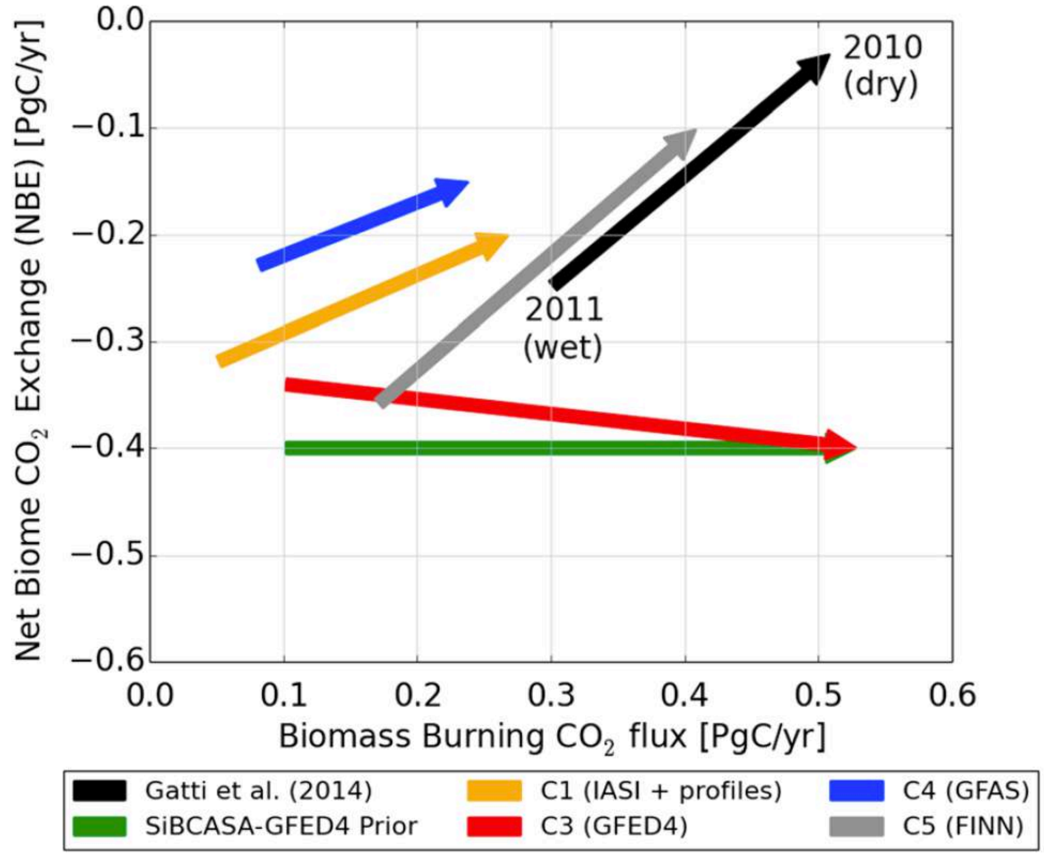


Gatti et al. 2014	2010 (Dry) (Pg C y^{-1})	2011 (Wet) (Pg C y^{-1})
Total	0.48 ± 0.18	0.06 ± 0.10
Fire	0.51 ± 0.12	0.30 ± 0.10
NBE	-0.03 ± 0.22	-0.25 ± 0.14

Gatti et al. 2014

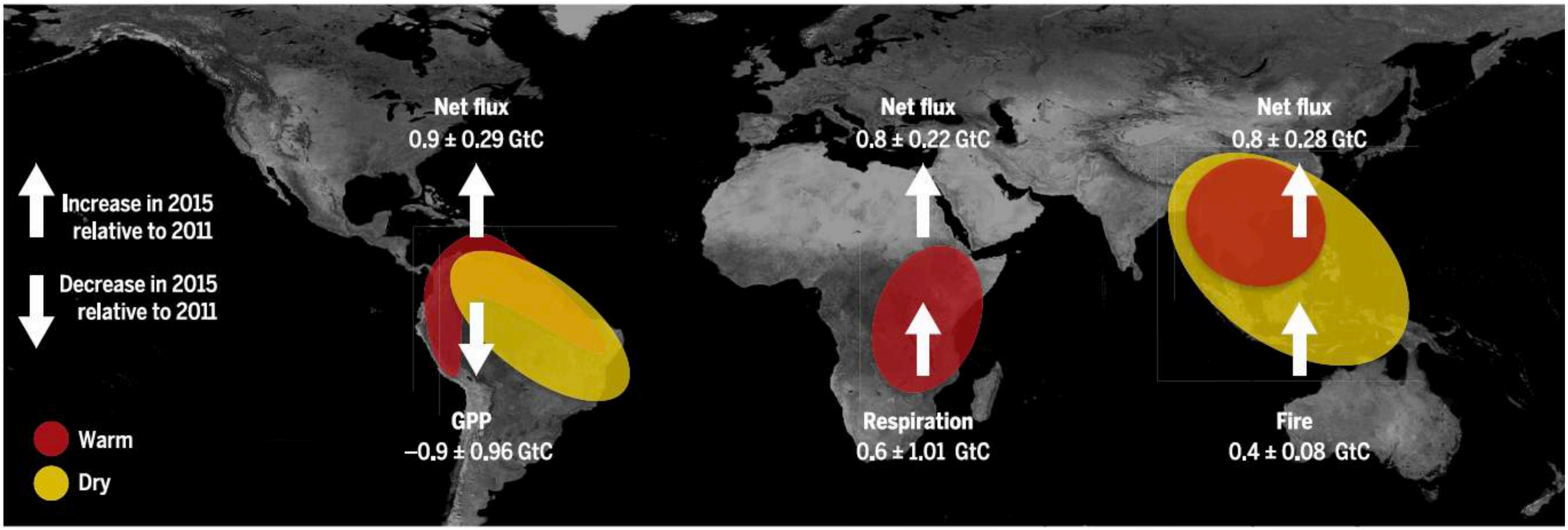
Carbon budgets from atmospheric sampling (revisited)

- Uncertainty in the results from Gatti et al. (2014) are illustrated here based on variable inputs for the CO_2 from fires.
- In most cases, the result is similar but the magnitude of the difference between dry and wet years is diminished.



van der Laan-Luijkx et al. 2015

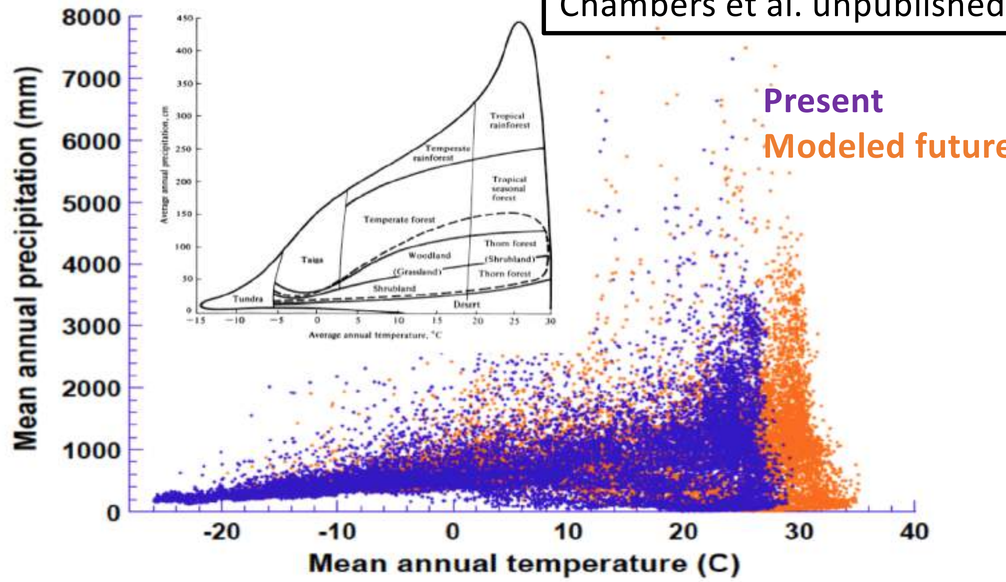
Present and future observations include total column CO_2 from space



Liu et al. 2017

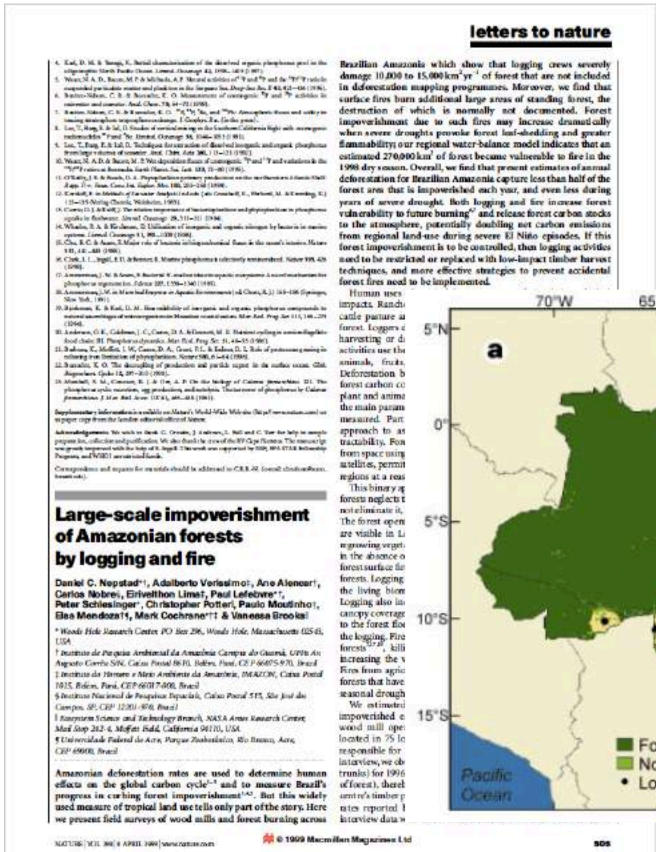
What about that sink?

Chambers et al. unpublished



- We are moving toward a no analog state for tropical forests!
- Is there an old growth forest sink?
- What is the cause of that sink?
  - CO_2 fertilization?
  - Recovery from disturbance?
- How will the old growth forest respond to changing climate conditions (temperature, rainfall, VPD)?
- If the old growth forest is a sink, how long can it remain so?
- That leads us to anthropogenic disturbance …

Anthropogenic forest disturbance (we did not call it degradation in 1999)


letters to nature

Large-scale impoverishment of Amazonian forests by logging and fire

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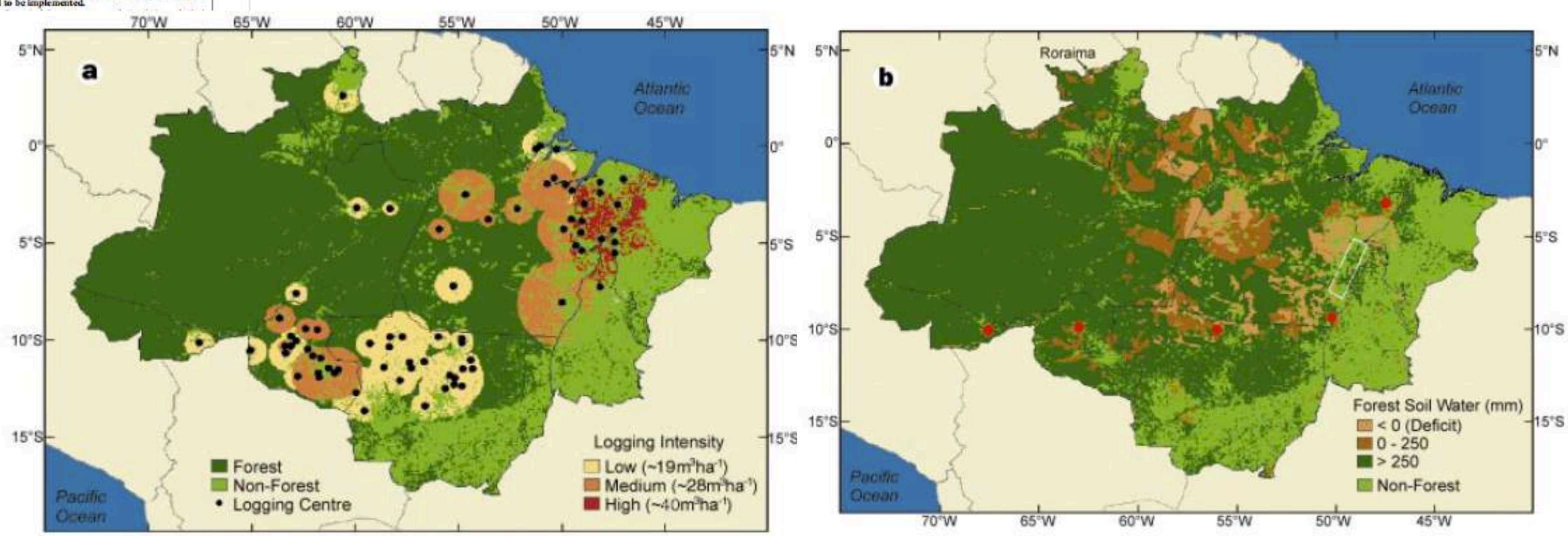
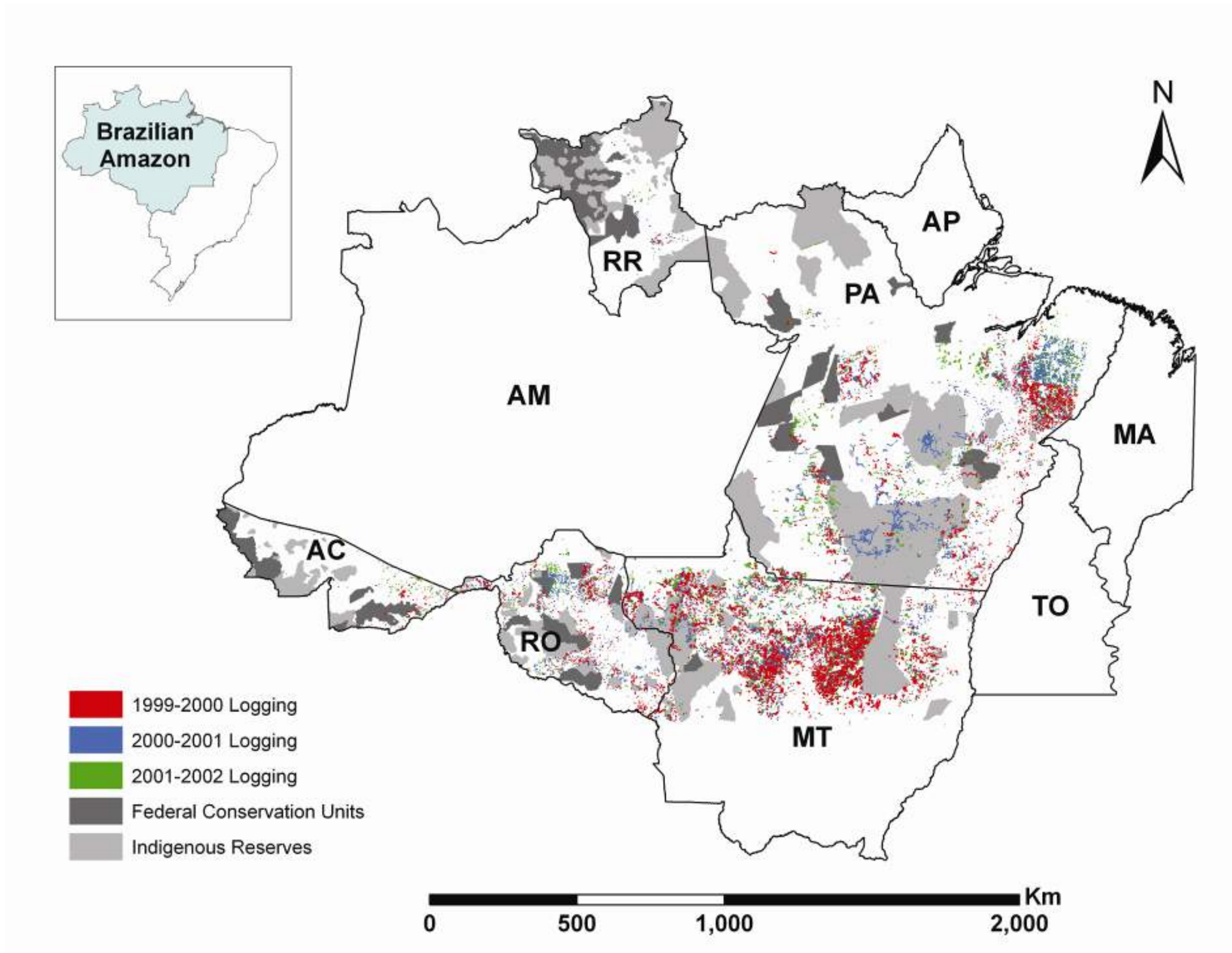


Nepstad et al. 1999

Logging

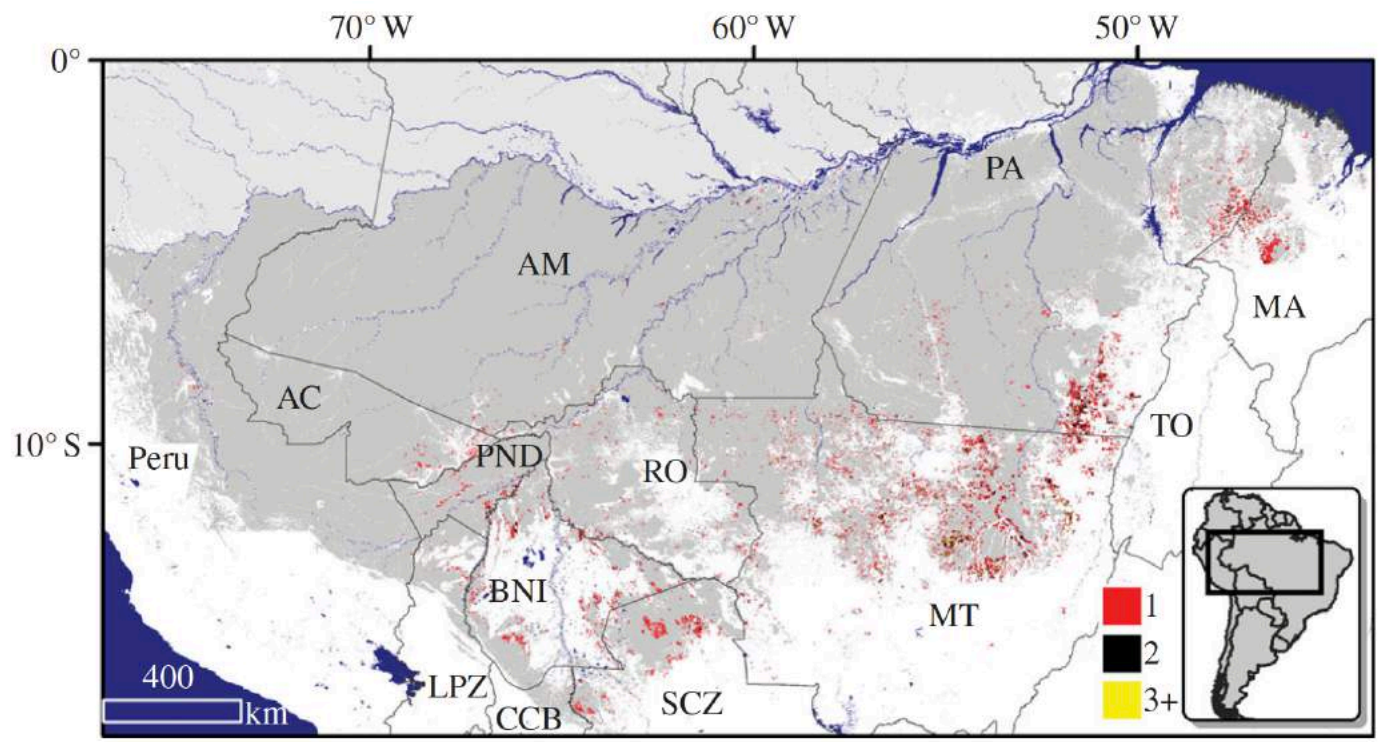
- Semi-automated interpretation of Landsat data based on a spectral mixing model
- Logging 1999-2002
- 12,000 to 20,000 km^2 y^{-1}
- Similar magnitude to deforestation at that time
- Similar magnitude to estimates based on sawmill surveys



Asner et al. 2005

Understory fire

- Results based on temporal filtering of MODIS NDVI
- 85,000 km^2 of understory fire from 1999-2010
- Forests that burned more than once accounted for 16% of all understory fires.

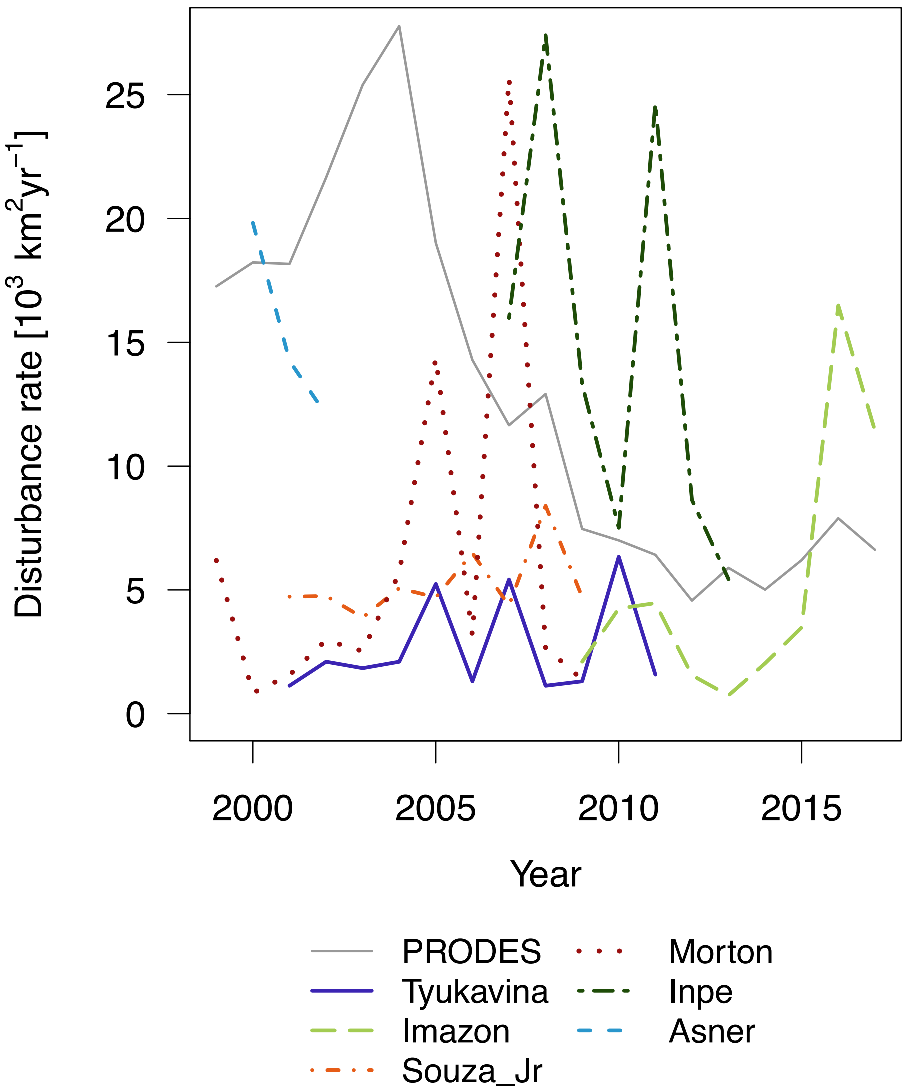


Morton et al. 2013

Fire continues to be a major threat to Amazon ecosystem integrity. In 2015 to 2016 over 40,000 km^2 of forest suffered fires exclusive of clear-cut deforestation

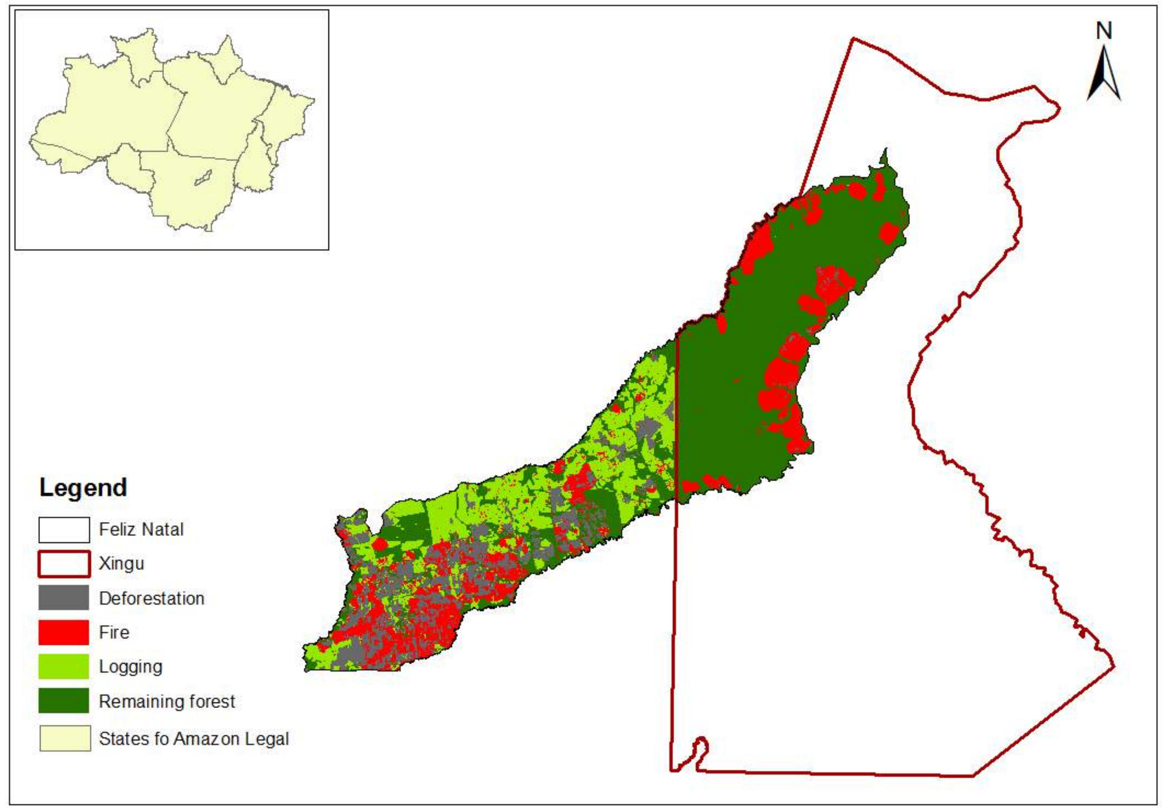
Degradation estimates are highly variable

- Estimates of degradation consider different processes (logging, burning, all), have different thresholds, spatial scales, and temporal definitions.
- Degradation can occur more than once.
- Forests recover from degradation at unknown rates
- Degradation estimates have been minimally validated and are not operational.



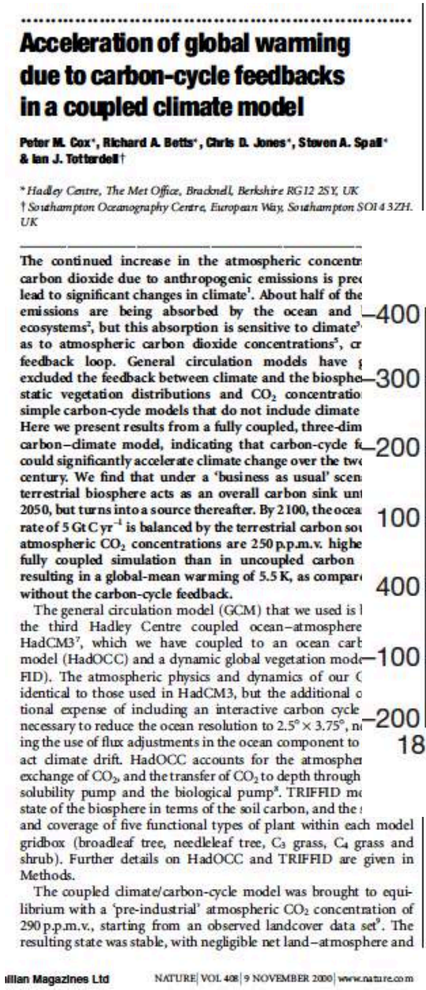
Degradation questions

- Where is degraded forest located and what is its extent?
- What is the rate of degradation?
- Is degraded forest recovering or continuing to degrade? At what rates?
- How does degradation affect forest energy, water, and carbon budgets?



Municipality of Feliz Natal, Mato Grosso, Brazil

Regional and global influences of Amazonia



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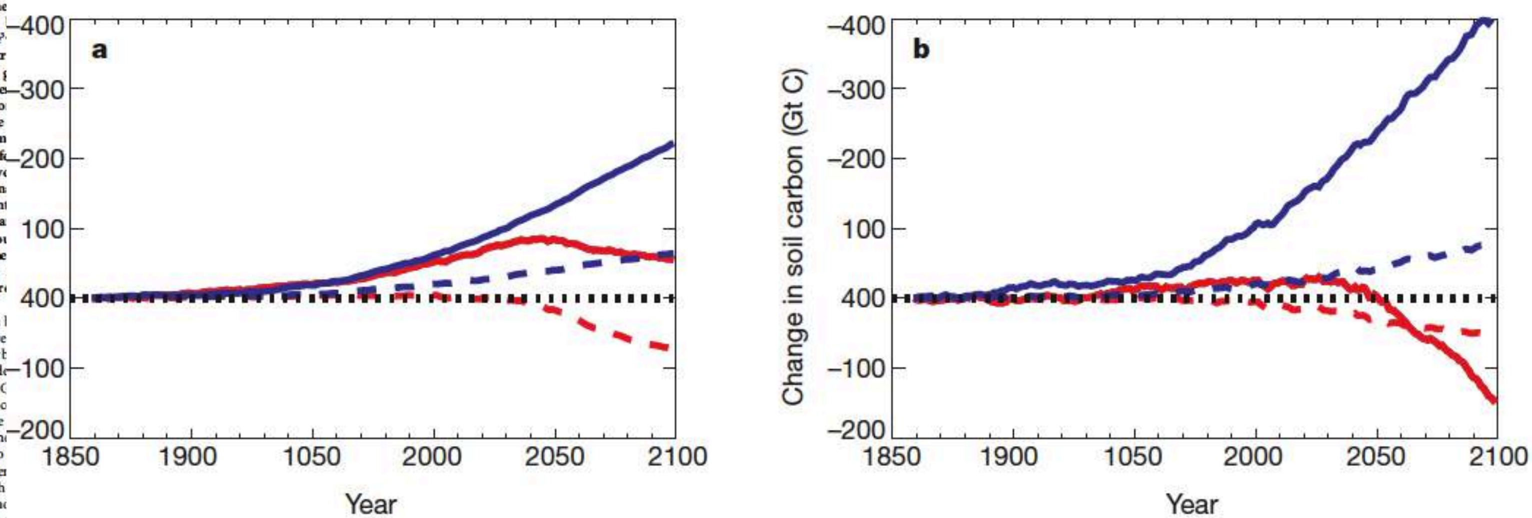
- Importance of climate + carbon cycle feedbacks
- Amazon tipping point concept for the Earth System

Vegetation carbon

Soil carbon



Global

South America

Fully coupled

Offline

Birth of the Amazon Tipping Point

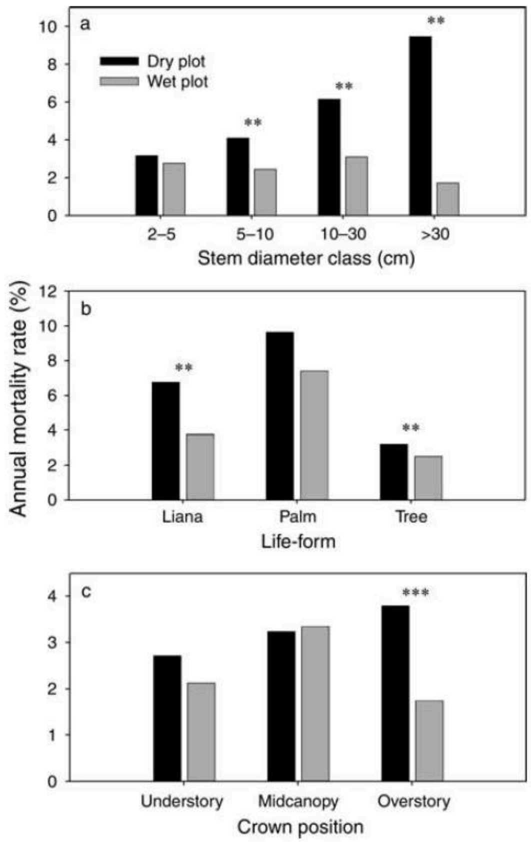
- “Amazon forest dieback” enters our vocabulary
- But, how do trees die? (Drought experiments)

Caxiuanã throughfall exclusion

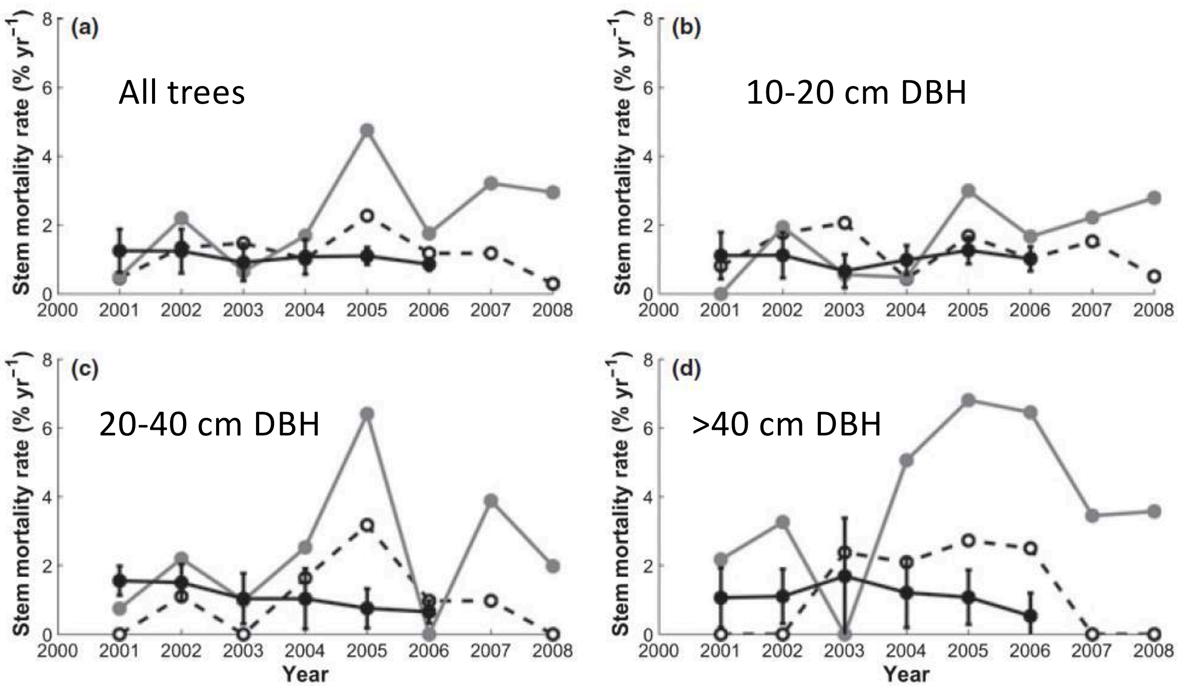
Drought experiments

- Mortality take years
- Large trees suffer greater mortality

Drought
Control
Ambient

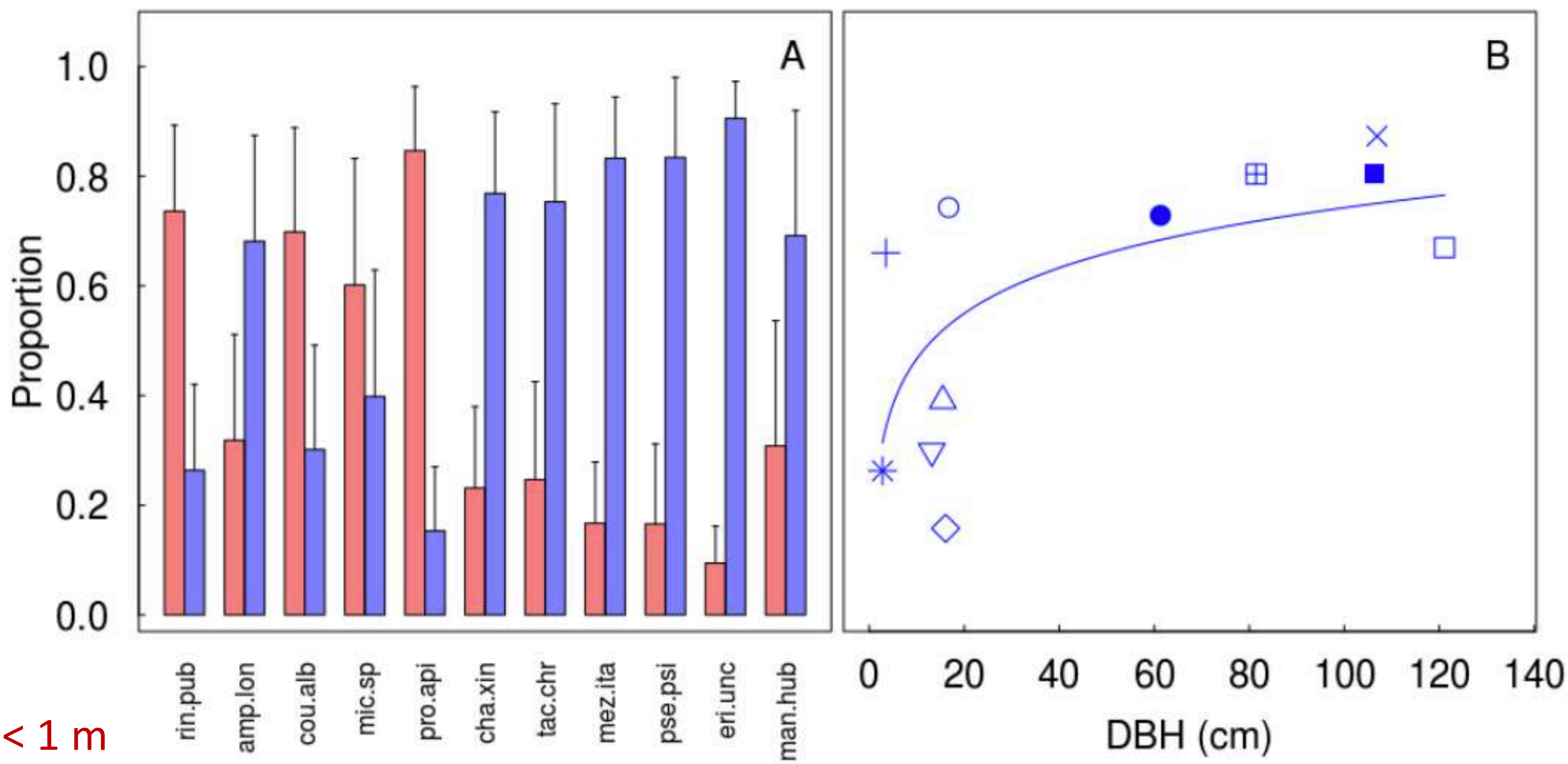


Nepstad et al. 2007



da Costa et al. 2010

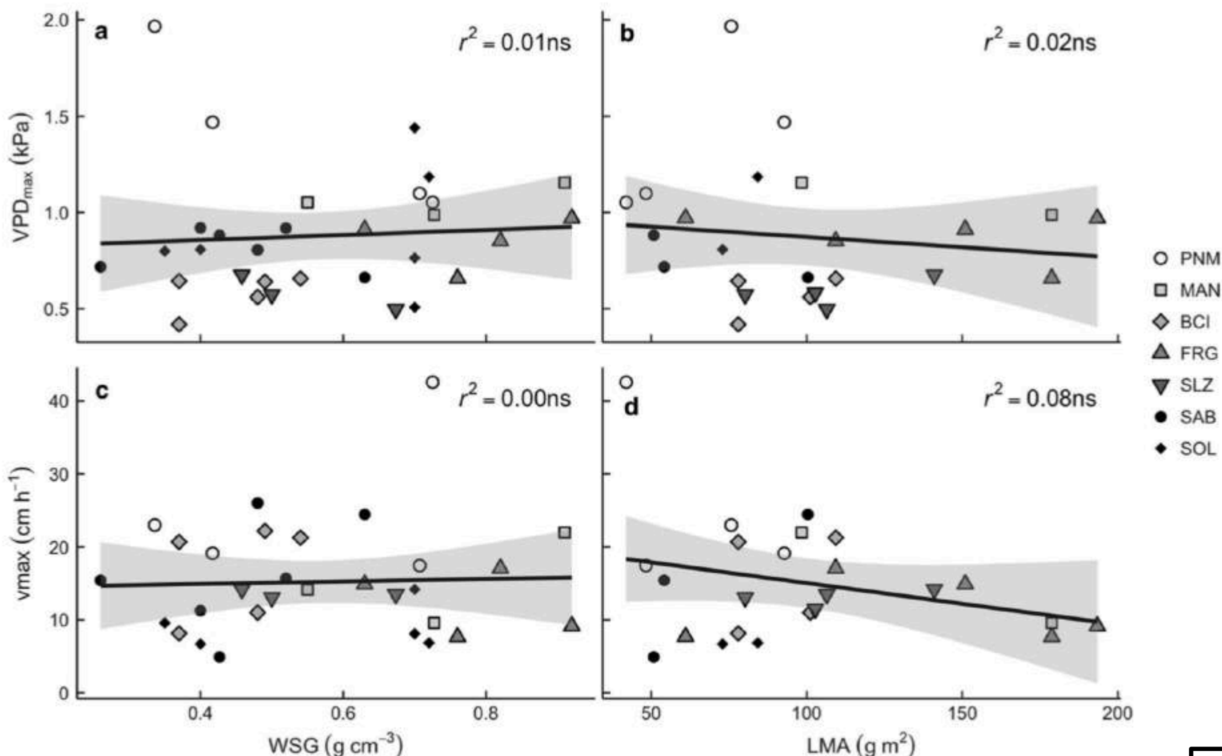
Big trees access deep water



$H_2O < 1$ m
$H_2O > 1$ m

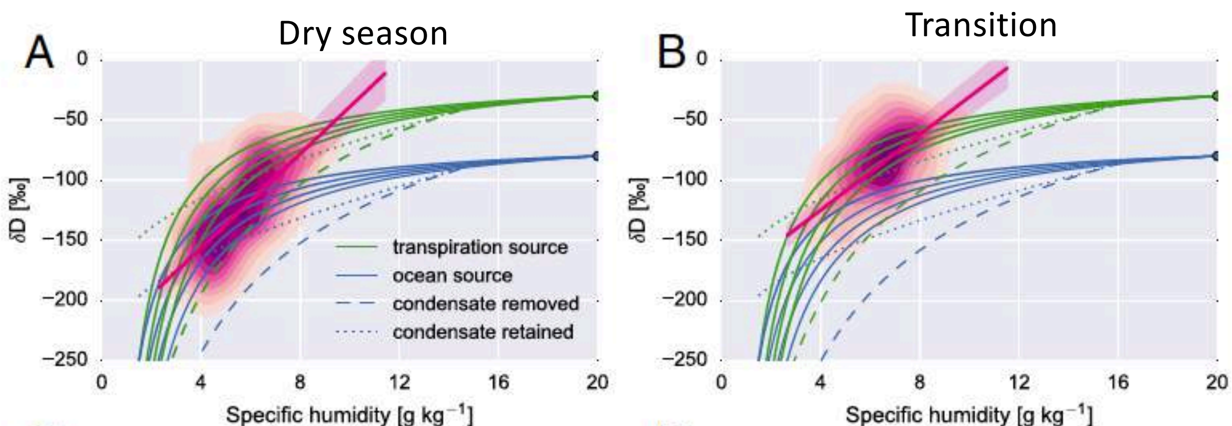
Brum et al. 2018

Response of evaporative demand related to traits for tropical forest trees



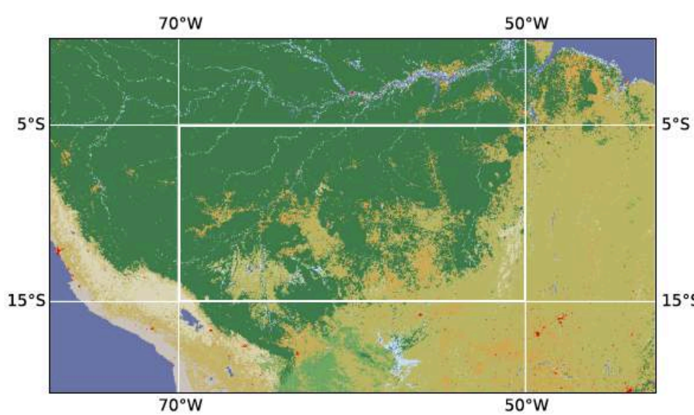
Grossiord et al. 2019

Transpiration is a key source of water to the atmosphere at the end of the dry season



Transpiration source

Ocean source



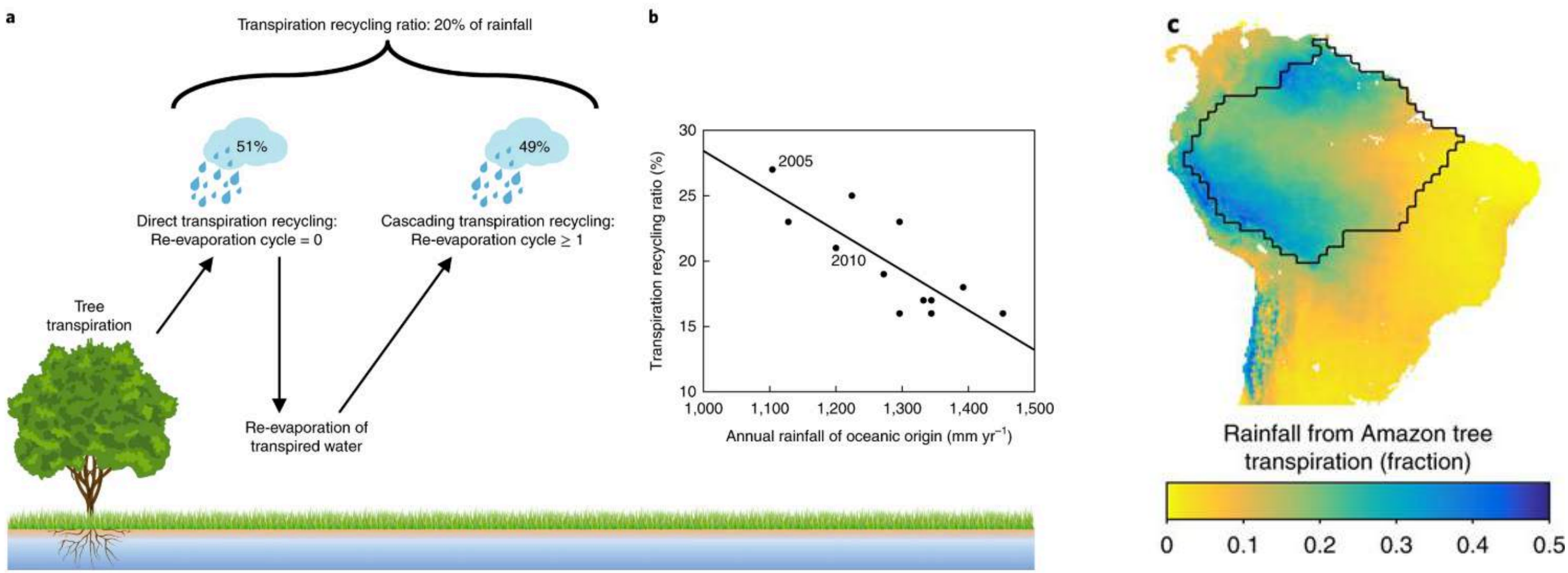
Days before wet season

A = -60 to -30 days

B = -30 to 0 days

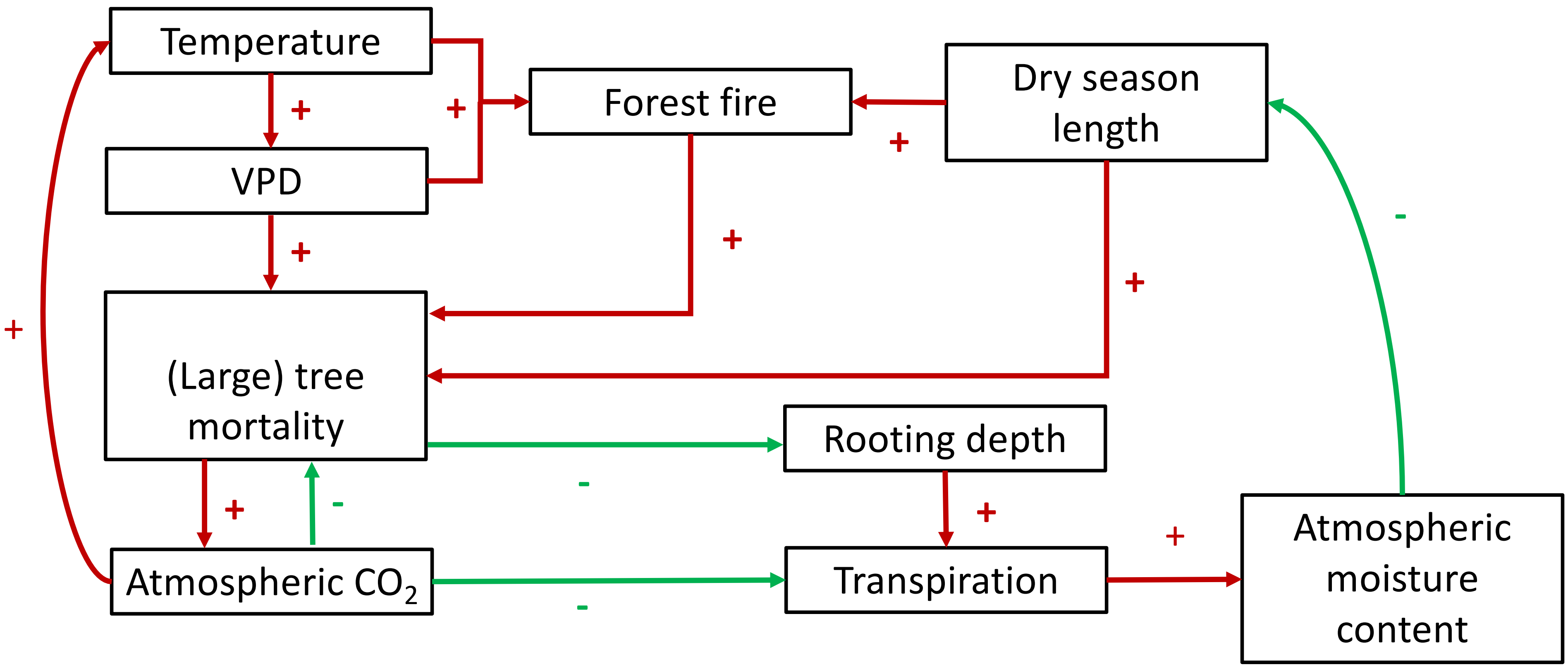
Wright et al. 2016

Transpiration is a key source of water to the atmosphere especially in drought years



Staal et al. 2018

Tipping point feedbacks (4)



Regional and global influences questions

- Is there a tipping point?
- What is the tipping point?
- How is the tipping point modified by changing climate and CO_2?
- How is the tipping point modified by forest degradation?

Summary questions:

- What is the rate of carbon uptake in old growth forests and what are the limitations to that uptake?
- What are the rates of forest degradation and regeneration and what are their landscape level controls?
- Is there an Amazon tipping point in the Earth system forced by deforestation and forest degradation? What is it and what the main controls?

Thanks to everyone who made LBA possible!