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

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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

• Carbon cycling in old-growth forests
  • Eddy covariance was still immature
  • Very few long term forest inventory studies, most oriented towards forestry

• Anthropogenic forest disturbance
  • 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

• Regional and global influence of Amazonia
  • 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 ...
Three key papers

• **Carbon balance of old growth forests**

• **Forest degradation by logging and fire**

• **Regional influences of Amazonia and Earth system feedbacks**
Carbon cycling in old growth forests ...

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


Measurements of carbon dioxide flux over undisturbed tropical rain forest in Brazil for 55 days in the wet and dry seasons of 1992 and 1993 show that this ecosystem is a net absorber of carbon dioxide. Photosynthetic gains of carbon dioxide exceeded respiratory losses irrespective of the season. These gains cannot be attributed to measurement error, nor to loss of carbon dioxide by drainage of cold air at night. A process-based model, fitted to the data, enabled estimation of the carbon absorbed by the ecosystem over the year as 8.5 ± 2.0 moles per square meter per year.

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 CO₂ coupled with lower deposition rates of nitrogen (1, 2). If this is the case, undisturbed tropical forest may be a large sink of CO₂ because of its huge area (3). 10¹⁰ m². Now we report direct measurements of CO₂ 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 CO₂, water vapor, and sensible heat over undisturbed forest (4) at Reserva Juru, Rondonia, Brazil (10°04'44'S, 61°56'00''W), during the dry and wet seasons (September 1992 and April to June 1993, respectively). An eddy co-
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?”


Be careful what you ask for!
Forest inventory plots of the RAINFOR network also find carbon uptake.
Forest inventory plots of the RAINFOR network also show carbon uptake ... Until they don’t.

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

Phillips et al. 1998

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

<table>
<thead>
<tr>
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<th>2010 (Dry) (Pg C y⁻¹)</th>
<th>2011 (Wet) (Pg C y⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.48 ± 0.18</td>
<td>0.06 ± 0.10</td>
</tr>
<tr>
<td>Fire</td>
<td>0.51 ± 0.12</td>
<td>0.30 ± 0.10</td>
</tr>
<tr>
<td>NBE</td>
<td>-0.03 ± 0.22</td>
<td>-0.25 ± 0.14</td>
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</tbody>
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Gatti et al. 2014

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
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.
Present and future observations include total column CO$_2$ from space.

Liu et al. 2017
What about that sink?

- 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)

“Most of the world’s tropical forest is mature and undisturbed and little is known about its carbon balance.” [Grace et al. 1995]

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 km² 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 km² 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

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

Vegetation carbon

Soil carbon

The continual increase in the atmospheric content of carbon dioxide due to anthropogenic emissions is problematic, leading to significant changes in climate. About half of the emissions are being absorbed by the ocean and vegetation, but this absorption is sensitive to climate, as atmospheric carbon dioxide concentrations are feedback loops. General circulation models have excluded the feedback between climate and the biogeophysical vegetation distribution and CO2 concentration, leading to overestimates of carbon feedbacks that do not include climate. 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 21st century. We find that under a business-as-usual scenario, net carbon storage in the terrestrial biosphere acts as an overall carbon sink until 2050, but then turns into a source thereafter. By 2100, the ocean receives 3.5 Gt C yr⁻¹ in balance with the terrestrial carbon, atmospheric CO2 concentrations are 400 ppmv, and fully coupled simulations that include the carbon cycle result in a global mean warming of 3.5 K, as compared to a simulation without the carbon-cycle feedback.

The general circulation model (GCM) that we used is the third Hadley Centre coupled ocean-atmosphere HadGEM1, which has been coupled to an ocean circulation model (HadCOC) and a dynamic global vegetation model (HIS). The atmospheric physics and dynamics of HIS, identical to those used in HadGEM1, but the additional computational expense of including an interactive carbon cycle is necessary to reduce the mean residence time to 200–300 yr, mimicking the use of soil feedbacks in the ocean component to act climate. HadCOC accounts for the atmospheric exchange of CO2 and the transfer of CO2 to depth through solubility pump and the biological pump. TRIPED is state of the biosphere in terms of the soil carbon, and the fraction of carbon allocated to each model grid cell (deciduous forest, needleleaf forest, C3 grass, C4 grass and shrub). Further details on HadCOC and TRIPED are given in Methods.

The coupled climate-carbon cycle model was brought to equilibrium with a pre-industrial atmospheric CO2 concentration of 280 ppmv, starting from an observed land cover data set. The resulting state was stable, with negligible net land–atmosphere and

![Graph showing changes in vegetation and soil carbon over time](https://example.com/graph.png)
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

Nepstad et al. 2007

da Costa et al. 2010
Big trees access deep water

\[ \text{H}_2\text{O} < 1 \text{ m} \]

\[ \text{H}_2\text{O} > 1 \text{ m} \]

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.

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)

- Temperature
  - VPD
- (Large) tree mortality
- Atmospheric CO$_2$

- Forest fire
- Dry season length
- Rooting depth
- Transpiration
- Atmospheric moisture content
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 CO₂?
• 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!