What is the fate of the Amazon under climate change?
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1. Background
   a. Amazon Forests in the context of climate change
   b. The Hadley model prediction of Forest dieback under climate change

2. Tests: Observations of responses ...
   a) to real-world drought
      - Remote sensing (Saleska et al., 2007)
      - Plot studies (Phillips et al., 2009)
   b) To experimentally-induced drought
      (Markewitz et al., 2010; Brando et al., 2008)

Amazon forests

Mean annual precipitation regime

- 6 million km² (largest extant tropical forest in the world)
- 120 ± 30 Pg C in biomass (15 years of fossil fuel emissions)
- Intact forests reportedly a sink of ≈0.6 Pg C yr⁻¹ (Phillips et al., 1998)
  (but see Clark, 2002 vs. Phillips et al., 2002; Chambers et al., 2002; Saleska et al., 2003)
- Forest metabolism provides "transpiration services":
  → 25-35% of precip is recycled through forest transpiration
  → significant cooling from forest latent heat fluxes

Source: TRMM satellite observations, 1998-2006
What will climate change do to precipitation:
- globally?
- in the tropics?
- in the Amazon?

**Climate Change effects on Global precip**

Projected (23-model) Mean Annual Precipitation: "2080-2099" minus "1980-1999"

- Robust high latitude & tropical wetting
- Possible drying of Amazônia
- Robust drying of the subtropics, 20-35N&S.

Note: Stippling is where model predictions are consistent: the multimodel average change exceeds the standard deviation among models
**How might the terrestrial carbon sink (~1.5 Gt C/yr in 90s) change over the next century?**

**Coupled carbon cycle/general circulation model simulations**

Hadley Ctr. (Cox et al., 2000) versus IPSL (Dufresne, Friedlingstein, et al., ’01)

<table>
<thead>
<tr>
<th>Year</th>
<th>Terrestrial Flux (Gt C/yr)</th>
<th>Atm. CO₂ (ppm)</th>
<th>Surface Warming (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050</td>
<td>980</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>2100</td>
<td>770</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

**Key factors driving model differences:**

- The importance of CO₂ fertilization in stimulating carbon uptake
- Drought-induced Dieoff of Amazon rainforest → savanna

**What is the future of Amazon forests under climate change?**

Forest? ...

or Savanna?
Two paths to “savannization” of the Amazon forest:

Will NOT talk more about this for now

1. Conversion to agriculture or pastureland (the primary driver of current tropical deforestation)

2. Climate-change drought and warming makes the forest biome biologically infeasible

Ecophysiological feedbacks in Hadley Model

Amazon Hydrolometeorology

25 to 35% of the rain that falls in the Amazon Basin (~7x10^6 km², or 2.3 m) comes from water recycled by the trees via evapotranspiration

Salati & Vose (1984)
Eltahir & Bras (1994)
Water vapor flux over the Amazon basin (mean climatology for December)

Eltahir & Bras (1994)

Betts et al. (2004): “The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming”

Trigger: onset of semi-permanent ENSO drought (no biology)

Key mechanism: amplification of drought by forest physiological response to initial drying (lots of biology!):

Initial Drought: reduces precip, reduces ET

Drought-induced Tree death

Evapo-transpiration

Rain
Changes in precip

By 2050

By 2080

3 mm/day less (relative to pre-industrial 5 mm)

Δprecip (mm/day)

Hadley model predictions

Changes in broadleaf tree-cover

By 2050

By 2080

Δcover (fraction)

By 2050 in Amazonia:

- Broadleaf tree cover has been reduced from >80% to <10%
- ~half of converted area is savanna grassland
- Some areas, where even grasses cannot survive, become desert

Contributing factors to extreme Amazon drought in the Hadley model world:

- Ecophysiological feedbacks
- Changes in vegetation = changes in land surface ('biogeophysical feedbacks')
- Carbon-cycle feedbacks
Positive Feedbacks Enhance drying in Hadley model

1. Plant physiological feedback
   \( \uparrow \text{CO2} \rightarrow \uparrow \text{WUE} \rightarrow \text{less ET} \)

2. Biogeophysical feedback:
   \( \text{difference in veg types} \)

3. Carbon-cycle feedback:

\[ \Delta \text{precip} \text{ (mm/day)} \]

\[ \text{RAD} \Delta \text{Phys} - \text{RAD} \]

\[ \text{DynVeg} - \text{FixVeg} \]

\[ \text{CCycle} - \text{DynVeg} \]

\( \text{Atmospheric CO2 prescribed} \)

\( \text{Atmospheric CO2 prescribed} \)

\( \text{Atmospheric CO2 interactive} \)

\( \text{Atmospheric CO2 prescribed} \)

Summary of feedbacks

\( \text{Climate change effect on Amazon precip (relative to pre-industrial):} \)

\[ \begin{align*}
\text{RAD} & : -1.5 \text{ mm/day} \\
\text{FixedVeg} & : -1.9 \\
\text{DynamicVeg} & : -2.4 \\
\text{CCycle} & : -3.0
\end{align*} \]

Feedback (magnitude):

\( \text{Physiology: 25\%} \)

\( \text{Biogeophysical: 25\%} \)

\( \text{Carbon cycle: 25\%} \)

Net: 100\% (twice the reduction)
Amazônia 2050: Forest or Savanna? Can we test the prediction?

**Trigger:** onset of semi-permanent ENSO drought (no biology)

**Key mechanism:** amplification of drought by forest physiological response to initial drying (lots of biology!):

- **Initial Drought:**
  - reduces precip
  - reduces ET

- **Drought-induced Tree death**

**Prediction** about today's Amazon forest under current climate: evapotranspiration and whole-system photosynthesis should be reduced during dry periods (dry seasons, and interannual droughts)

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**Test 1: Response to interannual drought**

**Model-Predicted Response**
- Hadley modeled GPP & precip in central Amazonia in years relative to El Nino drought
- Forest Photosynthesis (Mg C ha⁻¹ yr⁻¹)

**Empirical Test:** the 2005 drought
- Tropical Rainfall Measuring Mission (TRMM) satellite precip anomalies in 3rd quarter 2005

- Precip (mm mo⁻¹)
**Methods: TRMM satellite for Rainfall measurements**

TRMM = Tropical Rainfall Measuring Mission

**Blended precipitation product (3B43-v6) combines:**
- microwave data from TRMM
- Infrared from GOES
- Calibrated to data from global network of gauges

**Methods: MODIS satellite instrument measures canopy “greenness”**

MODIS = Moderate Resolution Imaging Spectroradiometer

**MODIS-derived Enhanced Vegetation Index (EVI):**
- focuses on spectral bands related to plant photosynthetic capacity
- Does not saturate with high Leaf Area Index (LAI) as does NDVI
- High-time resolution (16-day) allows detection of seasonal patterns
Methods: MODIS satellite instrument measures canopy “greenness”

\[ NDVI = \frac{\rho_{\text{NIR}} - \rho_{\text{red}}}{\rho_{\text{NIR}} + \rho_{\text{red}}} \]

But… NDVI saturates over dense (high-LAI) vegetation (e.g. Amazon forest)

\[ \text{EVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{red}}}{1 + \rho_{\text{NIR}} + 6 \rho_{\text{red}} - 7.5 \rho_{\text{blue}}} \]

Reduced sensitivity to red, relative to NIR, giving greater ability to detect increases in LAI

Empirical test: the 2005 Amazon drought

Satellite (TRMM)-derived precip anomalies in Amazônia for 2005 (as in Aragão, et al. 2007):
(relative to mean of 1998-2005)

Satellite (MODIS)-derived EVI anomalies in Amazônia for 2005:
(relative to mean of 2000-2006)
Only test so far: the 2005 Amazon drought

precipitation anomaly  vegetation “greenness” anomaly

Units: number of standard deviations in 2005 from the long-term mean for the July/Aug/Sept (JAS) quarter. I.e., for each pixel:

\[ \text{Anomaly}_{2005,\text{JAS}} = \frac{x_{2005,\text{JAS}} - \overline{x}_{\text{JAS}}}{\sigma_{\text{JAS}}} \]

Short term drought, contrary to model predictions, does not cause photosynthetic slow-down

Saleska et al., 2007

Best test so far: the 2005 Amazon drought

Hadley model-predictions of GPP & precip in central Amazonia in years relative to El Nino drought

Time-series of MODIS Observations through 2005 drought

Adapted from Jones et al. (2001)
Reported increase in tree mortality during the period that included the 2005 drought. "Amazon forests therefore appear vulnerable to increasing moisture stress, with the potential for large carbon losses to exert feedback on climate change."

*Phillips et al., (2009)*
TEST 2: Experimental Test of the effects of increased drought on Amazon rainforest

Nepstad et al., 2007

Root water uptake
(solid=control, dash=drought)

Markewitz et al., 2010

Mortality flux (Mg ha\(^{-1}\) yr\(^{-1}\))
(hatch=control, solid gray=drought)

Brando et al., 2008
**MECHANISMS for Green-up Response to Amazon Drought**

a) Fewer clouds during drought → more sunlight

b) Evergreen Amazon forests are biologically adapted to the Amazon climate (e.g. much deeper roots than elsewhere): dry seasons and regular El Nino droughts

c) Consistent with: Dry-season leaf flush inferred in central Amazon (2 Tapajos forest eddy sites):

Leaf-flush empirical model based on tower-measured photosynthetic capacity and litterfall (Restrepo-Coupe et al., in prep)
MECHANISMS for Green-up Response to Amazon Drought

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c) Consistent with:
   • Dry season leaf flush inferred in central Amazon (Tapajos forest eddy site)
   • Drought experiment in central Amazon (Tapajos Forest dry-down experiment, Nepstad et al., 2007)

Summary

Amazon vegetation may be more resilient than ecosystem models predict, at least in the short term (seasonal variation and short droughts).

→ Forests have Adapted to dry seasons and short interannual drought, but biological adaptation is not represented in most ecosystem models

Caveats: fire and long-term drought are serious threats to the future of the Amazon

Outstanding Question: what does it take to “break” an Amazon forest? Can climate change do it?

Two answers: (1) Survey of forest plots before and after drought (Phillips et al., 2009)

(2) drought experiments (Nepstad et al., 2007, Brando et al., 2008; Markewitz et al., 2010): takes 3 yrs to get large-tree mortality