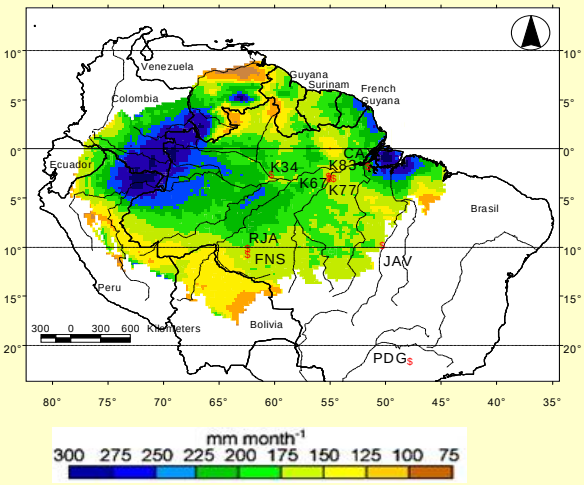
What is the fate of the Amazon under climate change?

S. Saleska, Ecol 596L
Sept. 10, 2010

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



Source: TRMM satellite observations, 1998-2006

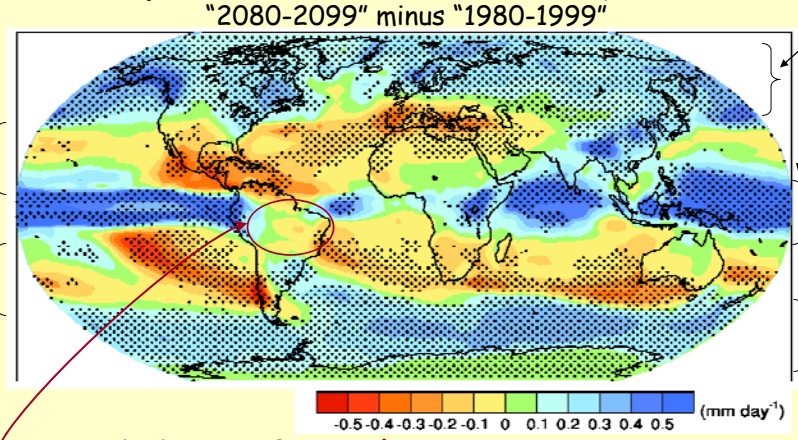
- 6 million km^2 (largest extant tropical forest in the world)
- 120 ± 30 Pg C in biomass (15 years of fossil fuel emissions)
- Intact forests reportedly a sink of ≈0.6 Pg C yr^{-1} (Phillips et al, 1998)
  (but see Clark, 2002 vs. Phillips et al., 2002; Chambers et al., 2002; Saleska et al., 2003)
- Forest metabolism provides "transpiration services":
  → 25-35% of precip is recycled through forest transpiration
  → significant cooling from forest latent heat fluxes

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.

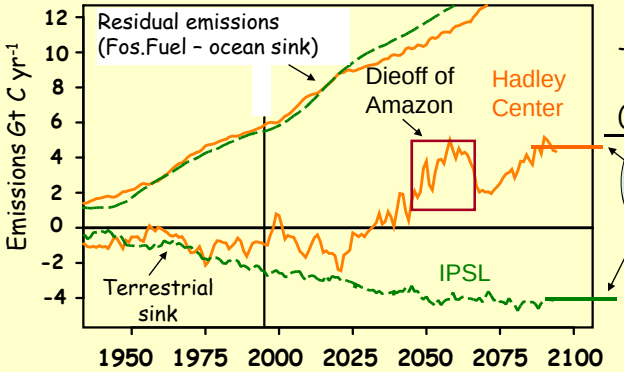
Scenario A1B
IPCC (2007)

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)



Predictions for 2100:

Terrestrial Flux (GtC/yr)	Atm. CO_2 (ppm)	Surface Warming (°C)
+ 5	980	5.2
- 3.5	770	3

8.5 Gt difference: huge!

Key factors driving model differences:

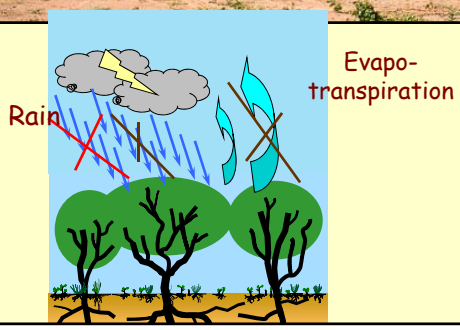
- The importance of CO2 fertilization in stimulating carbon uptake
- Drought-induced Dieoff of Amazon rainforest → savanna

What is the future of Amazon forests under climate change?

Forest? ...

or Savanna?

Two paths to "savannization" of the Amazon forest:

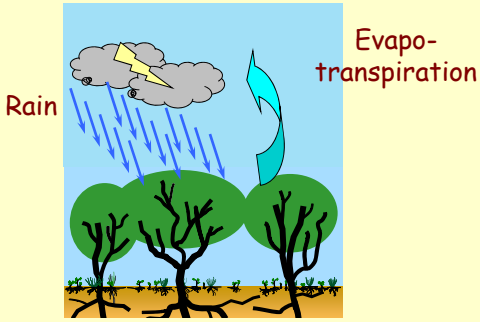


1. ~~Conversion to agriculture or pastureland (the primary driver of current tropical deforestation)~~

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

Ecophysiological feedbacks in Hadley Model

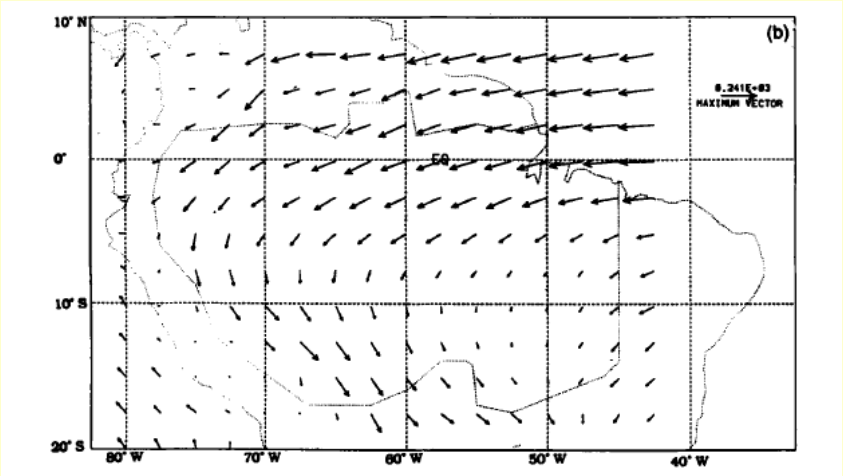
Amazon Hydrolometeorology



25 to 35% of the rain that falls in the Amazon Basin (~7×10^6 km^2, 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)

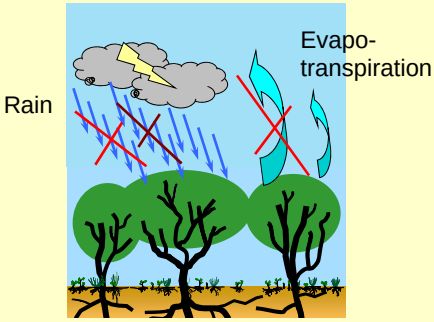


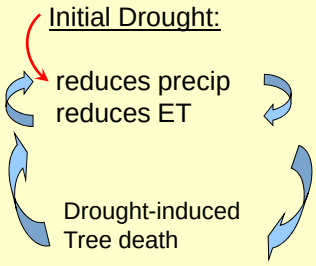
Eltahir & Bras (1994)

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!):





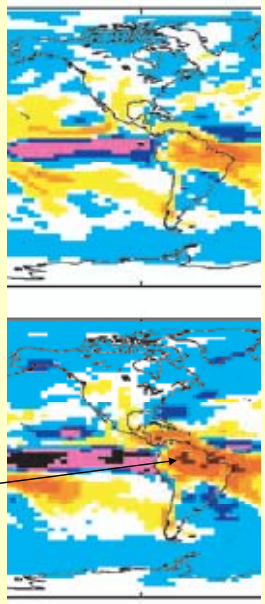
Hadley model predictions

Changes in precip

By 2050

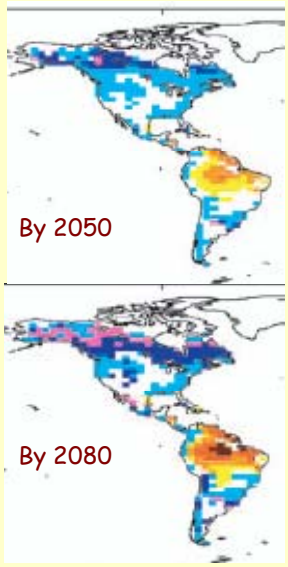
By 2080

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



Δprecip (mm/day)

Changes in broadleaf tree-cover



Δcover (fraction)

Hadley model predictions

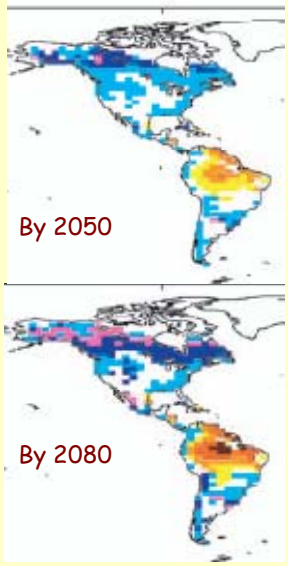
<u>By 2100 in Amazonia:</u>

-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

Changes in broadleaf tree-cover



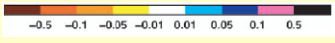
<u>Contributing factors to extreme Amazon drought in the Hadley model world:</u>

- Ecophysiological feedbacks

- Changes in vegetation = changes in land surface ('biogeophysical feedbacks')

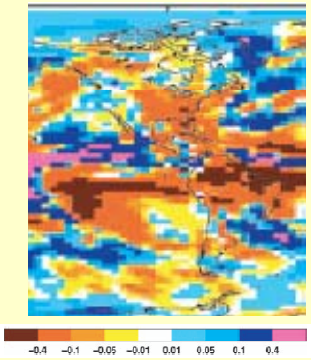
- Carbon-cycle feedbacks

Δcover (fraction)



Positive Feedbacks Enhance drying in Hadley model

1. plant physiological feedback (↑CO2 → ↑WUE → less ET) :



Determined by difference between model runs:

RAD&Phys - RAD

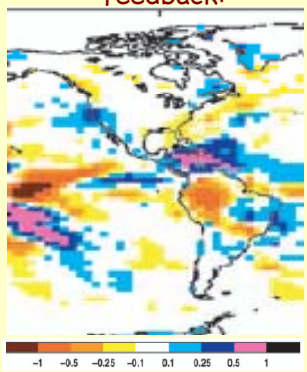
CO2 has both radiative forcing & physiological effects

CO2 has radiative forcing effects only (no direct effects on plants)

Atmospheric CO2 prescribed

Δprecip (mm/day)

2. Biogeophysical (=difference in veg types) feedback:



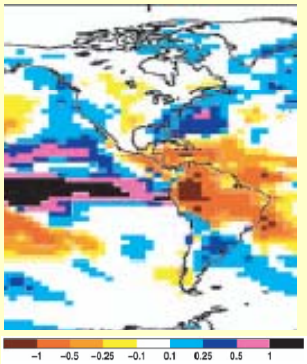
DynVeg - FixVeg

Dynamic vegetation

Fixed vegetation

Atmospheric CO2 prescribed

3. Carbon-cycle feedback:



CCycle - DynVeg

Atmospheric CO2 interactive

Atmospheric CO2 prescribed

Positive Feedbacks Enhance drying in Hadley model

Summary of feedbacks

Climate change effect on Amazon precip (relative to pre-industrial):

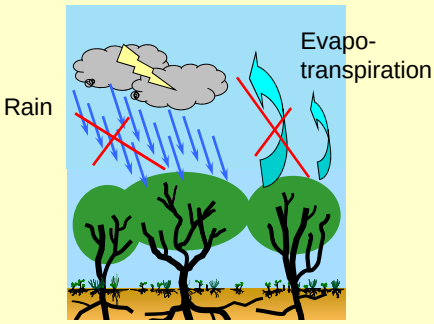
			Feedback (magnitude)
CO2 has radiative forcing effects only (no direct effects on plants) →	RAD :	-1.5 mm/day	Physiology: 25%
+ CO2 affects plants →	FixedVeg :	-1.9	Biogeophysical: 25%
+ changeable plant cover →	DynamicVeg:	-2.4	Carbon cycle: 25%
+ interactive atmospheric CO2 →	CCycle:	-3.0	

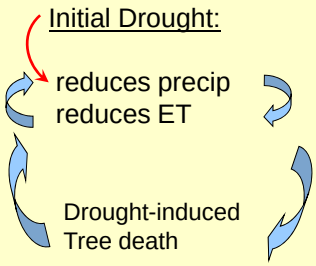
Net: 100% (twice the reduction)

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!):



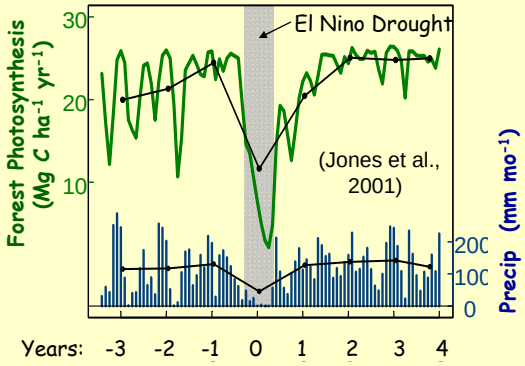


Prediction about today's Amazon forest under current climate:
evapotranspiration and whole-system photosynthesis should be reduced during dry periods (**dry seasons**, and **interannual droughts**)

Test 1: Response to interannual drought

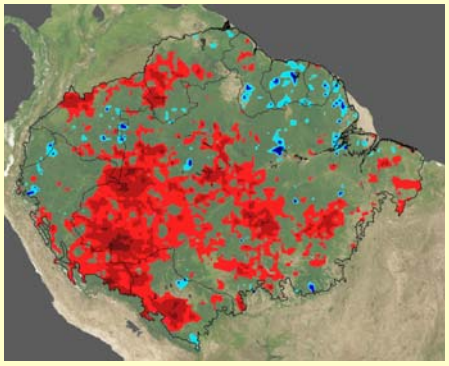
Model-Predicted Response

Hadley **modeled** GPP & precip in central Amazonia in years relative to El Nino drought



Empirical Test: the 2005 drought

Tropical Rainfall Measuring Mission (TRMM) satellite precip anomalies in 3rd quarter 2005



Methods: TRMM satellite for Rainfall measurements

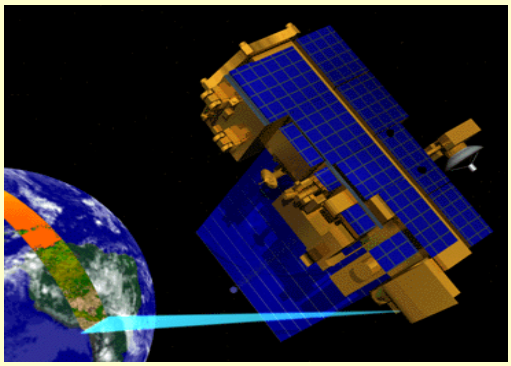
TRMM = Tropical Rainfall Measuring Mission

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



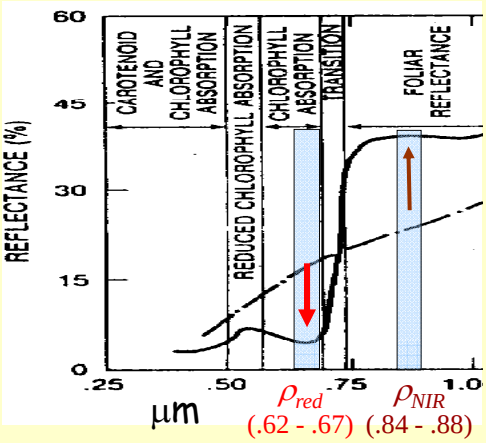
MODIS-derived Enhanced Vegetation Index (EVI):

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"



$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}$$

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

$$\mathbf{EVI} = \frac{\rho_{NIR} - \rho_{red}}{1 + \rho_{NIR} + 6\,\rho_{red} - 7.5\,\rho_{blue}}$$

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

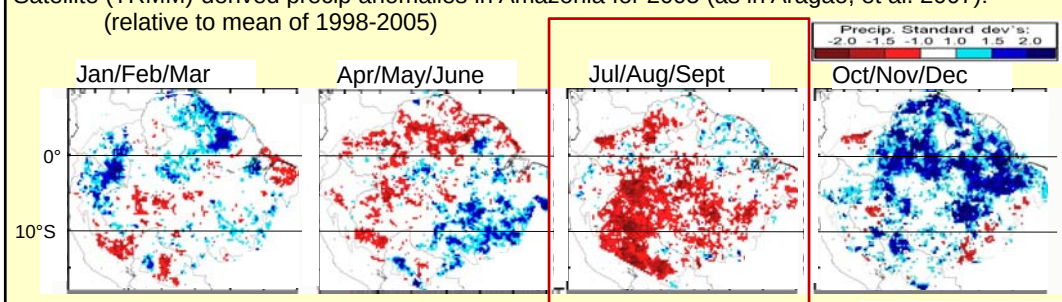
aerosol correction

↑ Chlorophyll ↓ reflectance

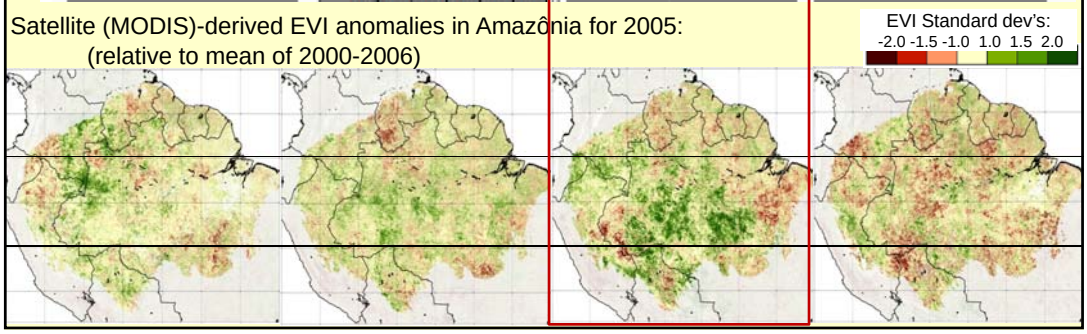
↑ leaf structure ↑ reflectance

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)

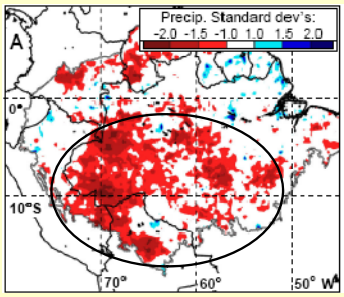


Satellite (MODIS)-derived EVI anomalies in Amazônia for 2005: (relative to mean of 2000-2006)

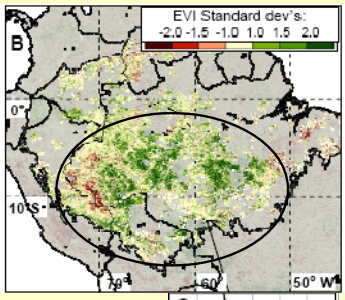


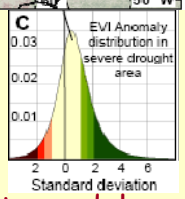
Only test so far: the 2005 Amazon drought

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:

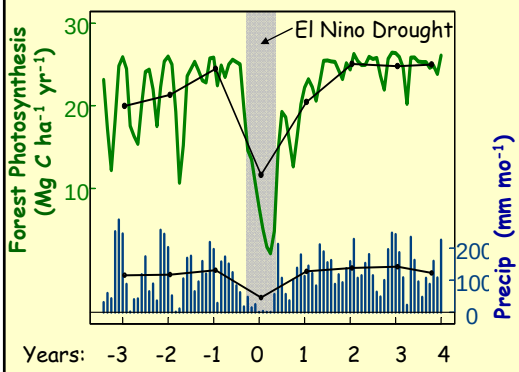
$$Anomaly_{2005,JAS} = \frac{x_{2005,JAS} - \overline{x}_{JAS}}{\sigma_{JAS}}$$

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

Saleska et al., 2007

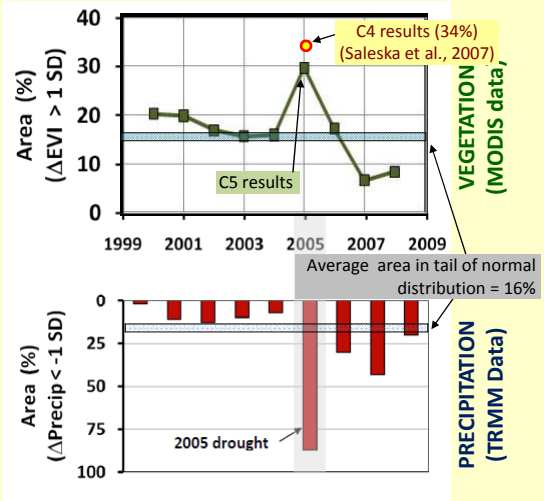
Best test so far: the 2005 Amazon drought

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



Adapted from Jones et al. (2001)

Time-series of MODIS ***Observations*** through 2005 drought



6 MARCH 2009 VOL 323 SCIENCE

REPORTS

Drought Sensitivity of the Amazon Rainforest

Oliver L. Phillips,[1*] Luiz E. O. C. Aragão,[2] Simon L. Lewis,[1] Joshua B. Fisher,[2] Jon Lloyd,[1] Gabriela López-González,[1] Yadvinder Malhi,[2] Abel Monteagudo,[3] Julie Peacock,[1] Carlos A. Quesada,[1,4] Geertje van der Heijden,[1] Samuel Almeida,[5] Iêda Amaral,[4,6] Luzmila Arroyo,[7,8] Gerardo Aymard,[9] Tim R. Baker,[1] Olaf Bánki,[10] Lilian Blanc,[11] Damien Bonal,[12] Paulo Brando,[13,14] Jerome Chave,[15] Átila Cristina Alves de Oliveira,[4] Nallaret Dávila Cardozo,[16] Claudia I. Czimczik,[17] Ted R. Feldpausch,[1] Maria Aparecida Freitas,[5] Emanuel Gloor,[1] Niro Higuchi,[18] Eliana Jiménez,[19] Gareth Lloyd,[20] Patrick Meir,[21] Casimiro Mendoza,[22] Alexandra Morel,[2] David A. Neill,[8,23] Daniel Nepstad,[24,25] Sandra Patiño,[1,11] Maria Cristina Peñuela,[19] Adriana Prieto,[26] Fredy Ramírez,[16] Michael Schwarz,[1,27] Javier Silva,[2] Marcos Silveira,[28] Anne Sota Thomas,[29] Hans ter Steege,[30] Juliana Stropp,[30] Rodolfo Vásquez,[3] Przemyslaw Zelazowski,[2] Esteban Alvarez Dávila,[31] Sandy Andelman,[6] Ana Andrade,[4] Kuo-Jung Chao,[1] Terry Erwin,[32] Anthony Di Fiore,[33] Eurídice Honorio C.,[34] Helen Keeling,[1] Tim J. Killeen,[7] William F. Laurance,[4,35] Antonio Peña Cruz,[3] Nigel C. A. Pitman,[36] Percy Núñez Vargas,[37] Hirma Ramírez-Angulo,[38] Agustín Rudas,[39] Rafael Salamão,[5] Natalino Silva,[40] John Terborgh,[41] Armando Torres-Lezama[38]

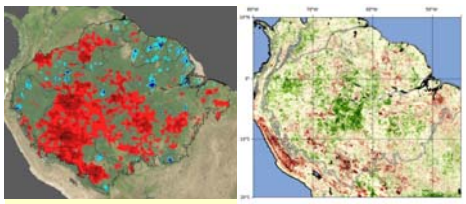
→ Reported increase in tree mortality during the period that included the 2005 drought.

"Amazon forests therefore appear vulnerable to increasing moisture stress, with the potential for large carbon losses to exert feedback on climate change."

26 OCTOBER 2007 VOL 318 SCIENCE

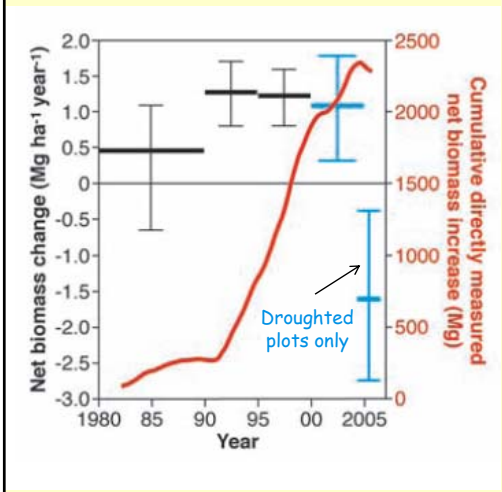
Amazon Forests Green-Up During 2005 Drought

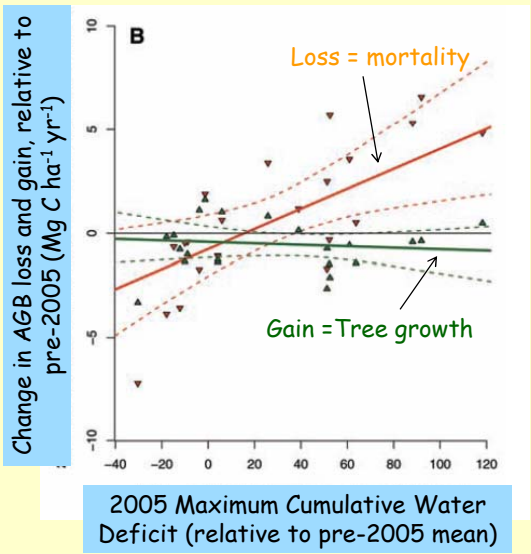
Scott R. Saleska,[1*†] Kamel Didan,[2*] Alfredo R. Huete,[2] Humberto R. da Rocha[3]



"intact Amazon forests may be more resilient than most ecosystem models assume, at least in response to short-term climate anomalies."

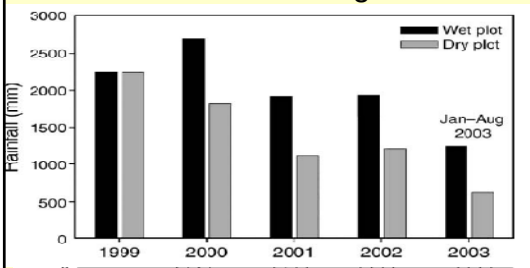
Net and cumulative biomass changes on field plots

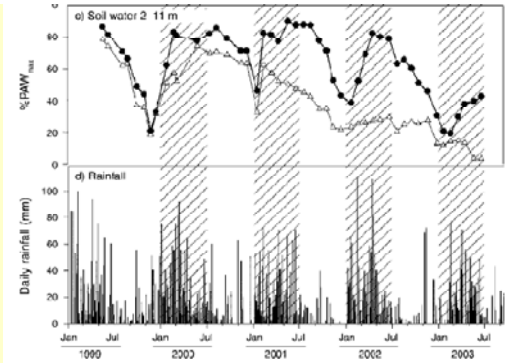


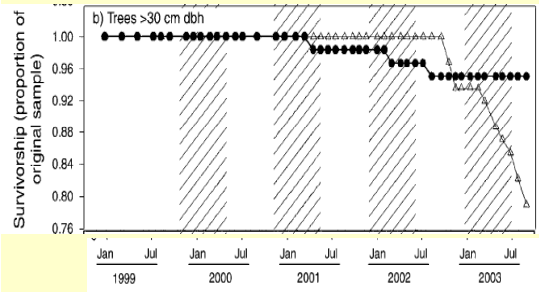


Phillips et al., (2009)

TEST 2: Experimental Test of the effects of increased drought on Amazon rainforest



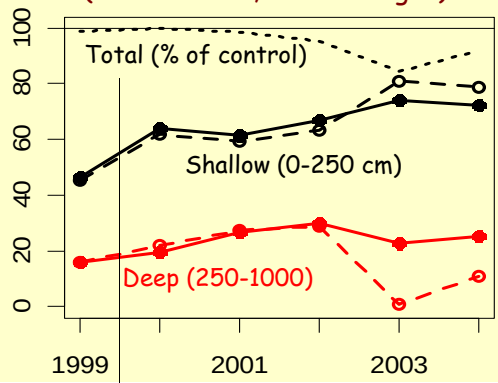




Nepstad et al., 2007

Root water uptake

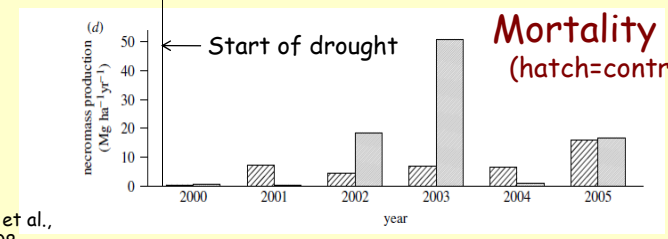
(solid=control, dash=drought)



Markewitz et al., 2010

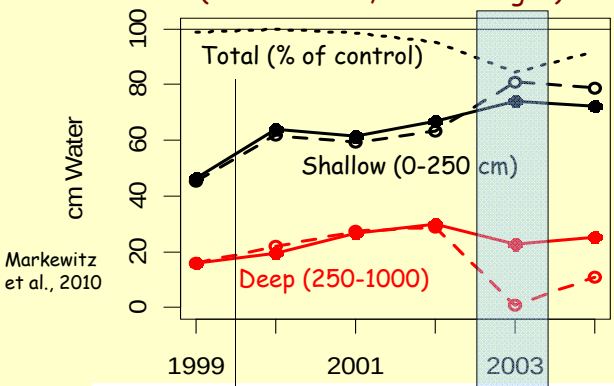
Mortality flux (Mg ha^{-1} yr^{-1})

(hatch=control, solid gray =drought)



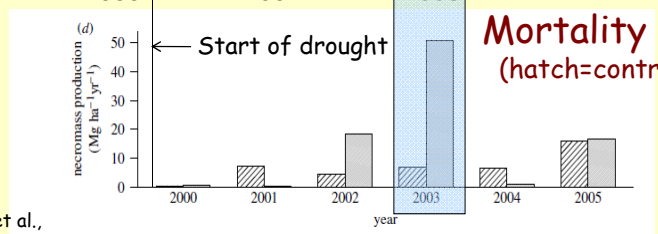
Brando et al., 2008

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



Markewitz et al., 2010

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



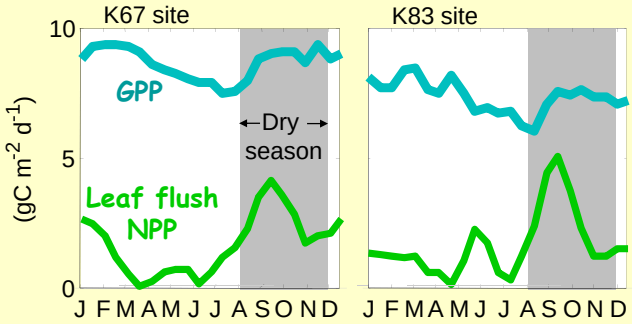
Brando et al., 2008

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 elswhere): dry seasons and regular El Nino droughts

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

a) Fewer clouds during drought → more sunlight

b) Evergreen Amazon forests are biologically adapted to the Amazon climate: dry seasons and regular El Nino droughts

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