## **SECOSTRESS**



ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station

An Earth Venture Instrument-2 Proposal
Submitted in response to
AO NNH12ZDA006O EVI2

Prepared for

National Aeronautics and Space Administration Science Mission Directorate

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Science Team Rick Allen (U. Idaho), Martha Anderson (USDA), Andy French (USDA), Glynn Hulley (JPL), Eric Wood (Princeton U.)

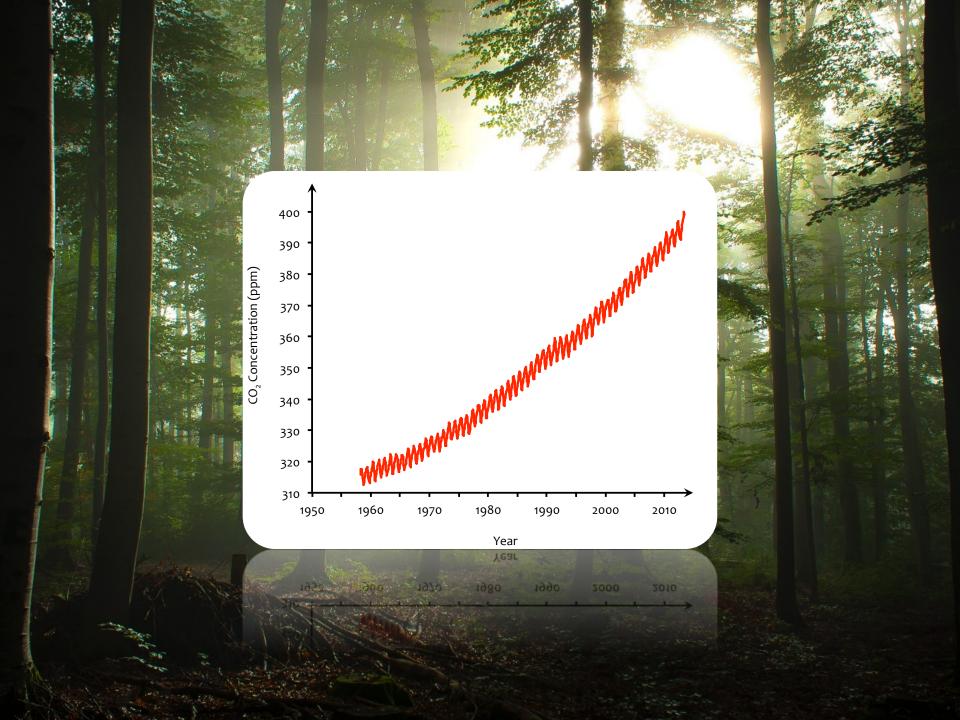
**National Aeronautics and Space Administration** 

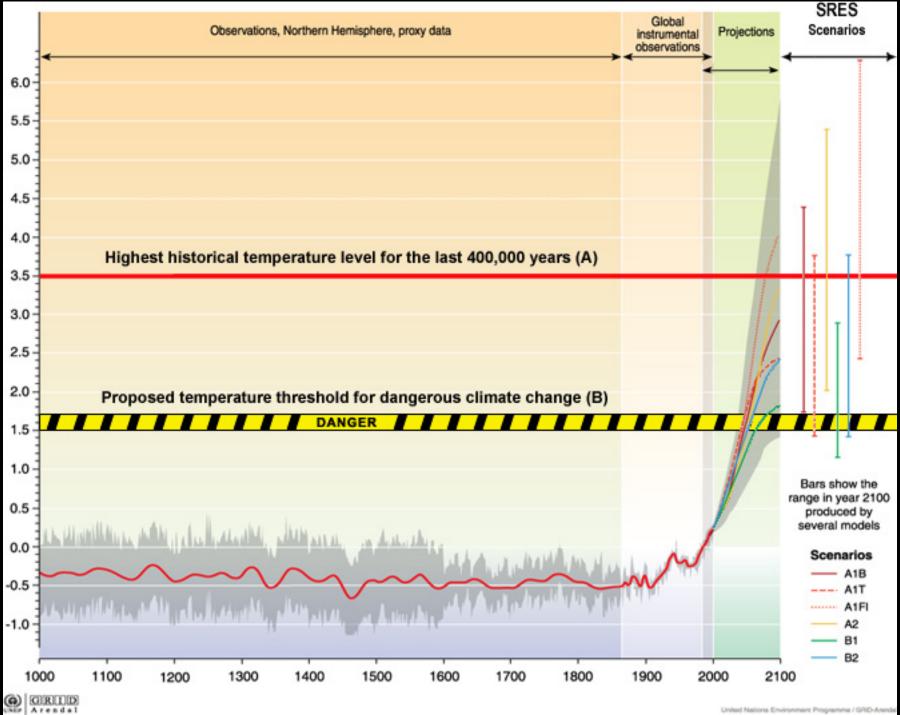
**Jet Propulsion Laboratory** California Institute of Technology Pasadena, California

November 25, 2013











#### **Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks**

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(Manuscript received 31 July 2012, in final form 4 September 2013)

#### **ABSTRACT**

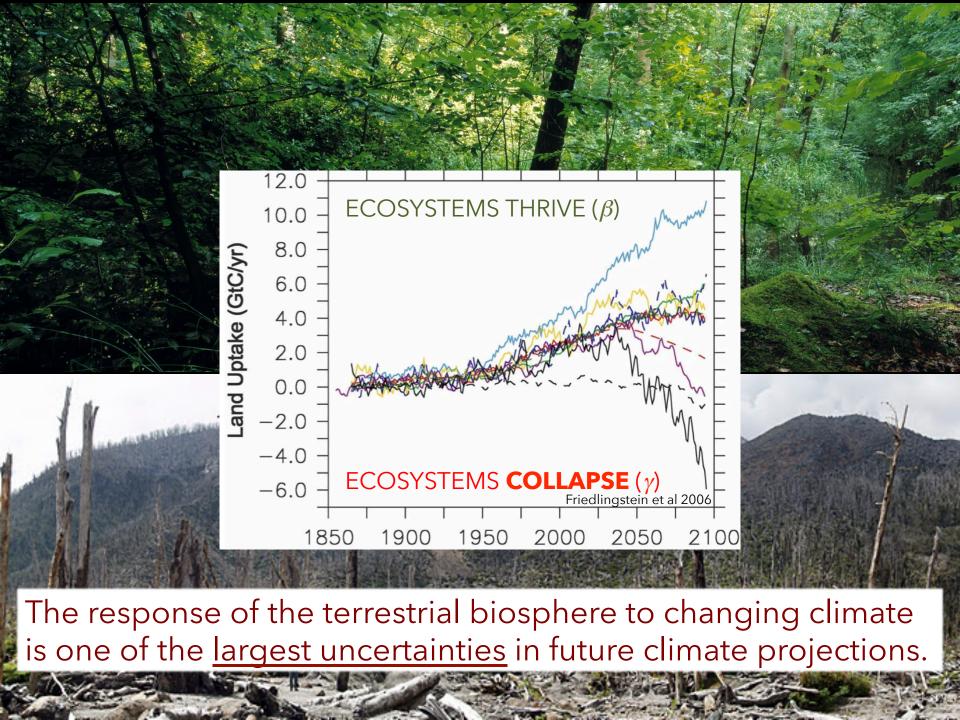
models already overestimate the present-day CO<sub>2</sub>, with the present-day biases reasonably well correlated with future atmospheric concentrations' departure from the prescribed concentration. The uncertainty in CO<sub>2</sub> projections is mainly attributable to uncertainties in the response of the land carbon cycle. As a result of simulated higher CO<sub>2</sub> concentrations than in the concentration-driven simulations, temperature projections

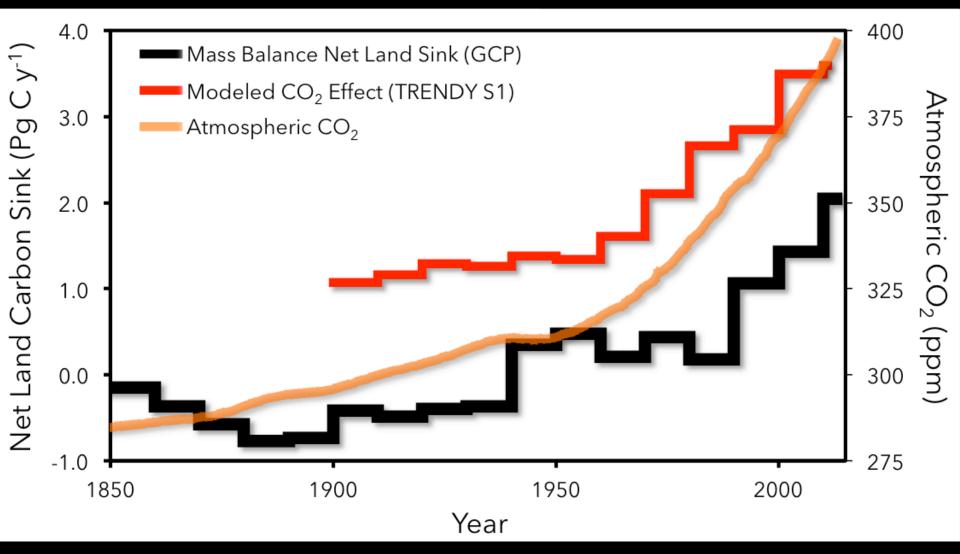
driven by  $CO_2$  emissions than for the concentration-driven scenarios (941 ppm). However, most of these models already overestimate the present-day  $CO_2$ , with the present-day biases reasonably well correlated with future atmospheric concentrations' departure from the prescribed concentration. The uncertainty in  $CO_2$  projections is mainly attributable to uncertainties in the response of the land carbon cycle. As a result of simulated higher  $CO_2$  concentrations than in the concentration-driven simulations, temperature projections are generally higher when ESMs are driven with  $CO_2$  emissions. Global surface temperature change by 2100 (relative to present day) increased by 3.9°  $\pm$  0.9°C for the emission-driven simulations compared to 3.7°  $\pm$  0.7°C in the concentration-driven simulations. Although the lower ends are comparable in both sets of simulations, the highest climate projections are significantly warmer in the emission-driven simulations because of stronger carbon cycle feedbacks.

#### 1. Introduction

In the Fourth Assessment Report of the Intergov-

best guess is not centered in the likely range interval; the distribution is asymmetrical with a -40/+60% distribution around the heat estimate (i.e., the guesses of the





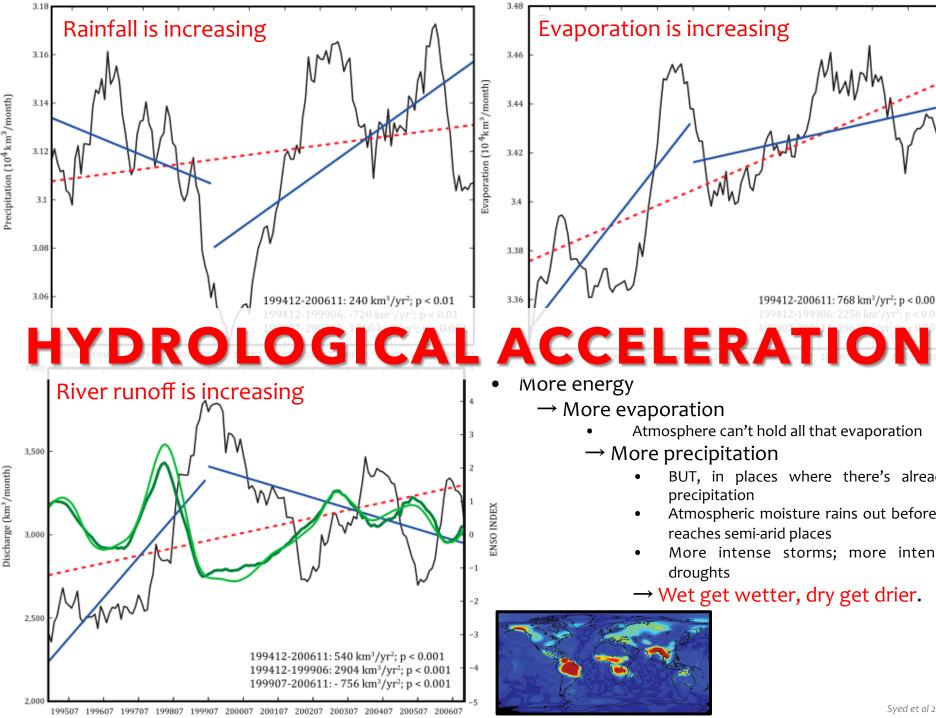
# $\overline{CO_2}$ FERTILIZATION ( $\beta$ )

Schimel, D., Stephens, B.B., **Fisher, J.B.**, in press. The effect of increasing  $CO_2$  on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences, USA*.



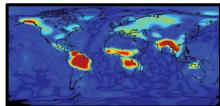




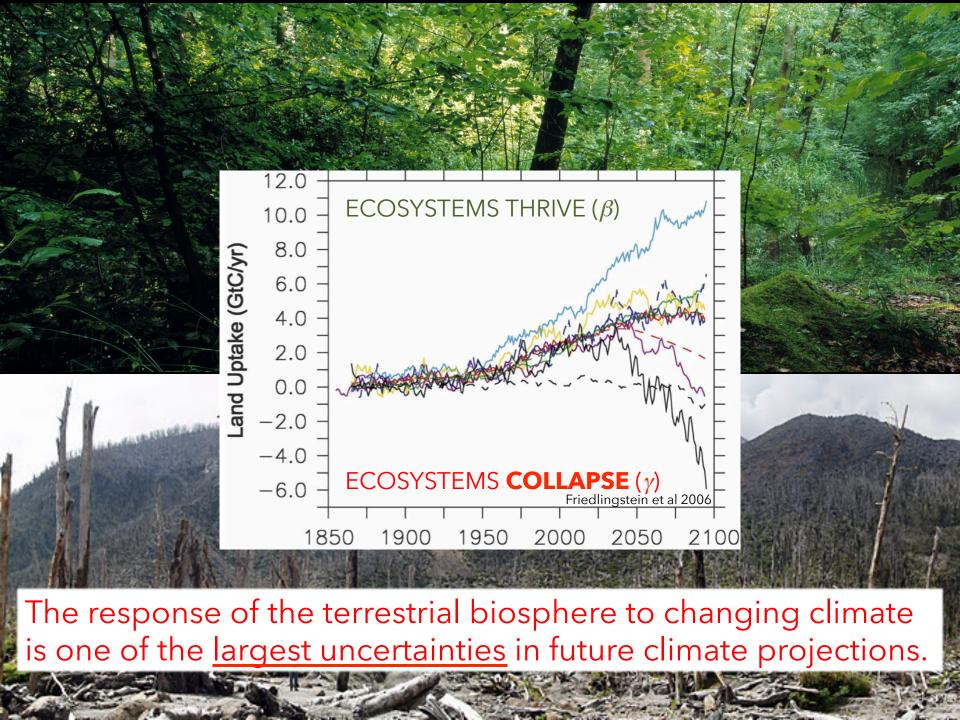


# Evaporation is increasing 3.46 3.44 3.4 199412-200611: 768 km3/yr2; p < 0.001

- More energy
  - → More evaporation
    - Atmosphere can't hold all that evaporation
    - → More precipitation
      - BUT, in places where there's already precipitation
      - Atmospheric moisture rains out before it reaches semi-arid places
      - More intense storms; more intense droughts
      - → Wet get wetter, dry get drier.







## CLIMA

Theor. Appl. Climatol. 78, 137-156 (2004) DOI 10.1007/s00704-004-0049-4

Theoretical and Applied Climatology

Printed in Austria

ACTS

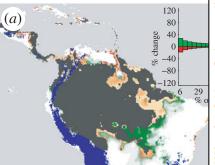


Figure 5. Change in the potential This scenario accounts for the de-Dark grey areas mark the niche green mark the potential HTF adjacent to HTFs, they define the on a change up to the plotted lev

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#### Amazonian forest dieback under climate-carbon cycle projections for the 21st century

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With 10 Figures

Received March 28, 2003; revised August 16, 2003; accepted October 9, 2003 Published online April 27, 2004 © Springer-Verlag 2004

#### Summary

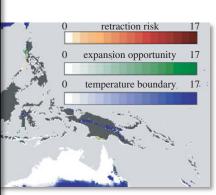
The first GCM climate change projections to include dynamic vegetation and an interactive carbon cycle produced a very significant amplification of global warming over the 21st century. Under the IS92a "business as usual" emissions scenario CO2 concentrations reached about 980 ppmv by 2100, which is about 280 ppmv higher than when these feedbacks were ignored. The major contribution to the increased CO2 arose from reductions in soil carbon because global warming is assumed to accelerate respiration. However, there was also a lesser contribution from an alarming loss of the Amazonian rainforest. This paper describes the phenomenon of Amazonian forest dieback under elevated CO2 in the Hadley Centre climate-carbon

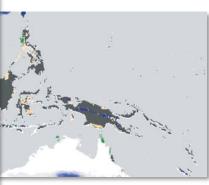
#### 1. Introduction

About half of the current anthropogenic emissions of carbon dioxide are being absorbed by the ocean and by land ecosystems (Schimel et al., 1996). The processes involved are known to be sensitive to climate. Temperature affects the solubility of carbon dioxide in sea-water and the rate of terrestrial and oceanic biological processes. Vegetation also responds directly to elevated CO2 through increased photosynthesis and reduced transpiration (Sellers et al., 1996; Field

et al., 1995), and may also change its structure and distribution in response to any associated climate change (Betts et al., 1997). The biosphere therefore has great potential to produce a feedback on the climate change due to anthropogenic CO2 emissions. However, simulations carried out with General Circulation Models (GCMs) have generally neglected the coupling between the climate and the biosphere. Instead, vegetation distributions have been static and atmospheric concentrations of CO2 have been prescribed based on results from simple carbon cycle models, which neglect the effects of climate change.

Recently some groups have begun to include representations of the carbon cycle within GCMs (Friedlingstein et al., 2001; Cox et al., 2001). The first climate change projection to include both an interactive carbon cycle and dynamic vegetation was carried out at the Hadley Centre, and this all AOGCMs. Shades of red and showed a significant acceleration of CO2 d in blue. In mountainous areas increase and climate change arising from the additional feedback loops (Cox et al., 2000). Under the IS92a "business as usual" emission scenario the Hadley Centre coupled-climate carbon cycle model produced a CO2 concentration of about 980 ppmv by 2100, compared to about





 $^{\circ}$ C and (b)  $4^{\circ}$ C global warming. urface scheme (see also figure 4). percentage of models that agree

Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S., Fisher, J.B., 2011. Changes in the potential distribution of humid tropical forests on a warmer planet. Philosophical Transactions of the Royal Society A - Mathematical, Physical & Engineering Sciences.

#### Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest

Yadvinder Malhi¤1, Luiz E. O. C. Aragãoª, David Galbraithb, Chris Huntingfords, Rosie Fisherd, Przemysław Zelazowskia,

Edited by Hans Joachim Schellnhuber, Potsda review June 10, 2008)

We examine the evidence for the po-climate change may cause a large-scale of Amazonian rainforest. We employ u uating the rainfall regime of tropical for precipitation-based boundaries for or then examine climate simulations by then examine climate simulations by (GCMs) in this context and find that in current rainfall. GCMs also vary greature climate change in Amazonia. current rainfall. GCMs also vary greature climate change in Amazonia. rainfall regimes in the 20th century. dry-season water stress is likely to incre 21st century, but the region tends to priate to seasonal forest than to sava may be resilient to seasonal drought sified water stress caused by highe vulnerable to fires, which are at prese mazonia. The spread of fire ignitio deforestation, logging, and fragme points that trigger the transition of t fire-dominated, low biomass forests. I tation of deforestation and fire may be maintain Amazonian forest resilience 21st-century climate change. Such inte navigate E. Amazonia away from a beyond which extensive rainforest w

carbon dioxide | drought | fire | tropical

The response of components of the levels of anthropogenic greenhous be continuous and gradual; instead elements" in the system (1). Among the Amazon rainforest, with some possibility of substantial and rapid ' zon forest biome is biologically th hosting ~25% of global biodiversity to the biogeochemical functioning large-scale degradation would leav functioning and diversity of the evidence for such a tipping elemen climate model projections in the co considering direct human pressures

There is clear and ongoing change of Amazonia, whether through inc more direct intervention because ation. Such perturbations are certain timescales. The challenge is to ident

#### determining the sensitivity-or

<sup>1</sup>Ecology and Global ( of Leeds, Leeds LS2 9 School of Geography ford OX1 3QY, UK. Pasco, Peru. <sup>4</sup>Instituto Andre Araujo, 1753 <sup>5</sup>Museu Paraense Em Firme, CEP: 66077-83

International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA. Museo de Historia Natural Noel Kempff Mercado, Casilla 2489, Av. Irala 565, Santa Cruz, Bolivia, 8 Missouri Botanical Garden, Box 299, St. Louis, MO 63166, USA. 9Programa de Gencias del Agro y del Mar. Herbario Universitario (PORT). Universidad Nacional Experimental de Los Llanos Occidentales Ezeguid Zamora, Mesa de Cavacas, Portuguesa 3350, Venezuela. 10 Nationaal Herbarium Nederland, W.C. van Unnikoebouw. Heidelberglaan 2, 3584 CS Utrecht, Netherlands, 11Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR EcoFoG, Campus Agronomique, BP 709, 97387 Kourou Cedex, French Guiana. 12 Institut National de la Recherche Agronomique (INRA), UMR EcoFoG, Campus Agronomique, BP 709, 97387 Kourou Cedex, French Guiana. <sup>3</sup>Instituto de Pesquisa Ambiental da Amazônia, Avenida

Nazaré 669, CEP-66035, Belém PA, Brasil. 34Department of

#### Seasonal and interannual variability of climate and vegetation indices across the Amazon

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ew Phytologist (2010) 187: 569-578

(ey words: advanced very high resolution

ectroradiometer, phenology, tropical

adiometer, Amazon basin, Brazil, green-up, andsat, moderate resolution imaging

Edited\* by Ruth S. DeFries, Columbia University. Drought exerts a strong influence on trop Drought exerts a strong influence on tropic carbon stocks, and ultimately the flux of carb's Satellite-based studies have suggested that \u00edu pduring droughts because of increased studies have reported increased tree mo droughts. In an effort to reconcile these a findings, we conducted an analysis of climate the confidence of the c ments, and improved satellite-based meathetic activity. Wet-season precipitation an (PAW) decreased over the Amazon Basin fro tosynthetically active radiation (PAR) and air vapor pressure deficit, VPD) increased from proved enhanced vegetation index (EVI) 2008), we show that gross primary productive declined with VPD and PAW in regions of across a wide range of environments for ea In densely forested areas, no climatic variable the Basin-wide interannual variability of EVI. study, we show that monthly EVI was rela study, we show that monthly EVI was relat area index (LAI) but correlated positively wir measured in the field. These findings sug-new leaves, even when unaccompanied by LAI, could play an important role in Basin-w lability. Because EVI variability was greate

PAW, we hypothesize that drought could in nizing leaf flushing via its effects on leaf bu drought | enhanced vegetation index | moderat spectroradiometer | tropical | carbon cycling

he accumulation of heat-trapping ga The accumulation of heat-trapping gase may subject large areas of the Amaz tropical forest formations to more frequen in the coming decades (1). This trend may i with regional inhibition of rainfall driven and more frequent sea-surface temperar move these tropical forest regions toward Drier and warmer climate in the region fa grasses and shrubs over trees in a proces ecurring fire (8).

It is difficult to assess the drought the

forest dieback might occur, in part because regarding the response of forest photosynth Some studies suggest that forest photosy productivity, GPP) increases during the because of higher photosynthetically active 16). In contrast, two partial throughfall conducted in the Amazon region found ductivity all declined under mild drought mortality increasing under high cumulative resulting from limited plant-available water ref. 17). These impacts were observed only af drought, with the lag probably resulting from reduced availability of soil water (18).

basin, but long-term station records indicate that annual rainfall is decreasing by an average 0.32% yr-1 (Li et al., 2008). Overlain on the long-term trend, there are El Nino-Southern Oscillation (ENSO) events and other sea surface temperature anomalies associated with intense drought in portions of Amazônia (Marengo, 1992; Costa & Foley, 1999; Aragao *et al.*, 2007). Droughts are expected to crease in frequency, extent and severity with climate hange (Williams et al., 2007; Malhi et al., 2009), which will likely have an important impact on biosphere functioning and biodiversity (Meir et al., 2008; Loarie et al., 2009).

Precipitation varies spatially and temporally in the Amazor

urnal compilation © New Phytologist Trust (2010)

Betty Moore Foundation, P.O. Box 29910, San Francisco, CA 94129, USA, 26 Instituto Alexander von Humboldt, Claustro de San Agustín, Villa de Lewa, Boyacá, Colombia. 27 Bayreuth Center of Ecology and Environmental Research, University of Bayreuth, 95440 Bayreuth, Germany. 28 Depto de Ciências da Natureza, Universidade Federal do Acre, Rio Branco AC 69910-900. Brasil. 29 Faculty of Agriculture and Horticulture, Humboldt University of Berlin, Phillipstrasse 13, 10557 Berlin, Germany,

Large-scale on-the-ground assessments of the ecological impacts of tropical droughts are completely lacking, precluding tests of these ideas. f the Amazon Basin

ost intense droughts providing a unique aluate the large-scale st to water deficits. not by El Niño, as onia, but by elevated

in AGB

nce in net change

#### Research review

Drought impacts on the Amazon forest: the remote sensing perspective

Gregory P. Asner1 ar Department of Global Ec 94305 USA; 2University of F

Summary

Drought varies spatially

efforts to assess ecolog

offers a range of region

studies of Amazônia w

during drought years;

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conditions and increa

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forest canopies Liana O. Anderson<sup>1</sup>, Yadvinder Malhi<sup>1</sup>, Luiz E. O. C. Ara

and Oliver Phillips7 xeter, Devon EX4 4RJ, UK; 5School of Geography and Environment, Oxfor mental Engineering, Federal University of Vicosa, Vicosa, Brazil: 5R. los Astronautas, 1758 Jardim da Granja, São José dos Campos, SP 12227-010 Hanter (AMAD). Boulevard de la Lirondo. TA 4-51/DS2. E-36309 Monte niversity of Leeds, Leeds LS2 9TT, UK

#### Summary

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(MODIS) satellite r

drought in Amazor

We combined

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mortality.

Remote sensing detection of droughts in Amazonian

drought and changes in iana O. Anderson 'el: +44 1392 848556 tereived: 30 March 2010 physiological, disturban

New Phytologist (2010) 187: 733–750 doi: 10.1111/j.1469-8137.2010.03355.

irought, MODIS (moderate resolution maging spectroradiometer), phenology, tree nortality, tropical forest, vegetation indices.

showed no spatial r tinct regions respo increase in the Enh tionship (P < 0.07)difference water (P < 0.09) with tre Previous studies drought was ass changes in the radi

he related to struct

#### Introduction

ion monitoring at regional and global scales. It provides full coverage of large and remote areas on a regular basis ver extended periods of time. Of the many remote sensing (RS) based techniques available for analysing vegetation dynamics, time-series analysis of vegetation indices (VIs) as become the most common approach for phenology and lrought assessment.

The normalized difference vegetation index (NDVI) was originally generated based on the advanced very high

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6 MARCH 2009 VOL 323 SCIENCE www.sciencemag.org

to the 2010 drought

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L07402, doi:10.1029/2011GL046824, 2011

Widespread decline in greenness of Amazonian vegetation due

#### Liang Xu,1 Arindam Samanta,1,2 Marcos H. Ramakrishna R. Nemani,5 and Ranga B. My

Received 19 January 2011; revised 3 March 2011; accepted

[1] During this decade, the Amazon region has sur severe droughts in the short span of five years -2010. Studies on the 2005 drought present a cor sometimes contradictory, picture of how these for responded to the drought. Now, on the heels of drought, comes an even stronger drought in indicated by record low river levels in the 100 bookkeeping. How has the vegetation in th responded to this record-breaking drought? Here widespread, severe and persistent declines in v greenness, a proxy for photosynthetic carbon fi the Amazon region during the 2010 drought analysis of satellite measurements. The 2010 dr measured by rainfall deficit, affected an area 1 larger than the 2005 drought - nearly 5 millio vegetated area in Amazonia. The decline in g during the 2010 drought spanned an area that times greater (2.4 million km²) and more sever 2005. Notably, 51% of all drought-stricken forest greenness declines in 2010 (1.68 million km2) co only 14% in 2005 (0.32 million km2). These de 2010 persisted following the end of the dry seaso and return of rainfall to normal levels, unlike Overall, the widespread loss of photosynthetic c Amazonian vegetation due to the 2010 dror represent a significant perturbation to the glob cycle. Citation: Xu, L., A. Samanta, M. H. Costa, S R. R. Nemani, and R. B. Myneni (2011). Widespread greenness of Amazonian vegetation due to the 2010 Geophys. Res. Lett., 38, L07402, doi:10.1029/2011Gl

[2] There is concern that in a warming climate the moisture stress could result in Amazonian rainfor replaced by savannas [Cox et al., 2004; Salazar et Huntingford et al., 2008; Malhi et al., 2008], in w the large reserves of carbon stored in these fore 100 billion tons [Malhi et al., 2006], could be relea

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Federal University of Viçosa, Viçosa, Minas Gerais, Brazil.

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\*Biospheric Science Branch, NASA Ames Research Cer
Field, California, USA.

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GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L19105, doi:10.1029/2011GL049118, 2011

#### Amazon vegetation greenness as measured by satellite sensors over the last decade

P. M. Atkinson, 1 J. Dash, 1 and C. Jeganathan 1

As drought

increases, live

trees decrease.

Received 3 August 2011; revised 9 September 2011; accepted 12 September 2011; published 12 October 2011.

2005 and another in 2010, occurred in the Amazon basin. 2011] and possible feedback effects of biomass loss on Several studies have claimed the ability to detect the effect of these droughts on Amazon vegetation response, measured through satellite sensor vegetation indices (VIs). Such monitoring capability is important as it potentially links climate changes (increasing frequency and severity of climate changes (increasing frequency and severity of drought), vegetation response as observed through vegetation greenness, and land-atmosphere carbon fluxes which directly feedback into global climate change. However, we show conclusively that it is not possible to detect the response of vegetation to drought from space using VIs. We analysed 11 years of dry season (July-September) Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) and normalised difference vegetation index (NDVI) images. The VI standardised anomaly was analysed alongside the absolute value of EVI and NDVI, and the VI values for drought years were compared with those for nondrought years. Through a series of analyses, the standardised anomalies and VI values for drought years were shown to be of similar magnitude to those for non-drought years. Thus, while Amazon vegetation may respond to drought, this is not detectable through satellite-observed changes in vegetation greenness. A significant long-term decadal decline in VI values is reported, which is independent of the occurrence of drought. This trend may be caused by environmental or noise-related factors which require further investigation. Citation: Atkinson, P. M., J. Dash, and C. Jeganathan (2011), Amazon vegetation greenness as measured by satellite sensors over the last decade, Geophys. Res. Lett., 38, L19105, doi:10.1029/2011GL049118.

#### 1. Introduction

[2] The Amazon region contains around 54% of the world's rainforest and stores more than 100 billion tonnes of carbon [Malhi et al., 2006]. A general increase in temper-ature since the 1970s, and decadal-scale variation in rainfall, have been recorded for the Amazon rainforest [New et al., 2000], while Li et al. [2008] reported a 0.32 per decade decline in the standard precipitation index between 1970 and 1999, suggesting increasingly dry conditions in the Amazon in recent years. Several global circulation models (GCMs) have projected these trends into the future [Marengo, 2005] leading to concerns over the effects of increased frequency and severity of drought on net primary productivity and

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[1] During the last decade two major drought events, one in biomass carbon storage in the Amazon basin [Lewis et al.,

climate change. [3] Changes in precipitation amount and duration may affect photosynthetic activity and the functioning and condition of the forest which, in turn, may affect overall carbon fluxes to the atmosphere. In a normal year, the Amazon rainforest absorbs approximately 1.5 billion tonnes of car-bon from the atmosphere. However, Lewis et al. [2011] predicted, based on a model, a net transfer of 2.2 billion tonnes of carbon to the atmosphere in 2010, a drought year. Thus, the prospect of increasingly dry conditions, and an increasing frequency of drought years, is of great concern as such conditions have the potential to turn the Amazon from a sink of carbon into a source of carbon, greatly affecting

rates of global climate change [Lewis et al., 2011]. [4] For an area as vast as the Amazon, satellite remote sensing provides the only possible means of monitoring the impact of droughts on vegetation at the basin scale. Such remote sensing approaches generally rely upon the use of vegetation indices (VIs) to measure vegetation "greenness". The ability to detect from space the effect of drought on vegetation response, in the form of vegetation green potentially of crucial importance in monitoring the effects of

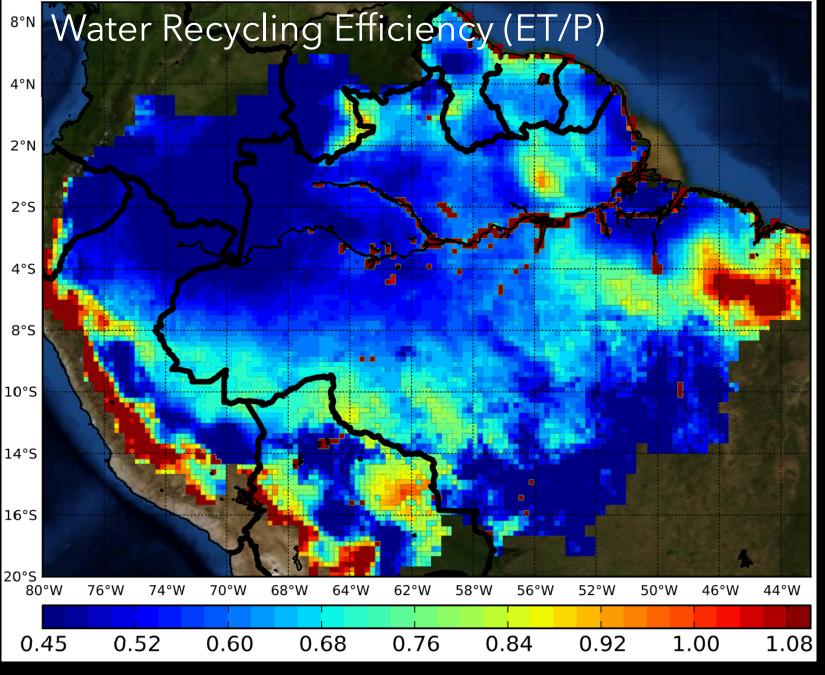
drought on carbon flux in the Amazon.

[5] During the last decade two severe drought events affected the Amazon basin; one in 2005 and the other in 2010. The drought in 2010 was spatially more extensive than that in 2005 and affected more than 3 million km [Lewis et al., 2011]. Saleska et al. [2007] were the first to report a significant increase in vegetation greenness over the Amazon during the 2005 drought using the enhanced vegetation index (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. However, this was later challenged by Samanta et al. [2010] on the basis of poor chairinged by Samanta et al. [2010] on the obasis of pool data quality and processing methodology. They suggested greater vegetation browning (or no change) than greening during the 2005 drought. Moreover, Anderson et al. [2010] reported positive EVI anomalies associated with higher tree mortality and questioned Saleska et al.'s [2007] interpreta-tion of the observed changes in VIs. Brando et al. [2010], using climate, satellite and field data found no relation ship between the inter-annual variability in plant available water (PAW) and EVI for densely forested areas in the Amazon, but observed a decline in EVI with decline in PAW for areas with low vegetation cover. Recently, a key paper published in this journal by Xu et al. [2011] suggested, using MODIS VIs, that vegetation browning in 2010 was four times greater than in 2005 affecting more than 50%

of the forested area in the Amazon and, thus, that the increased browning was a response to the 2010 drought.

Thus, controversy exists in the literature about the effects of

Phillips, O.L., Aragão, L., Lewis, S.L., Fisher, J.B., et al., 2009. Drought sensitivity of the Amazon rainforest. Science.



Vergopolan, N. and **Fisher, J.B.**, in review. The impact of deforestation on the hydrological cycle in Amazonia as observed from remote sensing. *Geophysical Research Letters*.





Global and Planetary Change 56 (2007) 274-296



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#### Climate-induced boreal forest change: Predictions

#### versus current observations

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#### Abstract

For about three decades, there have been many predictions of the potential ecological response in boreal warmer conditions. In essence, a widespread, naturally occurring experiment has been conducted over time. Ir previously modeled predictions of ecological change in boreal Alaska, Canada and Russia, and then we invest of current climate-induced change. For instance, ecological models have suggested that warming will induce t migration of the treeline and an alteration in the current mosaic structure of boreal forests. We present evide keystone ecosystems in the upland and lowland treeline of mountainous regions across southern Siberia. Ecolpredicted a moisture-stress-related dieback in white spruce trees in Alaska, and current investigations sh increase, white spruce tree growth is declining. Additionally, it was suggested that increases in infestation a would be catalysts that precipitate the alteration of the current mosaic forest composition. In Siberia, 7 of the extreme fire seasons, and extreme fire years have also been more frequent in both Alaska and Canada experienced extreme and geographically expansive multi-year outbreaks of the spruce beetle, which had be the cold, moist environment. We suggest that there is substantial evidence throughout the circumboreal regi biosphere within the boreal terrestrial environment has already responded to the transient effects of climat temperature increases and warming-induced change are progressing faster than had been predicted in som potential non-linear rapid response to changes in climate, as opposed to the predicted slow linear response © 2006 Elsevier B.V. All rights reserved.

Keywords: climate change evidence; fire; infestation disturbance; treeline progression; boreal; montane

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Atmos. Chem. Phys., 11, 7925-7942, 2011 www.atmos-chem-phys.net/11/7925/2011/ doi:10.5194/acp-11-7925-2011 © Author(s) 2011. CC Attribution 3.0 License.



Satellite- and ground-based CO total column observations over 2010 Russian fires: accuracy of top-down estimates based on thermal IR satellite data

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Abstract. CO total column data are presented from three space sounders and two ground-based spectrometers in Moscow and its suburbs during the forest and peat fires that occurred in Central Russia in July-August 2010. Also presented are ground-based in situ CO measurements. The Moscow area was strongly impacted by the CO plume from these fires. Concurrent satellite- and ground-based observations were used to quantify the errors of CO top-down emission estimates. On certain days, CO total columns retrieved from the data of the space-based sounders were 2-3 times less than those obtained from the ground-based sun-tracking spectrometers. The depth of the polluted layer over Moscow was estimated using total column measurements compared with CO volume mixing ratios in the surface layer and on the TV tower and found to be around 360 m. The missing CO that is the average difference between the CO total column accurately determined by the ground spectrometers and that retrieved by AIRS, MOPITT, and IASI was determined for the Moscow area between 1.6 and 3.3 × 1018 molec cm-2 These values were extrapolated onto the entire plume; subsequently, the CO burden (total mass) over Russia during the fire event was corrected. A top-down estimate of the total emitted CO, obtained by a simple mass balance model increased by 40-100 % for different sensors due to this correction. Final assessments of total CO emitted by Russian wildfires obtained from different sounders are between 34 and 40 Tg CO during July-August 2010.



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1 Introduction

Carbon monoxide (CO) is recogn biomass burning and anthropogen 1981; Edwards et al., 2004, 2006 CO total source is estimated by 2491 Tg yr-1 for the 1990's and in the range between 2236 and 2biomass burning emissions. Dunca per year downward trend from 198 this trend by a decrease in Europ tions from wildfires were counted by van der Werf et al. (2010), and v globally and regionally. From 2000 sions varied between 253 (2001) i.e. between 11 % and 16 % of to in these bottom-up calculations are of burned areas, fuel loads, emissi carry out top-down estimates of C measurements of CO are of great

CO has been measured from sp al., 1986). Those pioneering observations burning, especially over Africa, as CO feature and confirmed the Nor (TC) gradient discovered earlier trometer (Malkov et al., 1976). erationally by several satellite-box sults of most retrievals are availa very distinct spectral features: the first overtone, which are located in

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#### Mountain pine beetle and forest carbon feedback to climate change

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The mountain pine beetle (Dendroctonus ponderosae Hopkins, Coleoptera: Curculionidae, Scolytinae) is a native insect of the pine forests of western North America, and its populations periodically erupt into large-scale outbreaks1-3. During outbreaks, the resulting widespread tree mortality reduces forest carbon uptake and increases future emissions from the decay of killed trees. The impacts of insects on forest carbon dynamics, however, are generally ignored in large-scale modelling analyses. The current outbreak in British Columbia, Canada, is an order of magnitude larger in area and severity than all previous recorded outbreaks4. Here we estimate that the cumulative impact of the beetle outbreak in the affected region during 2000-2020 will be 270 megatonnes (Mt) carbon (or 36 g carbon m<sup>-2</sup> yr<sup>-1</sup> on average over 374,000 km2 of forest). This impact converted the forest from a small net carbon sink to a large net carbon source both during and immediately after the outbreak. In the worst year, the impacts resulting from the beetle outbreak in British Columbia were equivalent to ~75% of the average annual direct forest fire emissions from all of Canada during 1959–1999. The resulting reduction in net primary production was of similar magnitude to increases observed during the 1980s and 1990s as a result of global change5. Climate change has contributed to the unprecedented extent and severity of this outbreak6. Insect outbreaks such as this represent an important mechanism by which climate change may under mine the ability of northern forests to take up and store atmospheric carbon, and such impacts should be accounted for in

large-scale modelling analyses. Forest insect epidemics can have severe impacts on ecosystem dynamics by causing mortality and reducing the growth of millions of trees over extensive areas<sup>7</sup>. Native insects and alien invasive species affect both managed and natural forests. Beyond the ecological impacts are the associated economic (for example, disrupted timber supply to mills) and social (for example, unemployment, crime rates) effects8. The impact of insects on carbon (C) dynamics and global climate are not well documented9.

The current outbreak of mountain pine beetle in western Canada is an order of magnitude greater in area than previous outbreaks owing to the increased area of susceptible host (mature pine stands) and favourable climate4 (see also Supplementary Fig. 3). An expansion in climatically suitable habitat for the mountain pine beetle, including reduced minimum winter temperature, increased summer temperatures and reduced summer precipitation, during recent decades has facilitated expansion of the outbreak northward and into higher elevation forests 4,10. This range expansion, combined with an increase in the extent of the host, has resulted in an outbreak of unprecedented scale and severity. By the end of 2006, the cumulative outbreak area was 130,000 km2 (many stands being attacked in multiple years), with tree mortality ranging from single trees to most of a infested ranging from 74,000 km2 to 94,000 km2 (Fig. 3).

stand in a single year11. Timber losses are estimated to be more than 435 million m<sup>3</sup>, with additional losses outside the commercial forest12. The forest sector has responded by increasing harvest rates and reallocating some harvest, increasing the pine portion of the provincial total volume harvested from 31% to 45% over four years

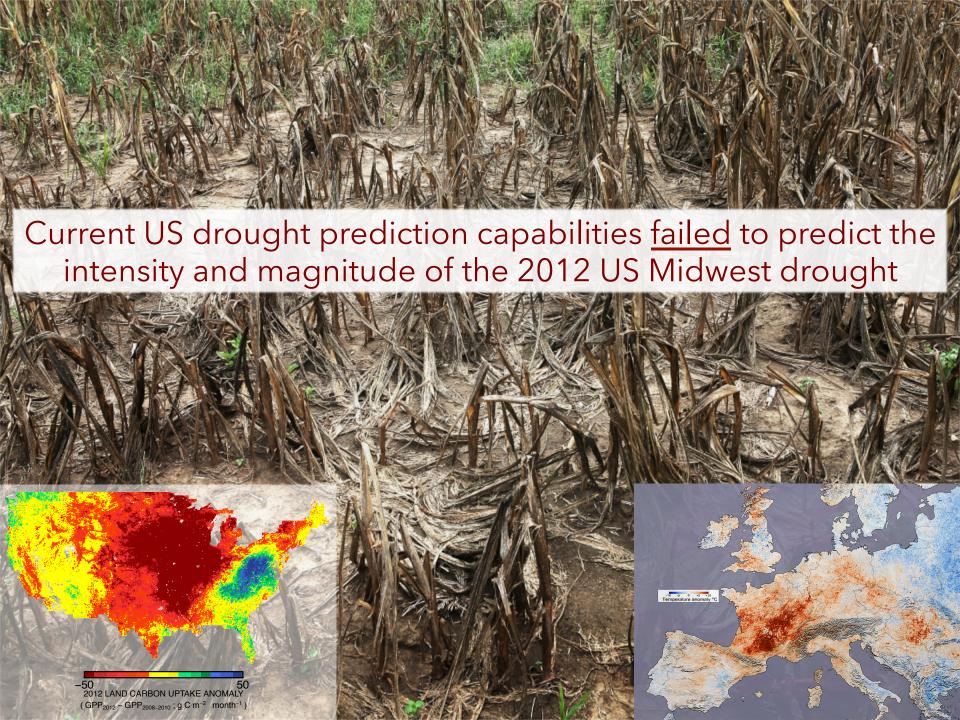
We estimated the combined impact of the beetle, forest fires and harvesting on forest productivity and carbon balance from 2000 until 2020 for the south-central region of British Columbia (Fig. 1). This area includes 374,000 km2 of productive forest, largely dominated by pine (Pinus) and spruce (Picea) species. We used a Monte Carlo design for simulating future net biome production (NBP) using a forest ecosystem model (the Carbon Budget Model of the Canadian Forest Sector, CBM-CFS3). This model accounts for annual tree growth, litterfall, turnover and decay, and it explicitly simulates harvest, beetle-caused mortality, and fire-caused mortality and fuel consumption. We developed regional probability distribution functions of the annual area burned and projected future beetle dynamics on the basis of the characteristics of the remaining host (that is, pine stands of suitable age) and the judgement of regional entomologists. We conducted 100 Monte Carlo simulations with different random draws from the probability distributions for the annual area of beetle outbreak and the annual area burned.

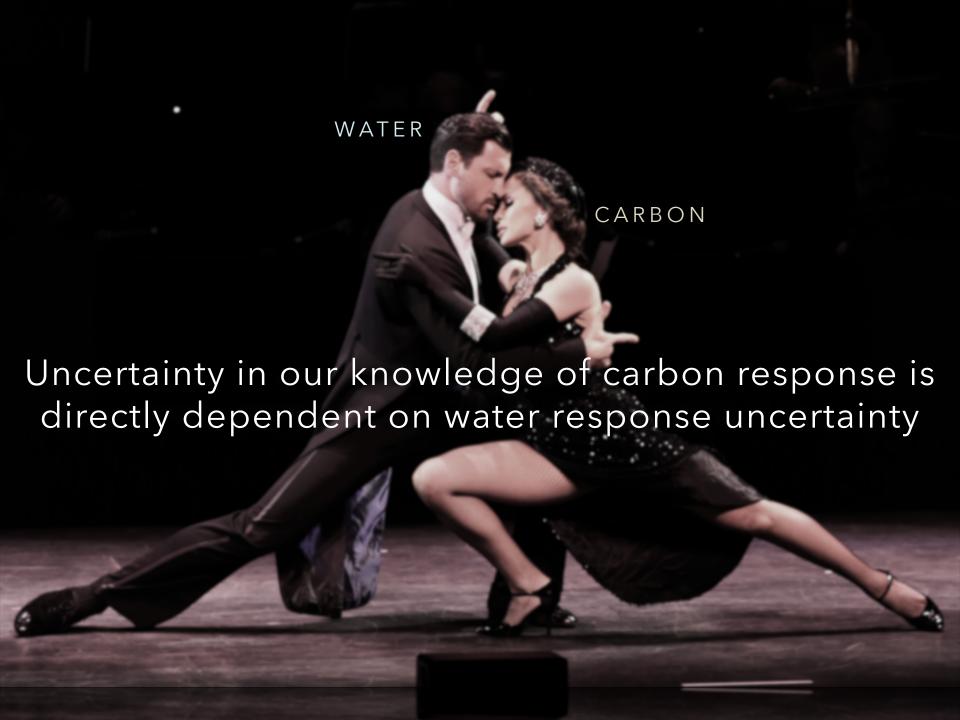
For the period 2000–2020, the average annual NBP was -15.8 ±  $^{-1}$  (or  $-42.4 \pm 21 \,\mathrm{g}\,\mathrm{C}\,\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$ ; Fig. 2). Carbon losses result from emissions from decomposition and fires and from the transfer of timber to the forest product sector. In a separate analysis13, we estimated that the study area was a net sink from 1990 to 2002. The first two years of this study also reported a net sink (0.59 Mt Cyr<sup>-1</sup>), but with increasing beetle impact (Fig. 3), the forest converted to a source of 17.6 Mt C yr 1 from 2003 to 2020. With decreasing beetle impact (Fig. 3), NBP began to recover, but by 2020, the estimated NBP had not yet returned to pre-outbreak levels. Although we can expect that forests will eventually recover from the beetle outbreak, we are reluctant to extend projections beyond 2020 or to speculate on the rate of recovery beyond 2020 given uncertainties about non-host responses, rates of regeneration, and future fires in a region in which major climate change impacts are

One component of the uncertainty in future NBP is that we do not know the future area that will be infested by the beetle. We projected the area infested during 2007-2020 using random draws from regionally calibrated probability distributions of outbreak area and duration that were based on: the 2000-2006 area; mortality and host statistics; historical, spatial and temporal dynamics; remaining host population; and judgment from entomologists. The outbreak was projected to peak between 2006 and 2008, with the maximum area

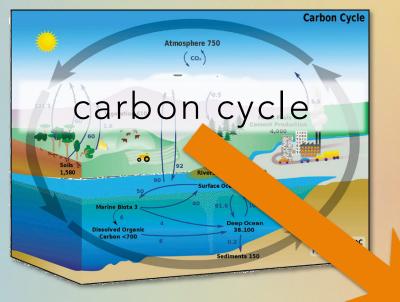
Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, VBZ 1M5, Canada. <sup>2</sup>British Columbia Ministry of Forests and Range, Victoria British Columbia, VBW 9C2, Canada.

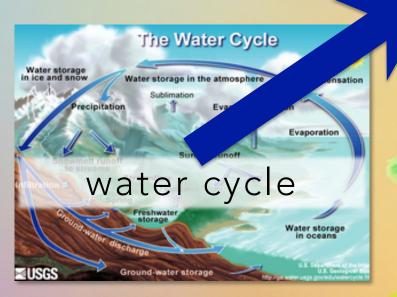
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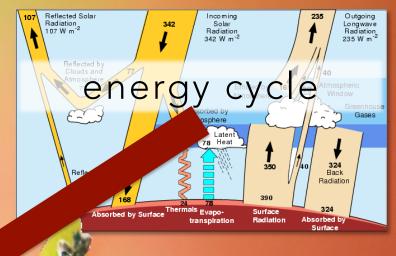












ET describes the net exchange of water vapor between the land surface and the atmosphere, and is comprised of water evaporated directly from the soil or other surfaces and water transpired (i.e., used; consumptive use) by plants.

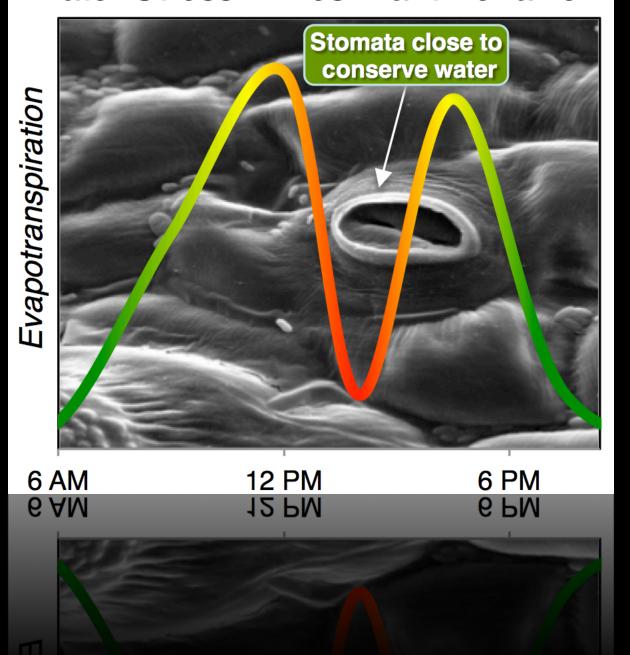
what is evapotranspiration (ET)?

Evapotranspiration is the key climate variable linking the water, energy, and carbon cycles



Plants regulate water loss (transpiration) by closing the pores on their leaves, but at the expense of shutting off CO<sub>2</sub> uptake for photosynthesis and risking **carbon starvation**. Transpiration also performs the same cooling function as sweat; if plants cannot adequately cool themselves, they risk **overheating** and **mortality** due to **heat stress**.

### Water Stress Drives Plant Behavior

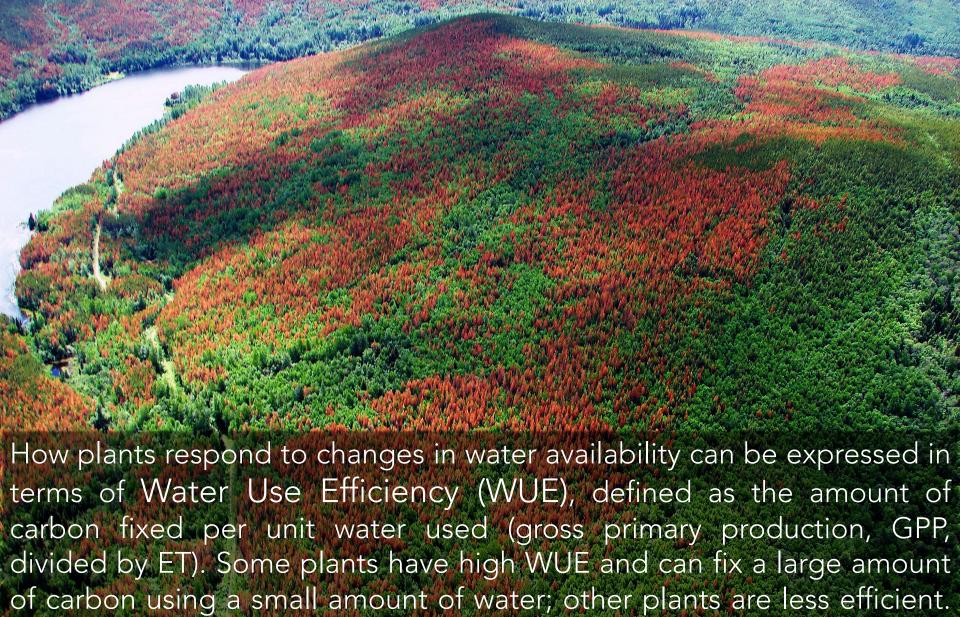












Low WUE plants risk replacement with increasing droughts.

### ECOSTRESS KEY SCIENCE QUESTIONS

- 1. How is the terrestrial biosphere responding to changes in water availability?
- 2. How do changes in diurnal vegetation water stress impact the global carbon cycle?
- 3. CAN AGRICULTURAL VULNERABILITY BE REDUCED THROUGH ADVANCED MONITORING OF AGRICULTURAL CONSUMPTIVE USE AND IMPROVED DROUGHT DETECTION?

### ECOSTRESS SCIENCE OBJECTIVES

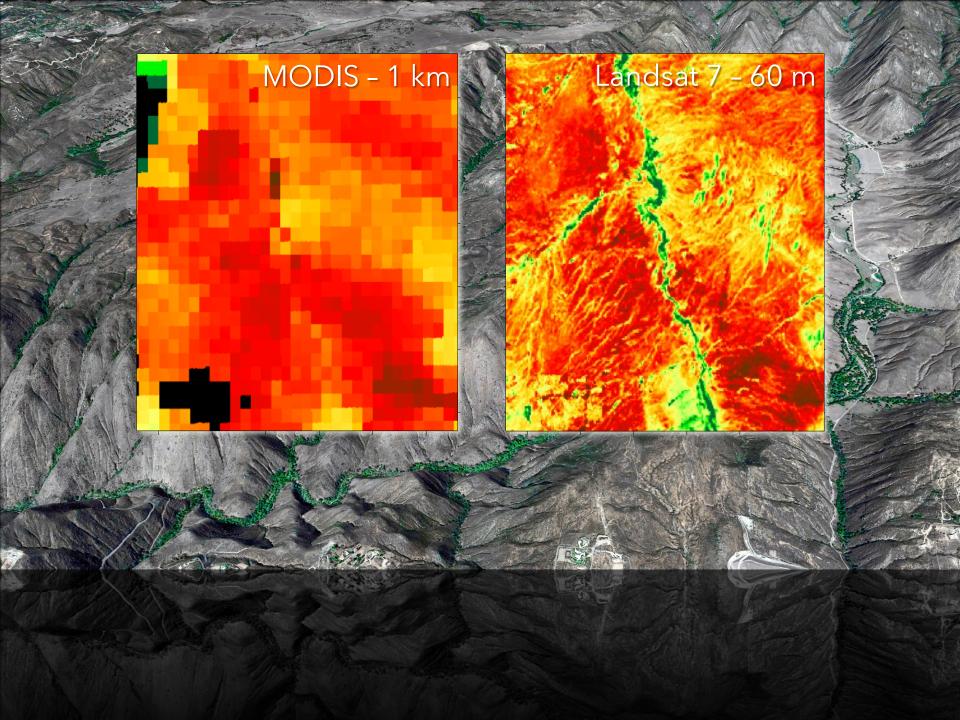
- 1. IDENTIFY **CRITICAL THRESHOLDS** OF WATER USE AND WATER STRESS IN KEY CLIMATE SENSITIVE BIOMES (E.G., TROPICAL/DRY TRANSITION FORESTS, BOREAL FORESTS);
- 2. DETECT THE TIMING, LOCATION, AND PREDICTIVE FACTORS LEADING TO PLANT WATER UPTAKE DECLINE AND/OR CESSATION OVER THE **DIURNAL CYCLE**;
- 3. MEASURE AGRICULTURAL WATER CONSUMPTIVE USE GLOBALLY AT SPATIOTEMPORAL SCALES APPLICABLE TO IMPROVING DROUGHT ESTIMATION ACCURACY.

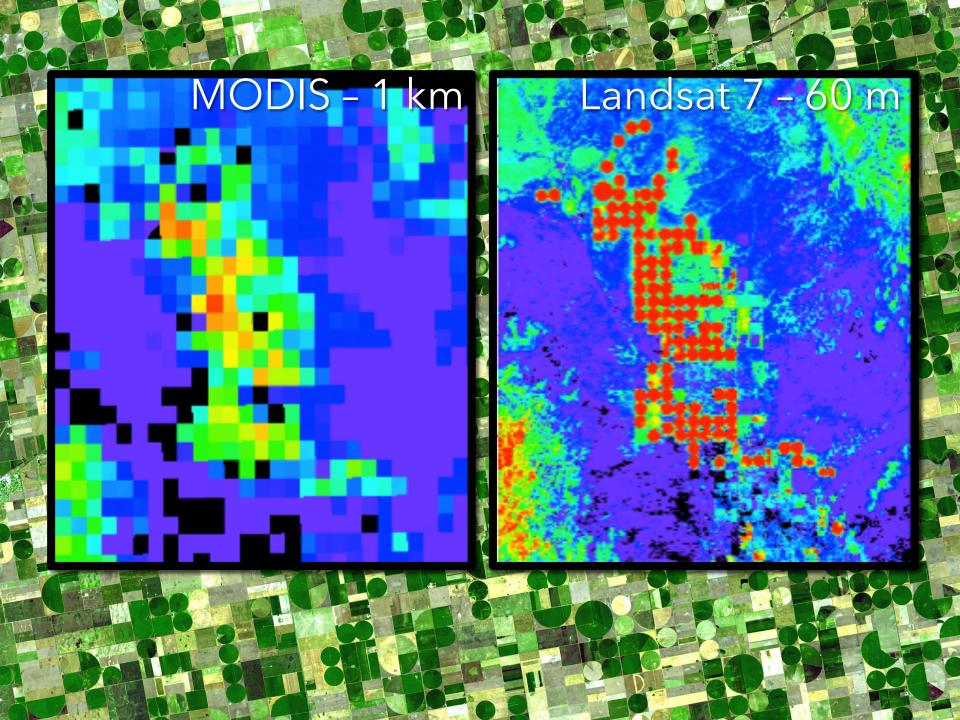
## APPROACH

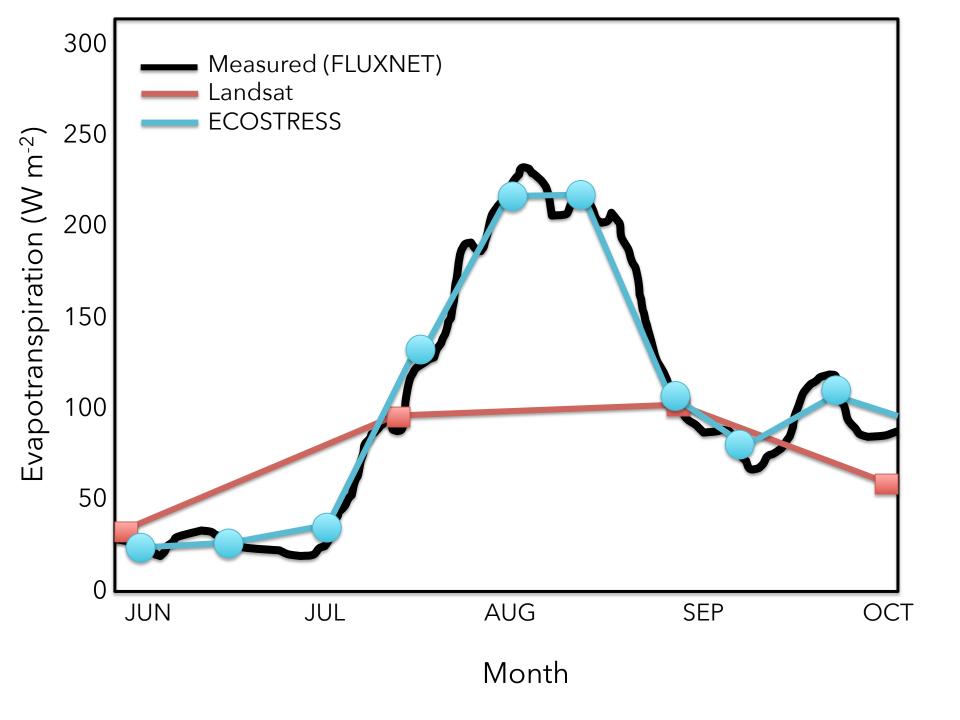


What we need: accurate, high spatial, high temporal, diurnal cycle, global, ET.

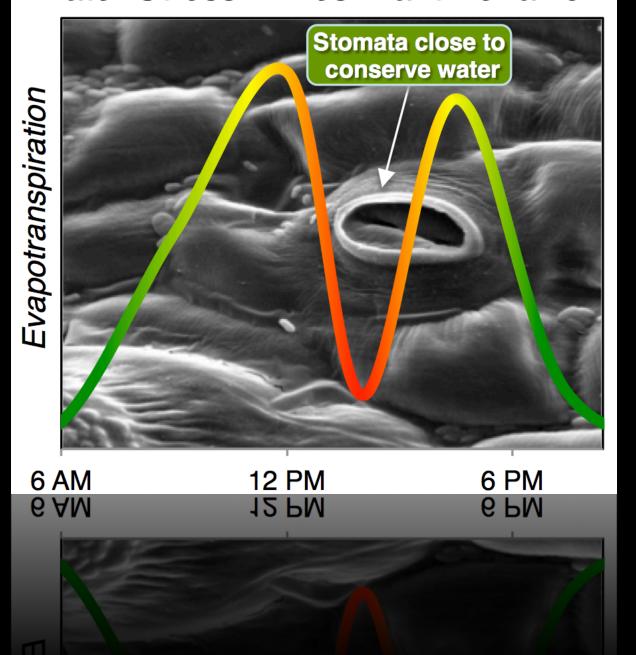








### Water Stress Drives Plant Behavior

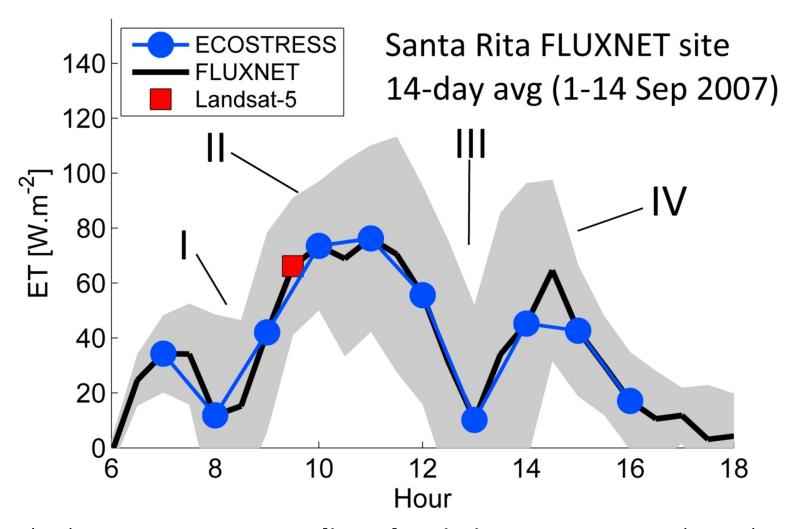


# GOES-R



NEXT GENERATION WEATHER SATELLITE

# The International Space Station **Number of Overpasses** Overpass time (hour of day)



Gray shading represents mean **diurnal variation** in ET over 14-days. The afternoon decline in ET is related to water stress (clear day).

- Xylem refilling after initial water release.
- II ET at maximum/potential rate in the morning.
- III Stomata shut down water flux in the afternoon.
- IV ET resumes at maximum/potential in early evening when demand is reduced.

## ET Spaceborne Measurements Requirements

Parameters	Minimal	Optimum	Landsat 8	MODIS	HyspIRI*	ECOSTRESS
Return Cycle (days)	≤8	≤4	16	1	5	3-5
Number of TIR bands	1	>2	2	3	8	5
Spatial resolution (m)	120	30	100	1000	60	38x57
Coverage	US always on	World always on	US always on	World always on	World always on	World always on+

Source: Letter to Anne Castle on "Water Resources Needs" dated November 22, 2011, R. Allen, U. Idaho, referencing Allen 2010, Allen et al 2011.

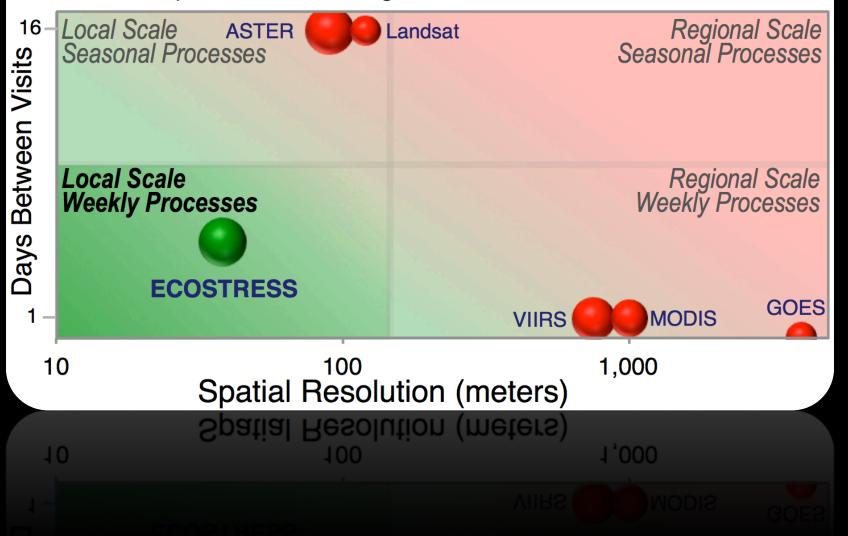
<sup>\*</sup> Proposed mission >2023.



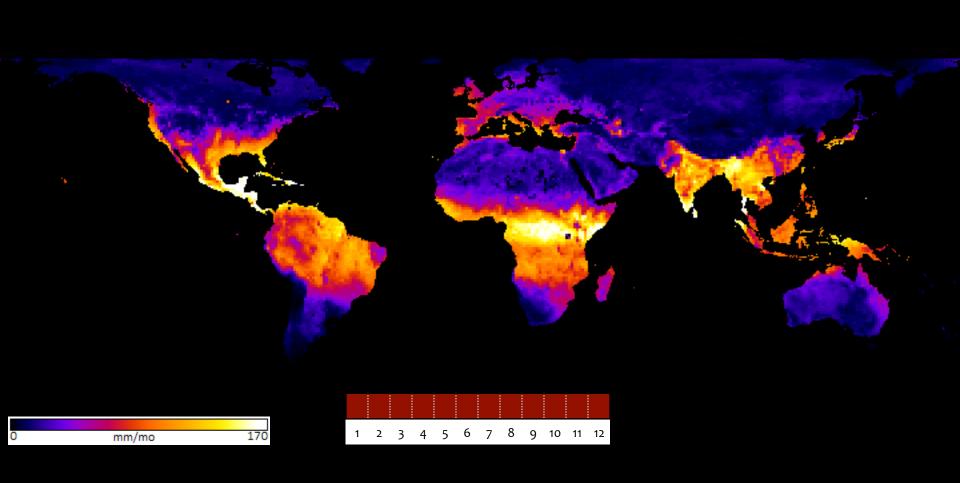


## Revisit Time versus Spatial Resolution

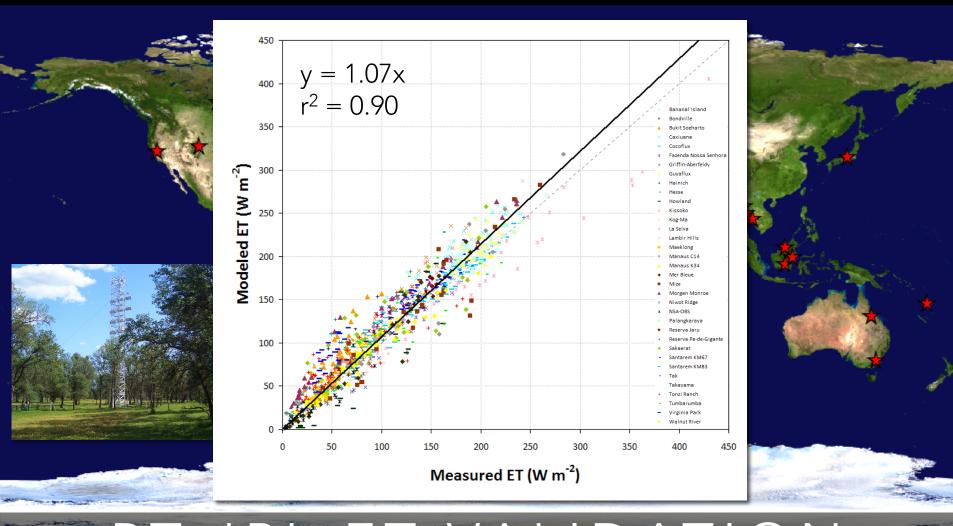
With sphere size indicating # of thermal infrared window bands



# PT-JPL GLOBAL ET

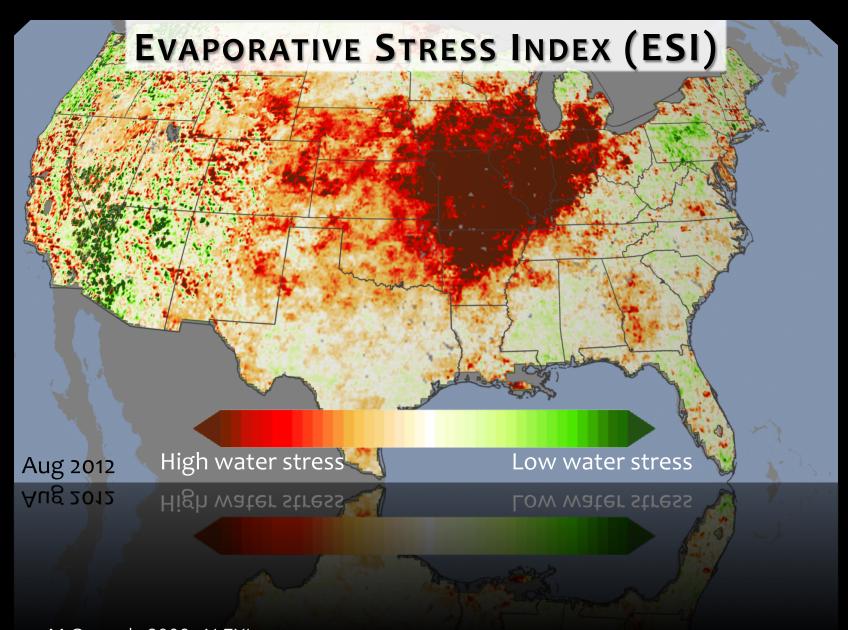


**Fisher, J.B.**, Tu, K.P., Baldocchi, D.D., 2008. *Remote Sensing of Environment.* 



## PT-JPL ET VALIDATION

**Fisher, J.B.**, Tu, K.P., Baldocchi, D.D., 2008. Remote Sensing of Environment.



Anderson, M.C., et al., 2008: ALEXI. Remote Sensing of Environment.



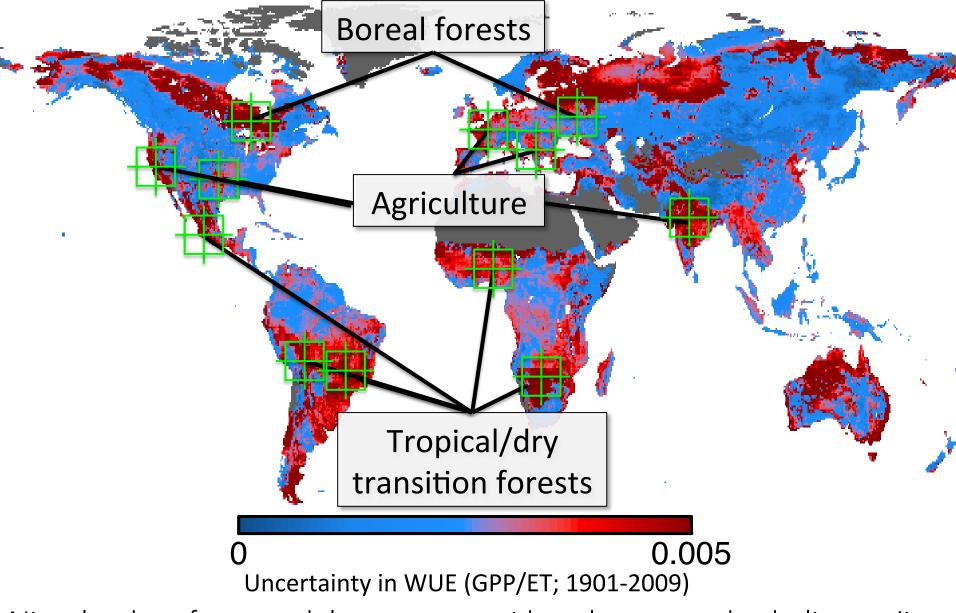


An Earth Venture Instrument-2 Proposal
Submitted in response to
AO NNH12ZDA006O EVI2

National Aeronautics and
Space Administration
Science Mission Directorate

ECOSTRESS will provide critical insight into **plant-water dynamics** and how **ecosystems change with climate** via **high spatiotemporal** resolution thermal infrared radiometer measurements of evapotranspiration from the International Space Station (ISS).

E.		
ECC	OSTRESS Science Data Products	
L2	Surface Temperature Surface Emissivity	
L3	Evapotranspiration	
L4	Water Use Efficiency Evaporative Stress Index	November 25, 2013



Nine land surface models were run with only a perturbed climate (i.e.,  $CO_2$ , land use constant) over the  $20^{th}$  century, representing the  $\gamma$ -response, or climate sensitivity to identify key WUE uncertainty hotspots.



#### ECOSTRESS CORE SCIENCE HYPOTHESES

H1: THE WUE OF A CLIMATE SENSITIVE HOTSPOT IS SIGNIFICANTLY LOWER THAN NON-HOTSPOTS OF THE SAME BIOME TYPE;

H<sub>2</sub>: Daily ET is overestimated when extrapolating from Morning-only observations;

H<sub>3</sub>: Remotely sensed ET measured at the field scale will improve drought prediction over managed ecosystems.

## Our first objective on <u>climate sensitivity and biome response</u>, focused on <u>water limitation and droughts</u>, is specifically called out in:

- **Decadal Survey**: recommended observations, key questions and science themes [US NRC, 2007; Chapter 2: p27; Chapter 7: p196];
- WCRP: grand science challenges [WCRP, 2012];
   NASA Earth Science: big questions [NASA Earth Science, 2013].
- Our second objective on <u>plant-water dynamics</u> and the <u>functioning of terrestrial ecosystems over</u>
- the diurnal cycle is encompassed within:
   Decadal Survey: role of satellites in understanding ecosystems [US NRC, 2007; Chapter 7:
- p192; Chapter 9: p257];
   NASA Terrestrial Hydrology, Ecology, and Carbon Cycle Programs: primary scientific objective and goals [e.g., A.20-1 ROSES2013].
- NRC: "Global Change and Extreme Hydrology" [US NRC, 2011], "Assessment of Intraseasonal and Interannual Climate Prediction and Predictability" [US NRC, 2010], and "Landsat and

Our third objective with relevance to agricultural applications and water management is

- Beyond: Sustaining and Enhancing the Nation's Land Imaging Program" [US NRC, 2013];
   Decadal Survey: key questions and science themes [US NRC, 2007; Chapter 7: p196]; and
   USGCRP: strategic goals [USGCRP, 2012].
- White House: National Drought Resilience Partnership [Council on Environmental Quality, 2013].
- ECOSTRESS also addresses many of the science goals of the NRC Decadal Survey HyspIRI mission and Landsat mission [*US NRC*, 2013], providing lower cost, higher spatial, spectral and temporal resolution thermal infrared measurements.

## **EVOLVING ECOSTRESS, AND BEYOND...**

- $\rightarrow$  HyspIRI  $\rightarrow$
- → Landsat/SLI →

