On vapor pressure deficit (VPD) versus CO_2 impacts from stomata to global climate

Nate McDowell and Ruby Leung

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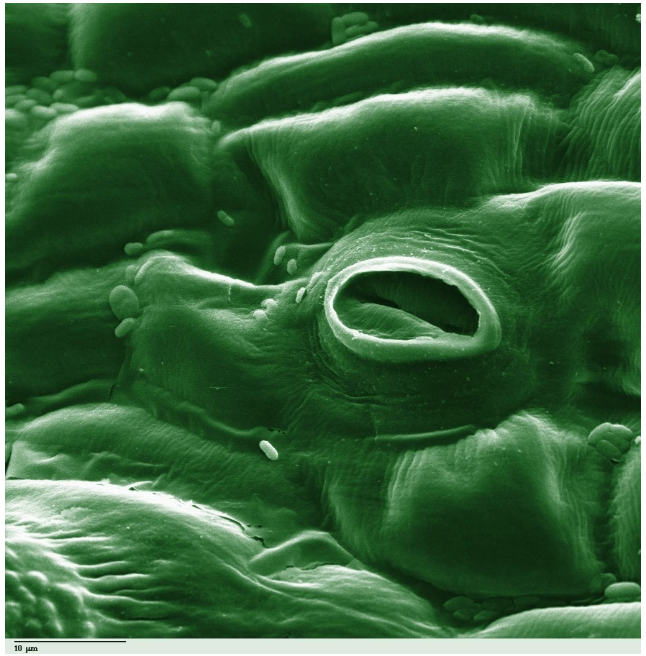
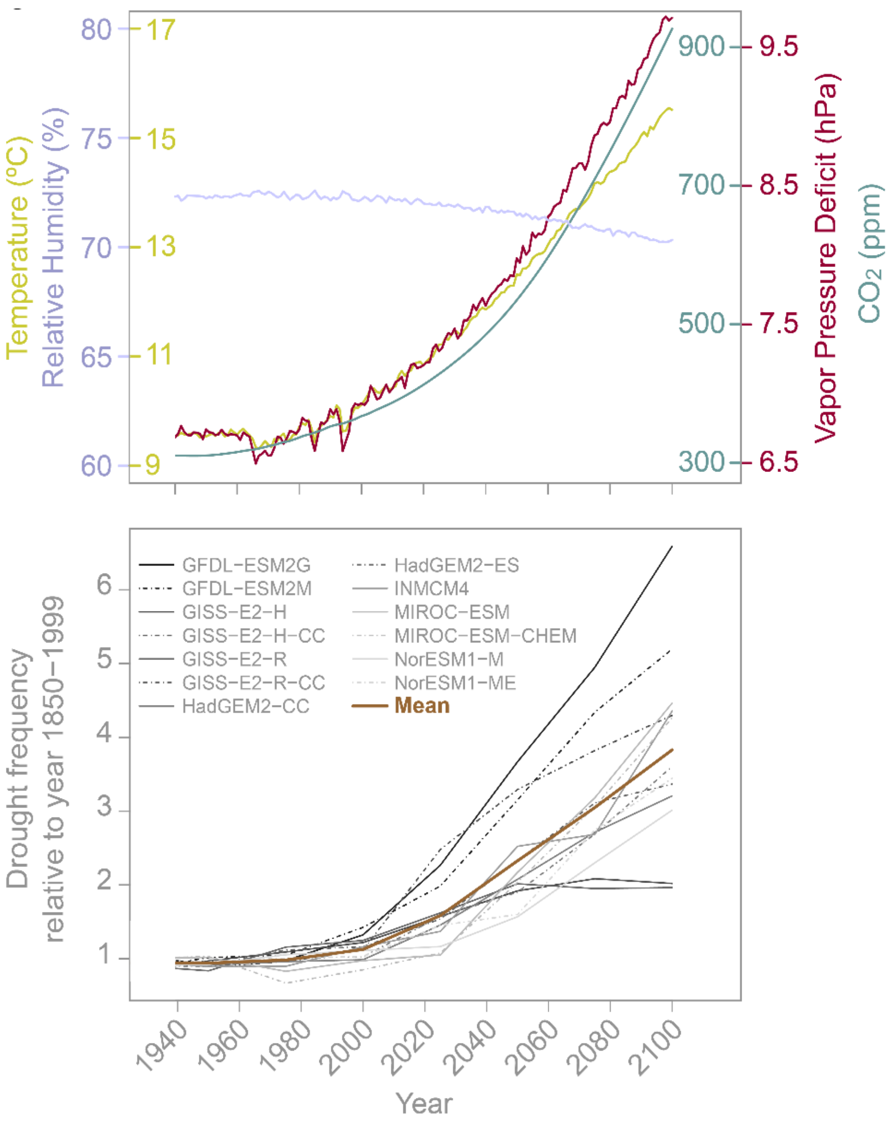


VPD and CO_2 are rising



With large impacts on modeled soil drought

McDowell et al. *in review*

Some big questions

What are the…

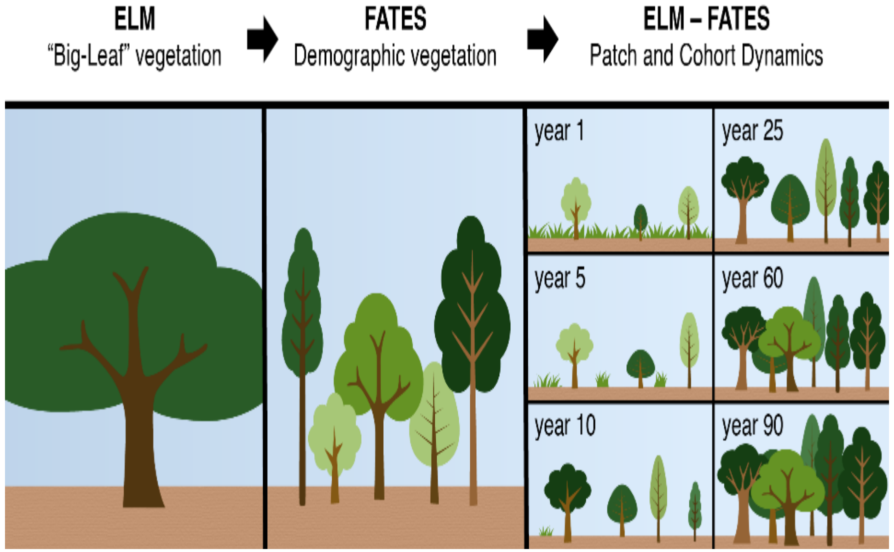
- **plant-scale** responses to rising VPD? And to rising CO_2?
- **landscape-scale** responses to rising VPD (including disturbances)? And, landscape-scale responses to rising CO_2?
- **global** climate impacts of rising VPD? And, of rising CO_2?
- **net global** climatic impacts of rising VPD and CO_2?

Alaska, USA

Our ultimate goals

1) to disentangle the antagonistic effects of rising VPD and CO_2 on plants and subsequently on global climate

2) to improve model representation as necessary for predictive accuracy



e.g. Fisher et al. 2015

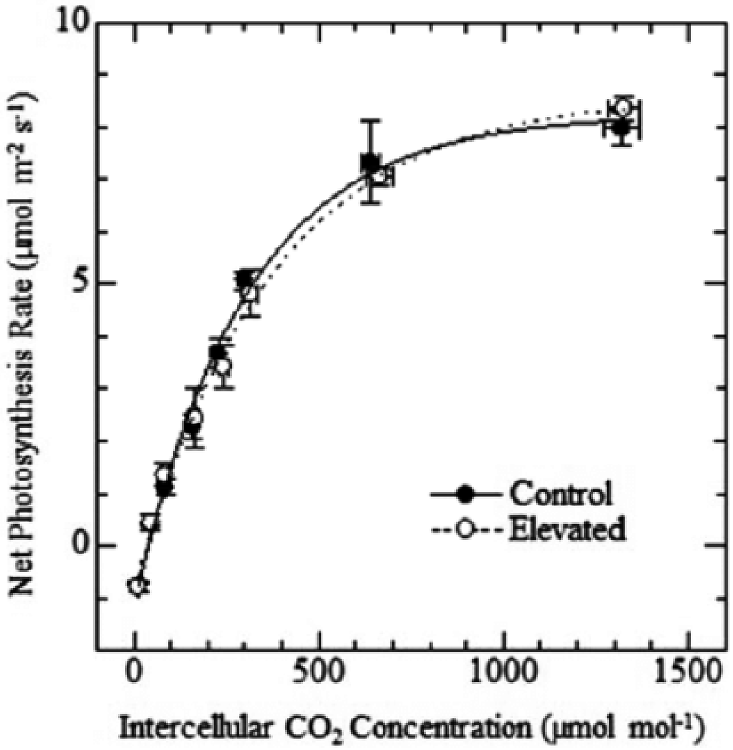
VPD and CO_2 impacts on plant physiology

Amazon forest, Manaus Brazil

Rubisco and stomata cover the Earth

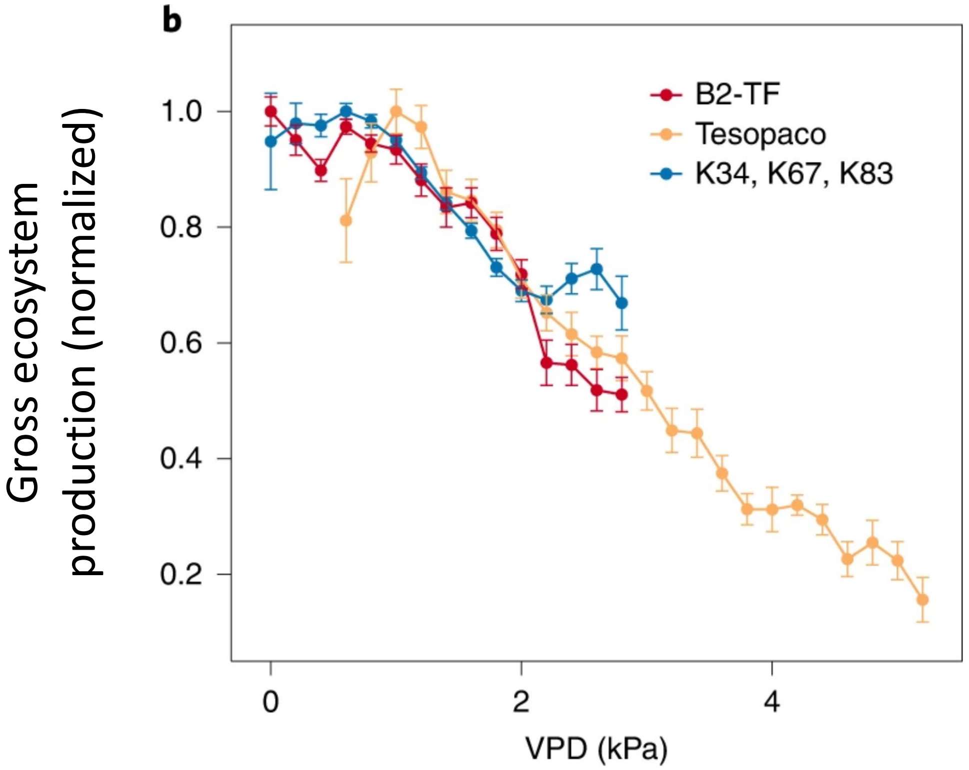
West Kalimantan, Indonesia. Nanang Sujana/CIFOR

What is the role of rising VPD and CO_2? A physiological conflict



Rising CO_2 drives higher rubisco carboxylation

Lee et al. 2013

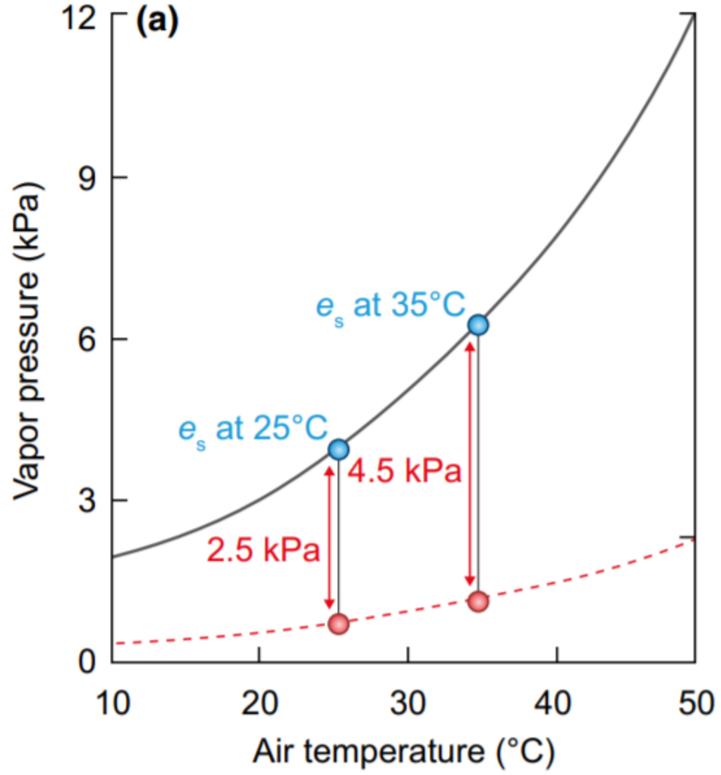


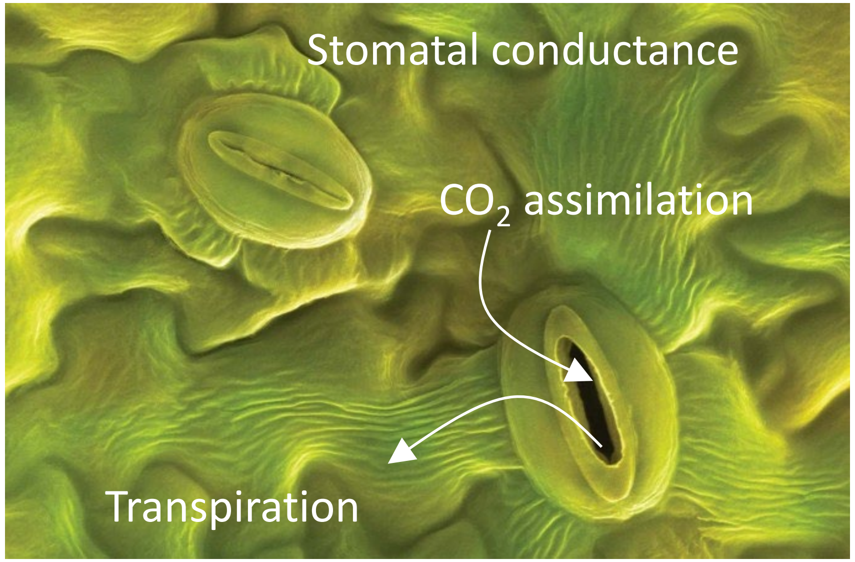
Declining stomatal conductance forces a decline in the CO_2 diffusion gradient

Smith et al. 2020

VPD and stomata

1) VPD is the evaporative demand for water from ecosystem surfaces.
2) VPD is an exponential function of temperature.
3) VPD strongly controls stomatal conductance and hence photosynthesis.

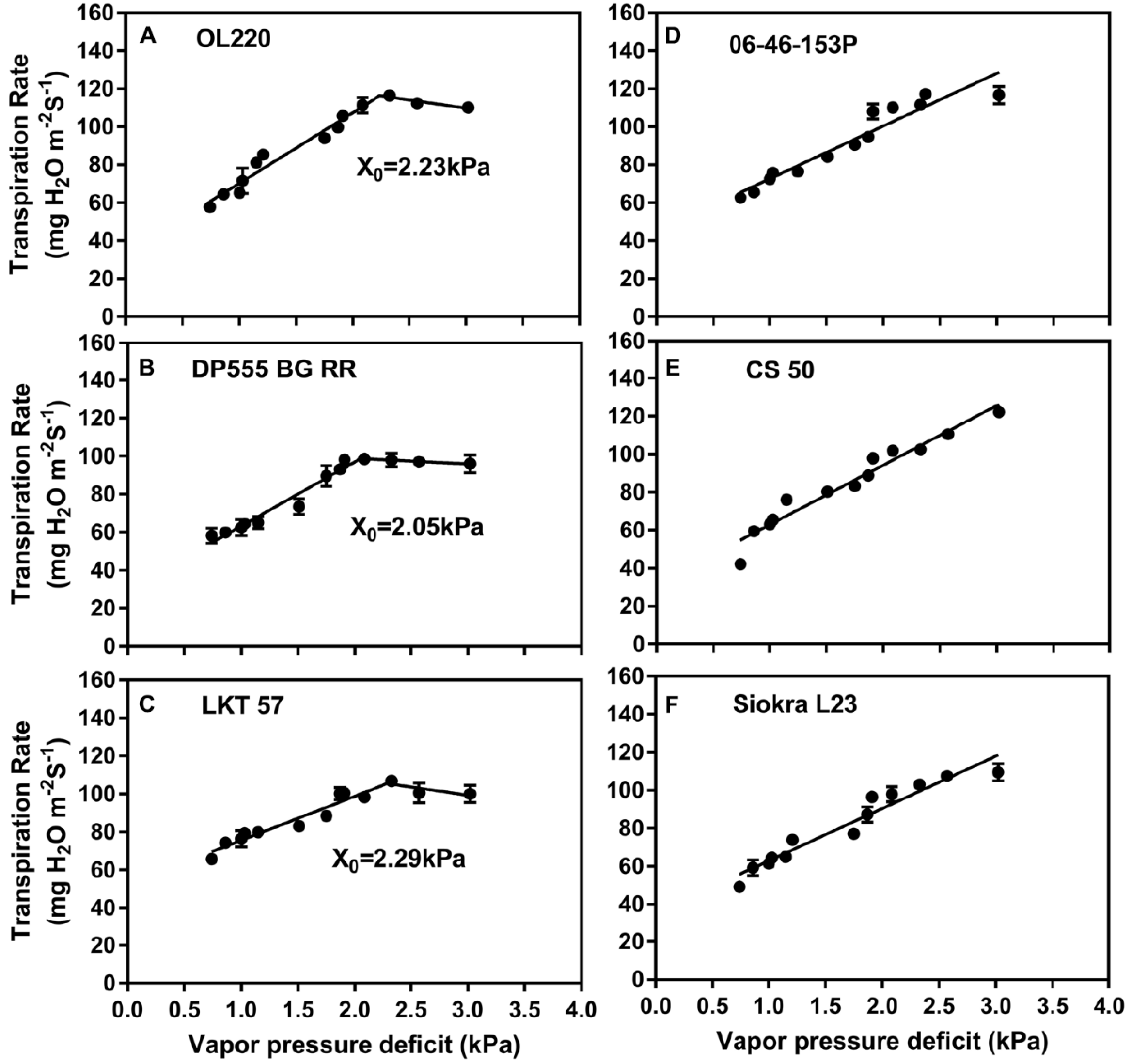




Transpiration = conductance*VPD

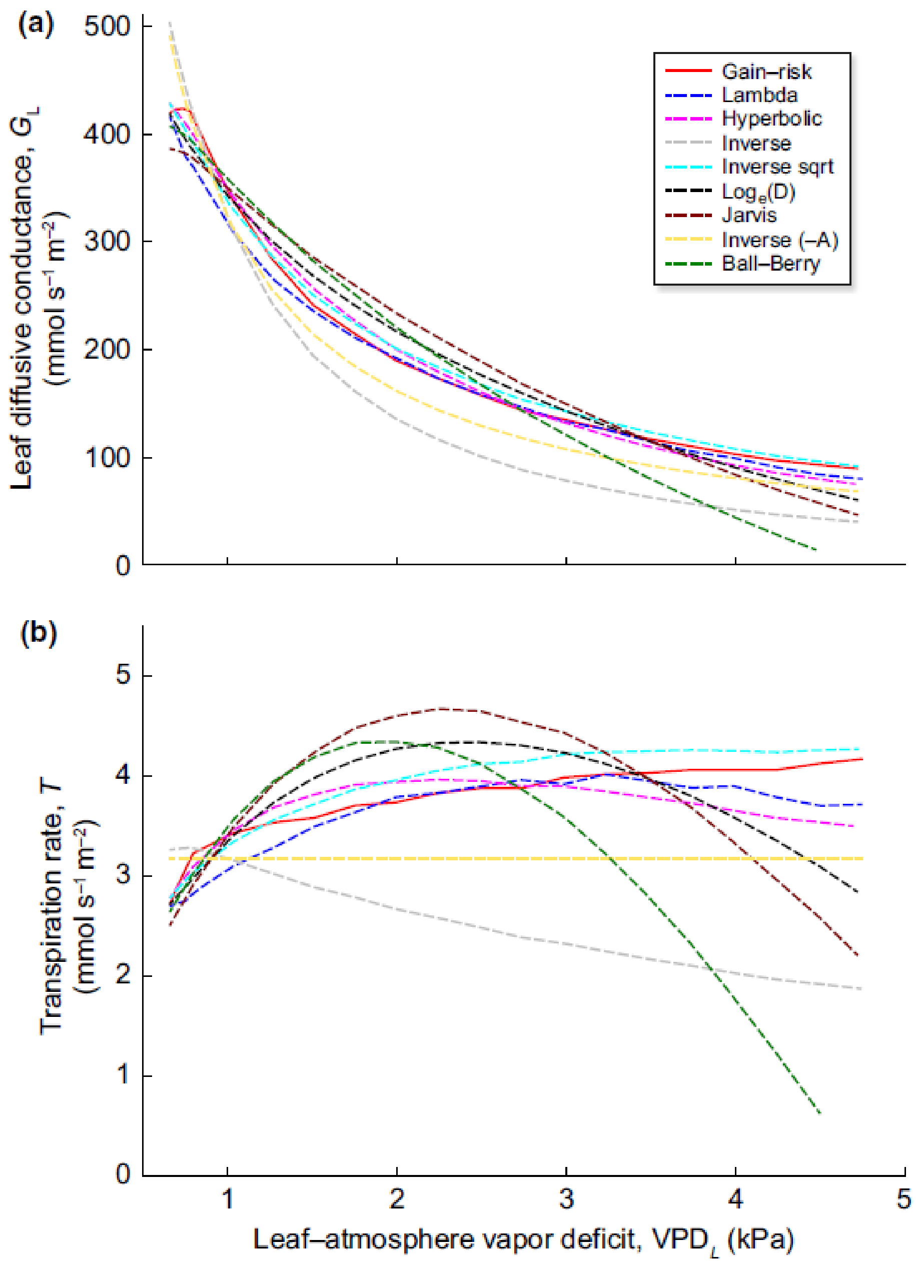
Grossiord et al. 2020

Transpiration increases with VPD if stomata remain open, and is stable with rising VPD as stomata close



Devi and Reddy 2018

Conductance declines yet transpiration increases with VPD, until conductance nears zero.

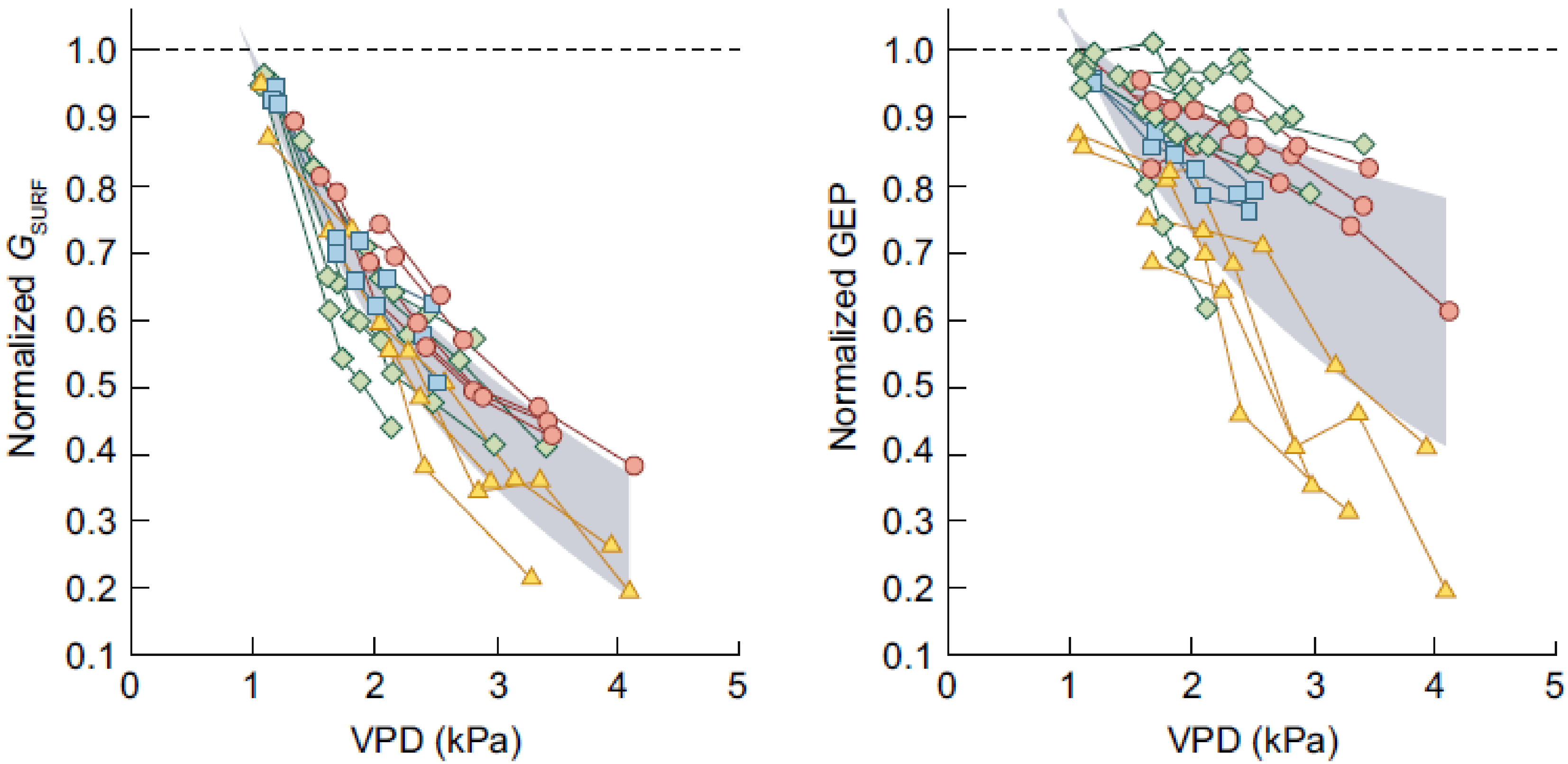


Results from a hydraulic model assuming assimilation is maximized relative to hydraulic risk (Sperry et al. 2017).

Validated by data.

Grossiord et al. 2020

VPD closes stomata at the ecosystem scale

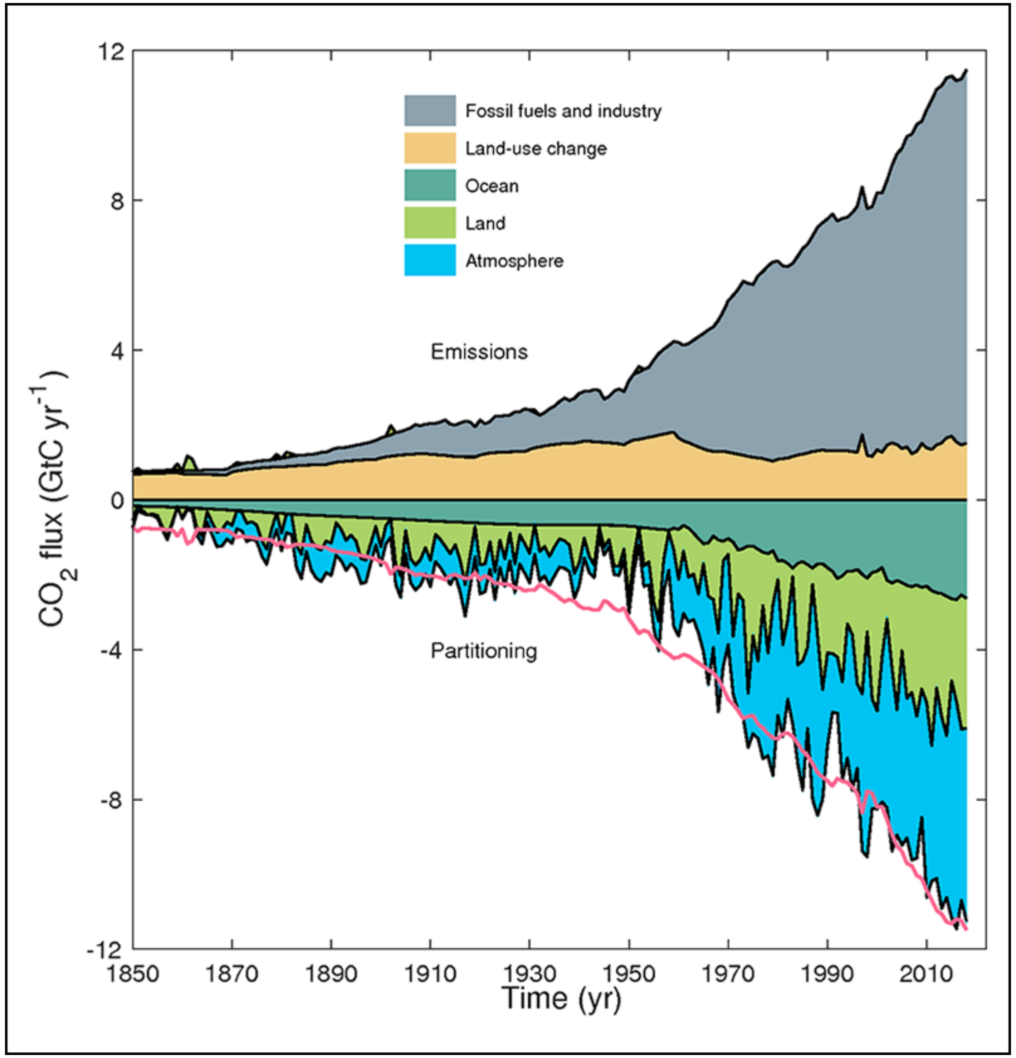


Grossiord et al. 2020

Rising CO_2 impacts on water and carbon fluxes

1) higher photosynthesis
2) reduced stomatal conductance?
2) higher leaf area
3) net impacts on transpiration?

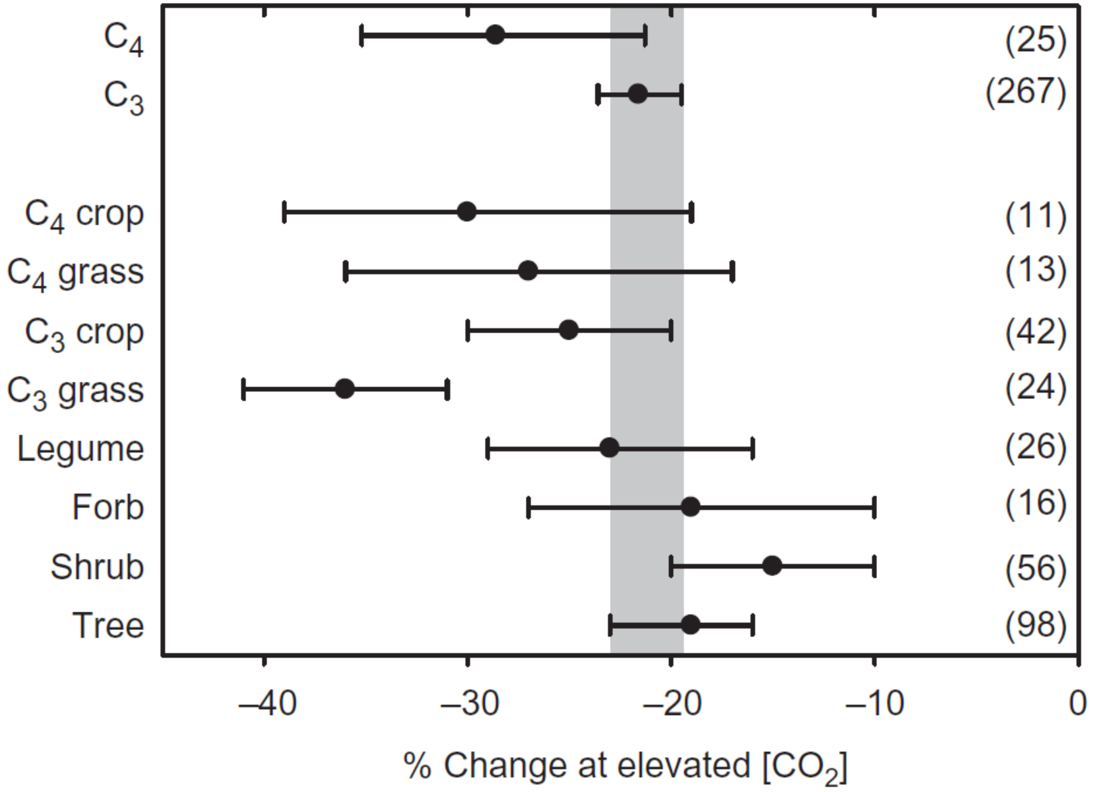
El Yunque, Puerto Rico.
Rich Norby



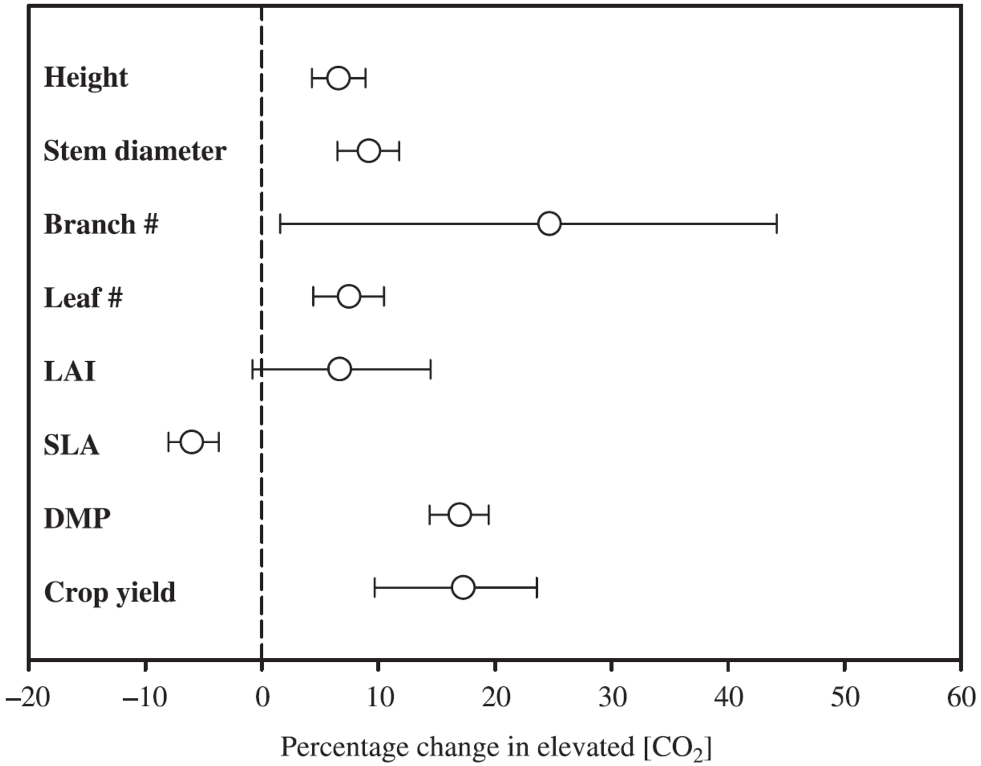
Friedlingstein et al. 2019

Experiments show reduced stomatal conductance (but only in crops/grasses) and greater leaf area with elevated CO_2

Stomatal conductance

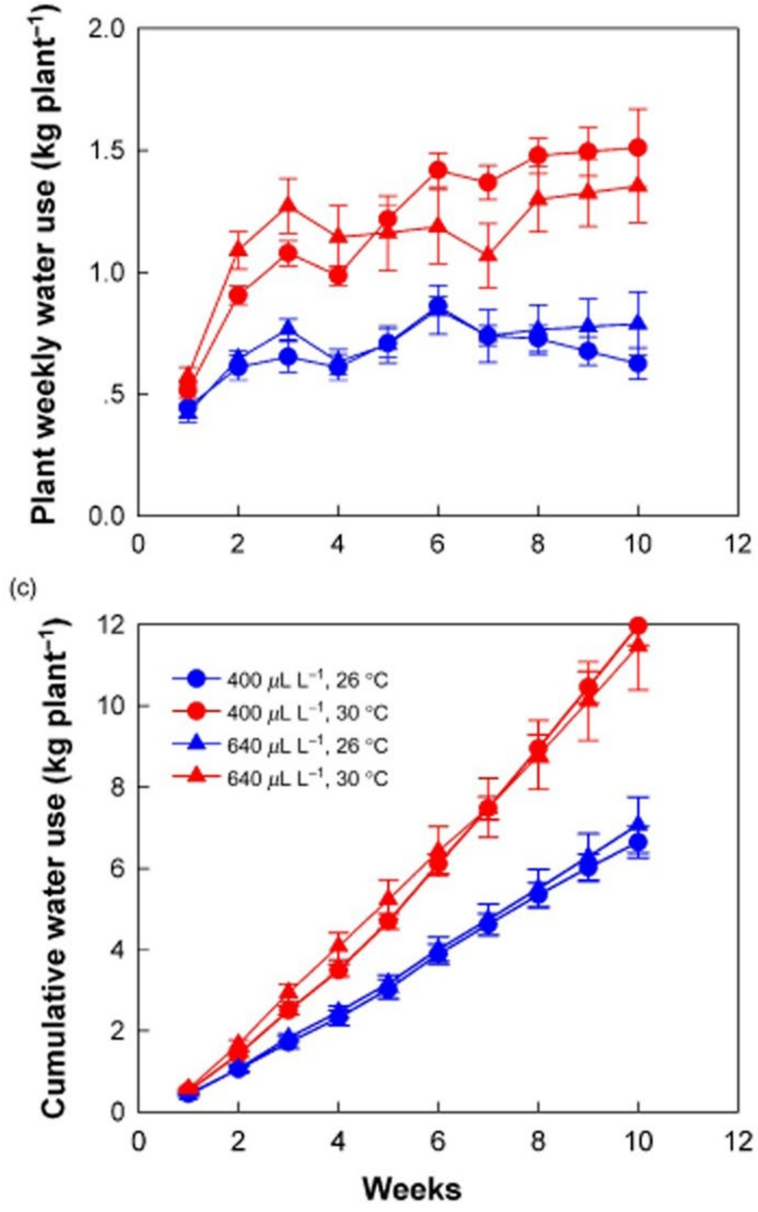


Growth variables



Ainsworth and Rogers 2007

Ainsworth and Long 2005



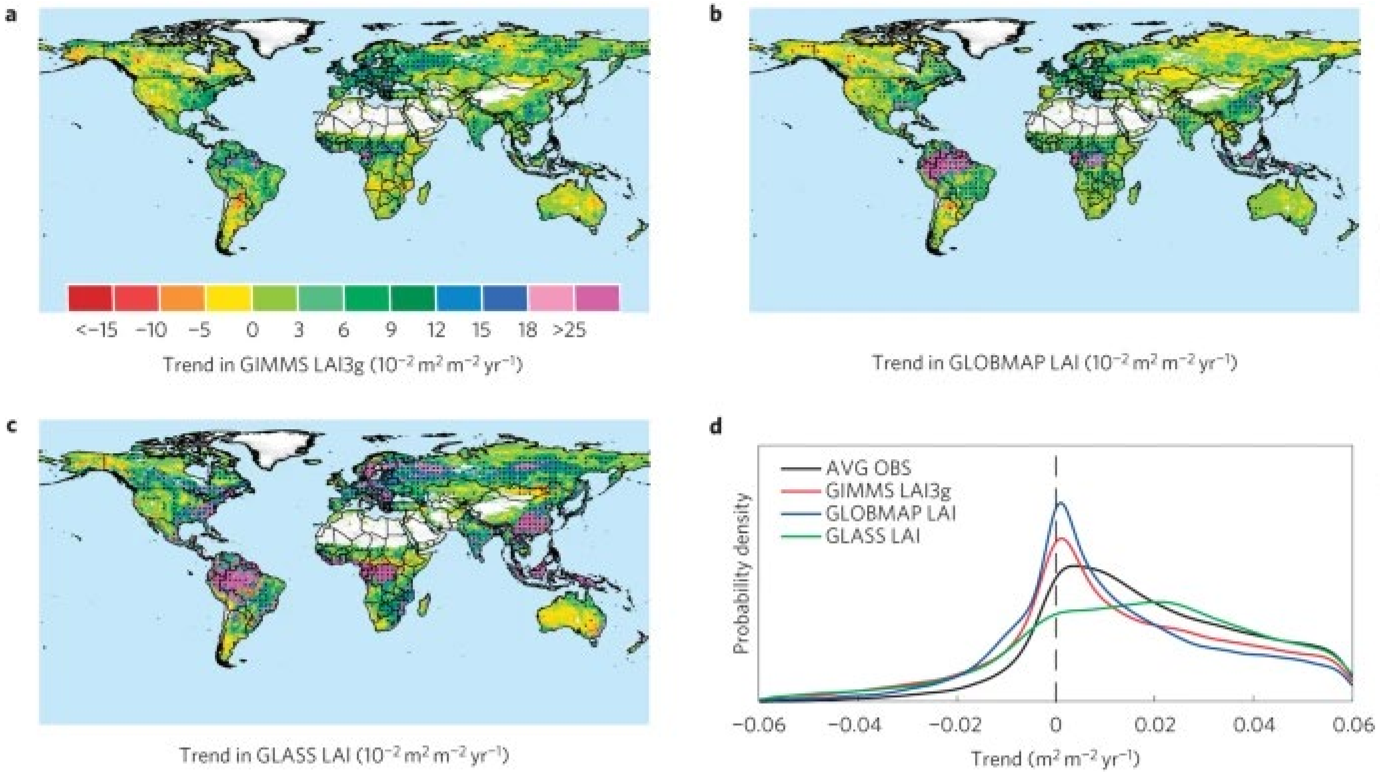
Duan et al. 2014, 2018

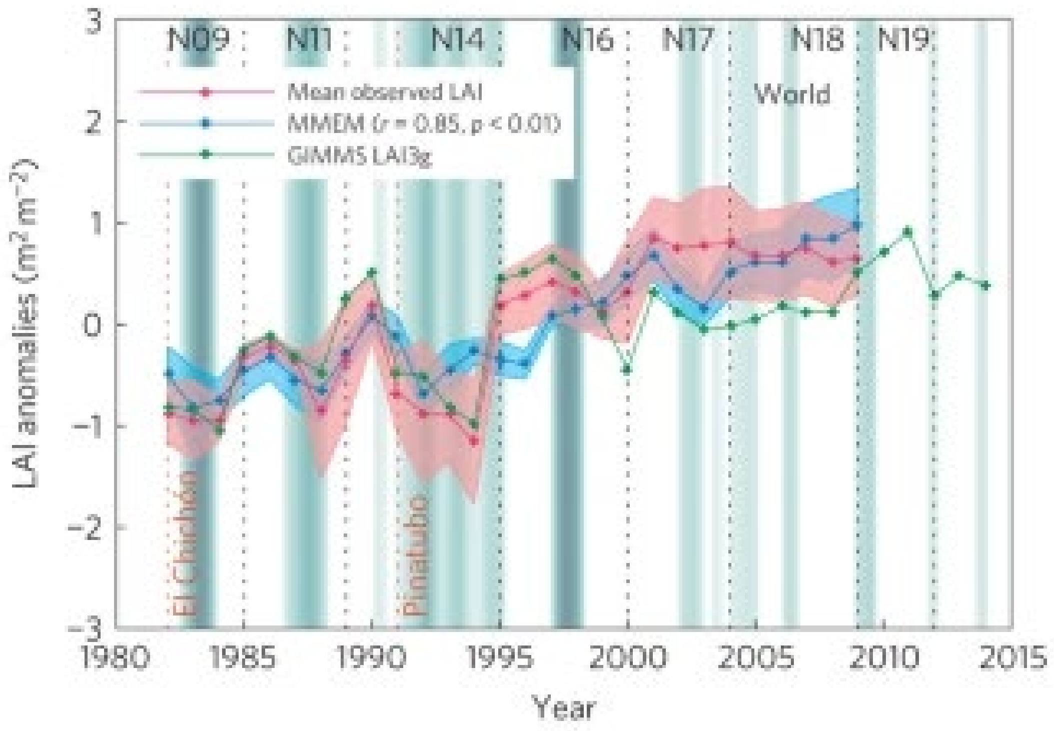
CO_2 has no impact on water use due to leaf area-conductance trade-off.

Temperature overwhelms CO_2 in driving total water use.

- Higher leaf area with higher CO_2 compensates equally for lower conductance, leading to similar water use (blue lines).
- Elevated temperature increases water use (red lines).

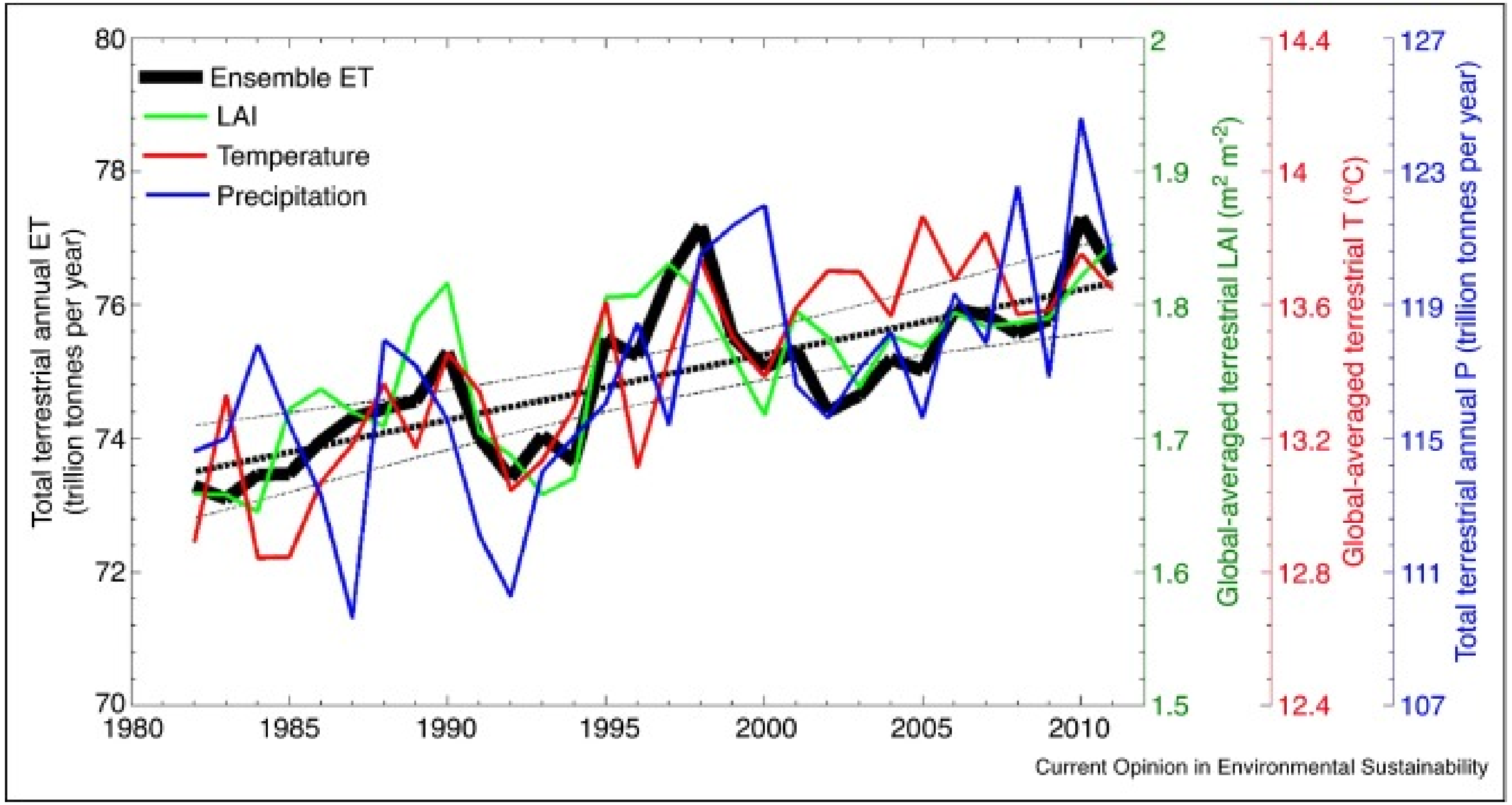
Increasing global leaf area





Zhu et al. 2016

Global evapotranspiration increases with leaf area



Zeng et al. 2018

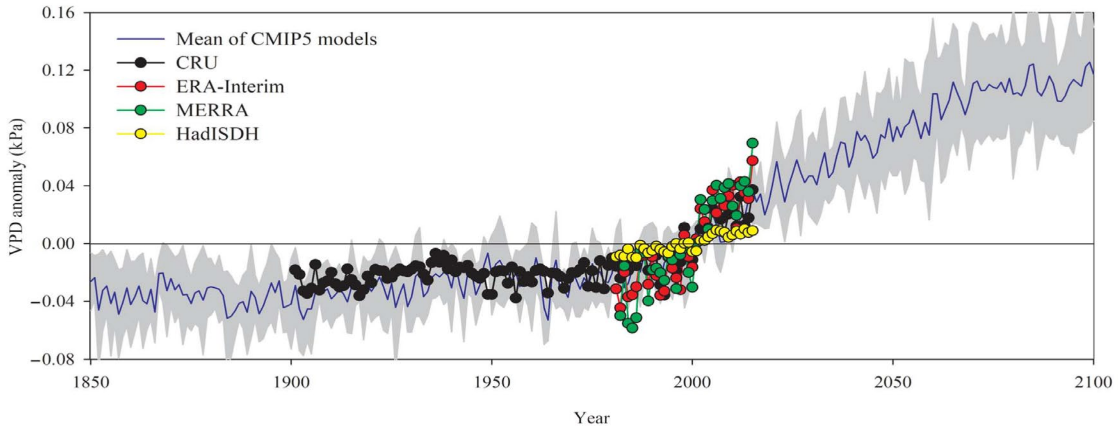
Are we shifting from a CO_2 to a VPD dominated world?

SCIENCE ADVANCES | RESEARCH ARTICLE

ECOLOGY

Increased atmospheric vapor pressure deficit reduces global vegetation growth

Wenping Yuan[1,2]*, Yi Zheng[1], Shilong Piao[3], Philippe Ciais[4], Danica Lombardozzi[5], Yingping Wang[6,7], Youngryel Ryu[8], Guixing Chen[1,2], Wenjie Dong[1,2], Zhongming Hu[9], Atul K. Jain[10], Chongya Jiang[11], Etsushi Kato[12], Shihua Li[1], Sebastian Lienert[13], Shuguang Liu[14], Julia E.M.S. Nabel[15], Zhangcai Qin[1,2], Timothy Quine[16], Stephen Sitch[16], William K. Smith[17], Fan Wang[1,2], Chaoyang Wu[18], Zhiqiang Xiao[19], Song Yang[1,2]



Rising CO_2 positively impacts leaf area

Rising VPD negatively impacts leaf area

RESEARCH ARTICLE

CLIMATE CHANGE

Recent global decline of CO_2 fertilization effects on vegetation photosynthesis

PERSPECTIVE
DOI: 10.1038/s41559-017-0274-8
nature ecology & evolution

Shifting from a fertilization-dominated to a warming-dominated period

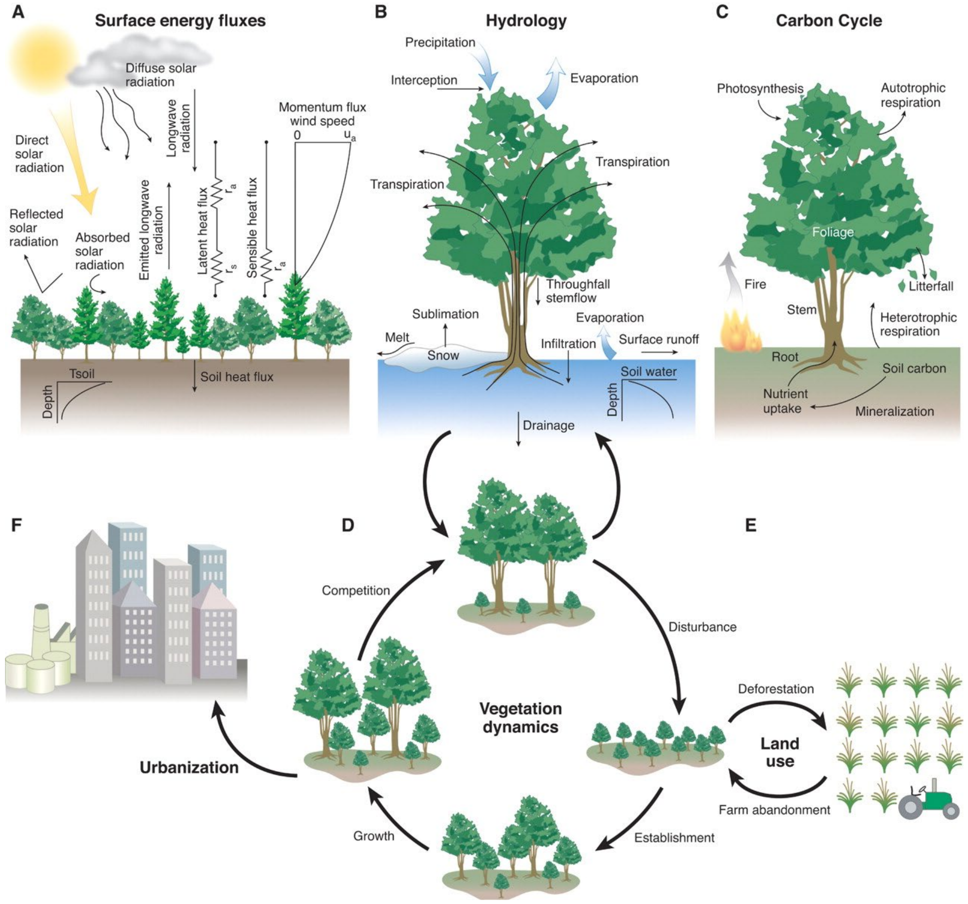
Josep Peñuelas[1,2]*, Philippe Ciais[3], Josep G. Canadell[4], Ivan A. Janssens[5], Marcos Fernández-Martínez[1,2], Jofre Carnicer[1,2], Michael Obersteiner[6], Shilong Piao[7], Robert Vautard[3] and Jordi Sardans[1,2]

More complexity: VPD-driven disturbances

Dead pine forest, Santa Fe New Mexico. C. Allen

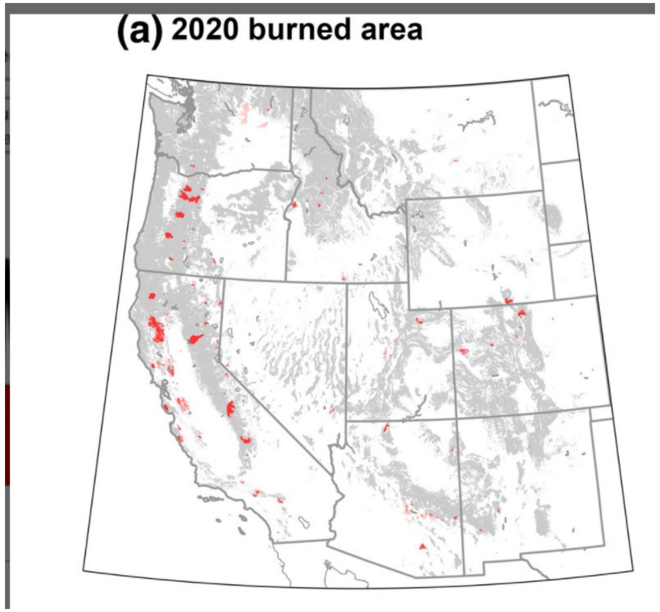
Rising VPD promotes large-scale disturbances with feedbacks on climate

Dying spruce from drought and insect outbreak, Colorado 2019. Notice surviving aspen, promoting a large PFT change Nate McDowell

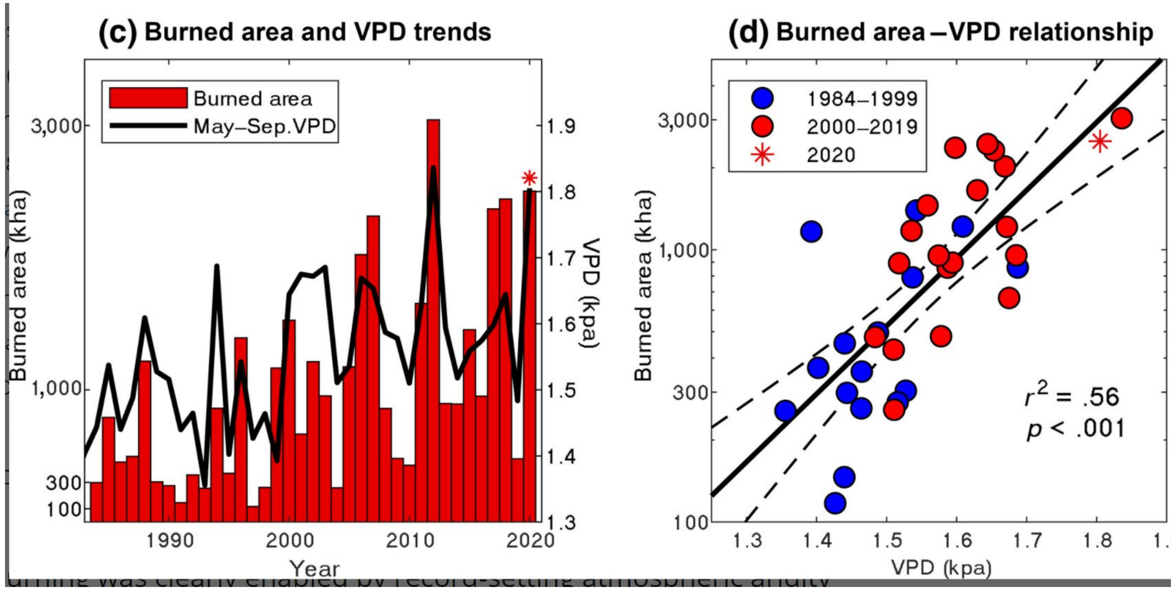


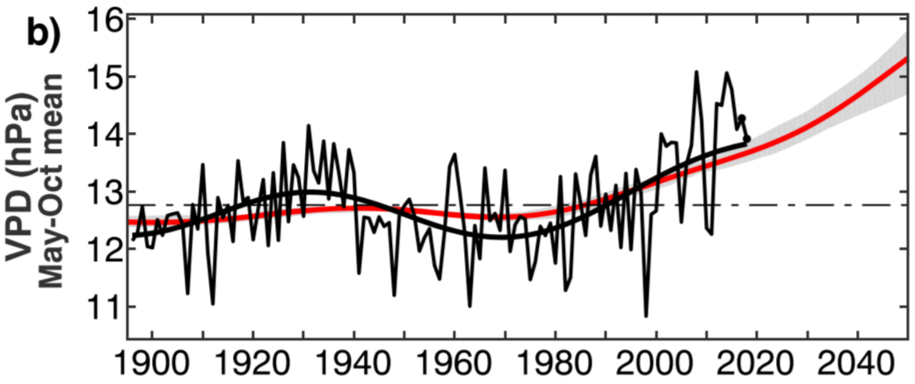
Bonan 2008

Wildfire's are growing due largely to rising VPD and human mgt.



Higuera and Abatzoglou 2020

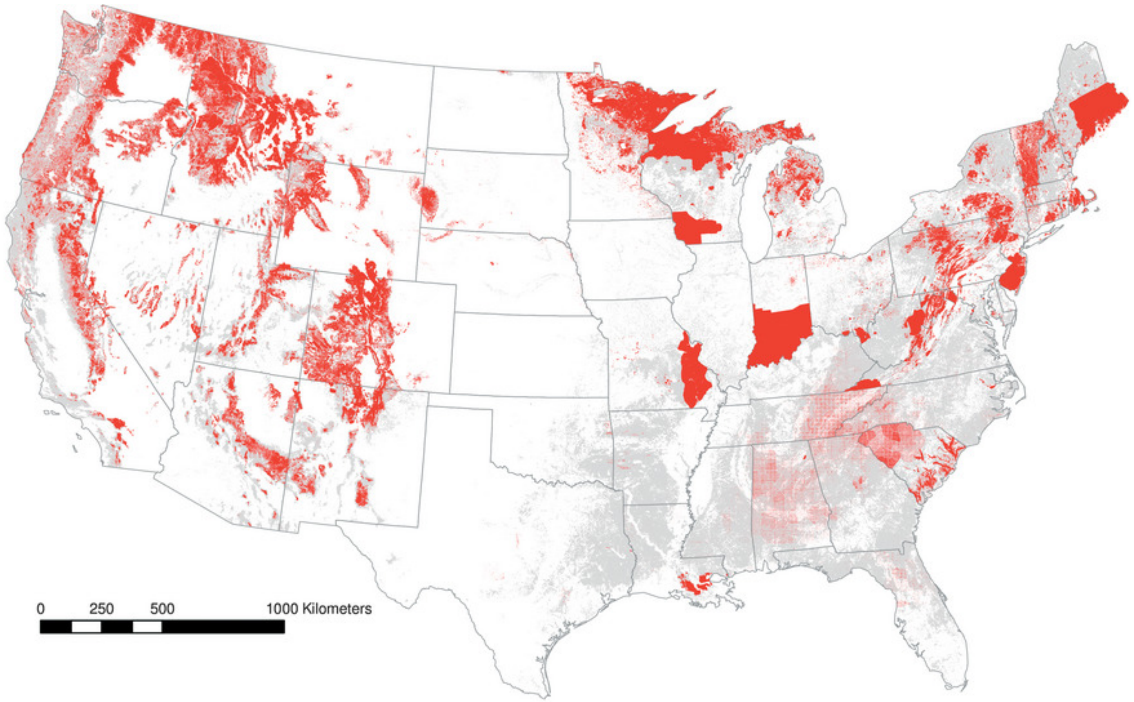


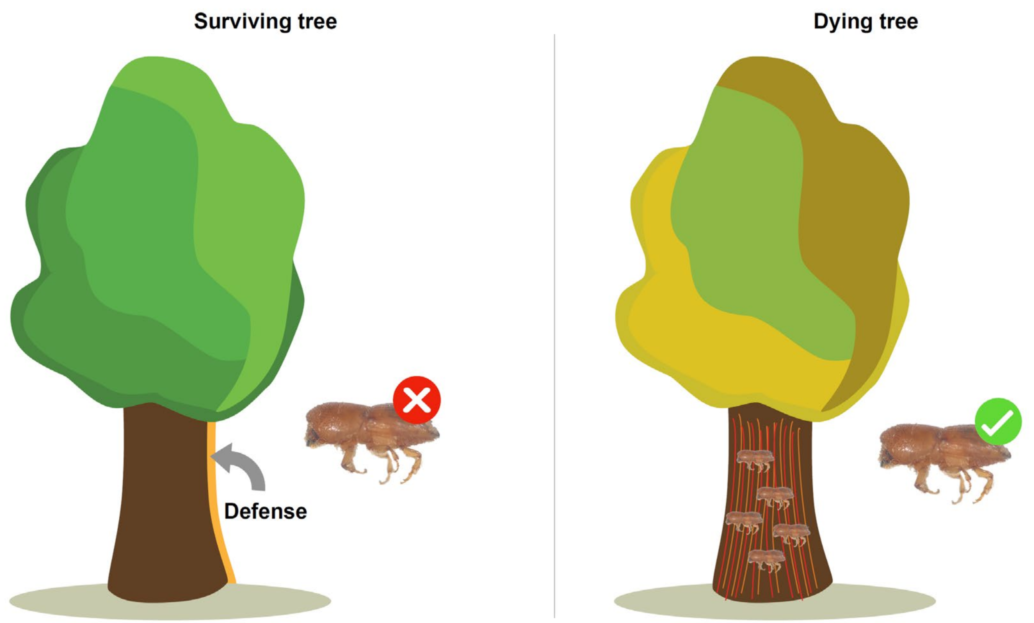


And VPD is rising

Williams et al. 2019

Insect outbreaks are promoted by increasing temperature via insect maturation rates, and VPD through increased tree vulnerability.

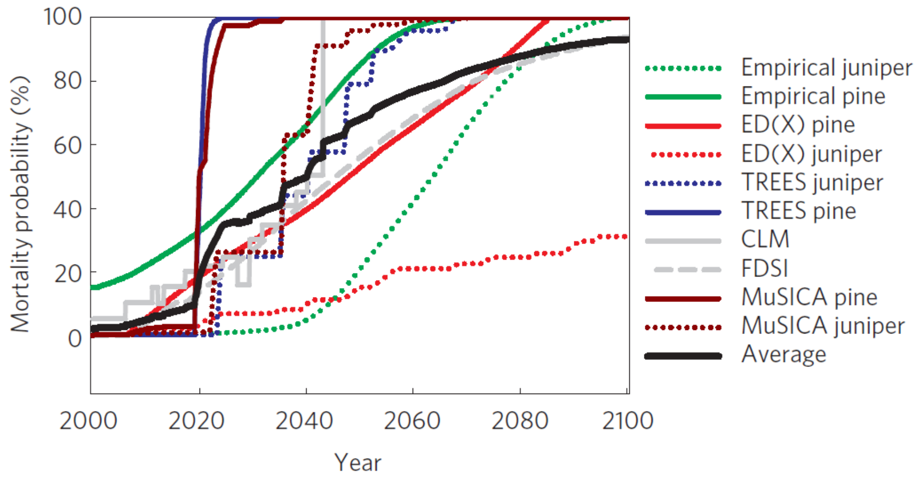


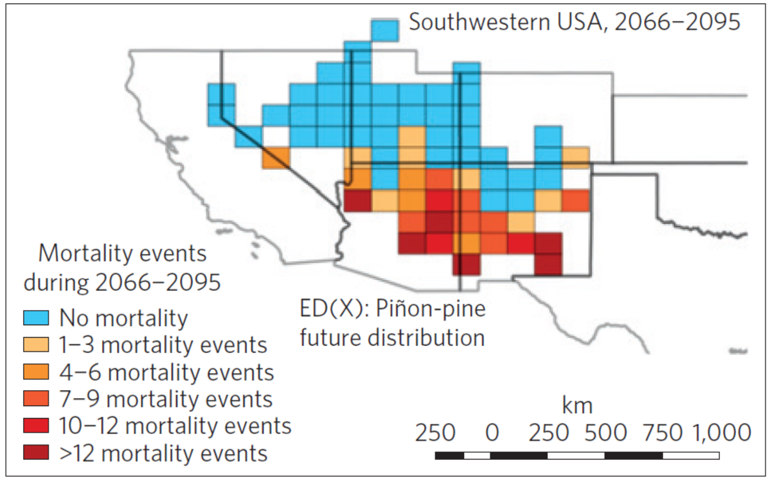


Aerial detection of insect attacks, USA

Hicke et al. 2011

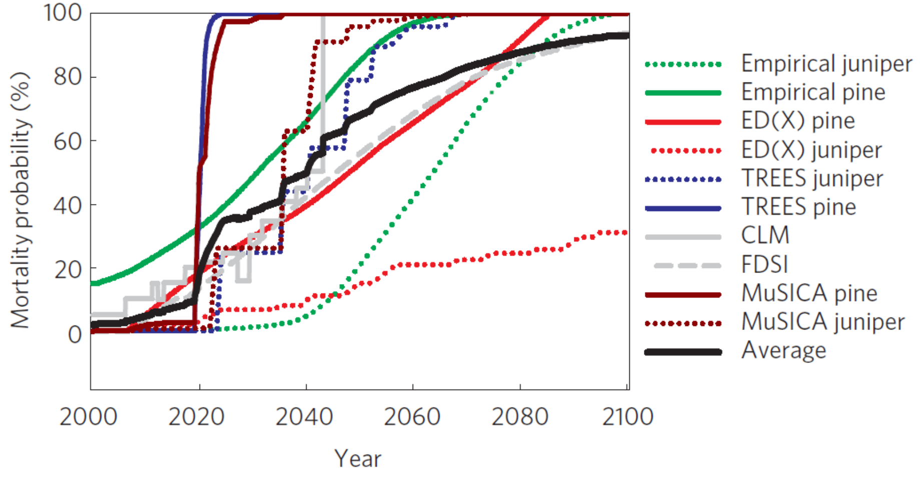
Rising VPD promotes rising tree death

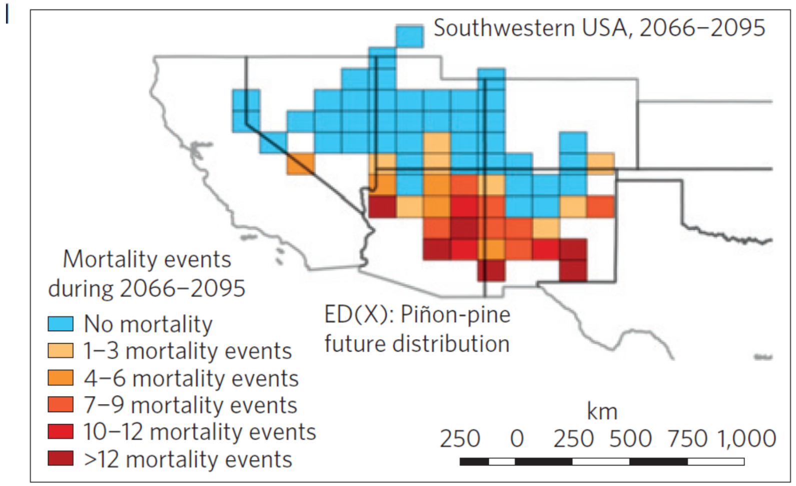


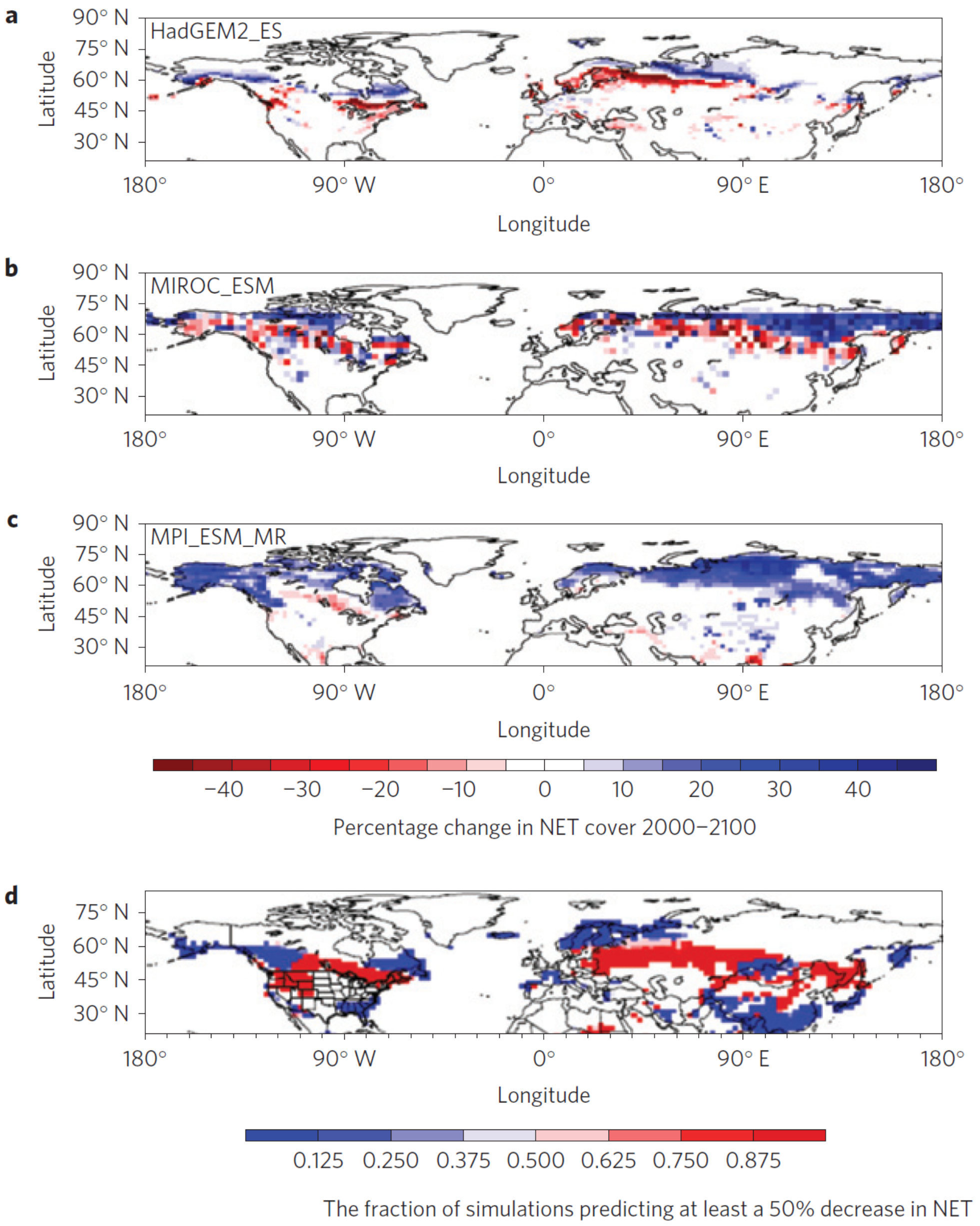


McDowell et al. 2016 In Southwestern USA

Rising VPD promotes rising tree death





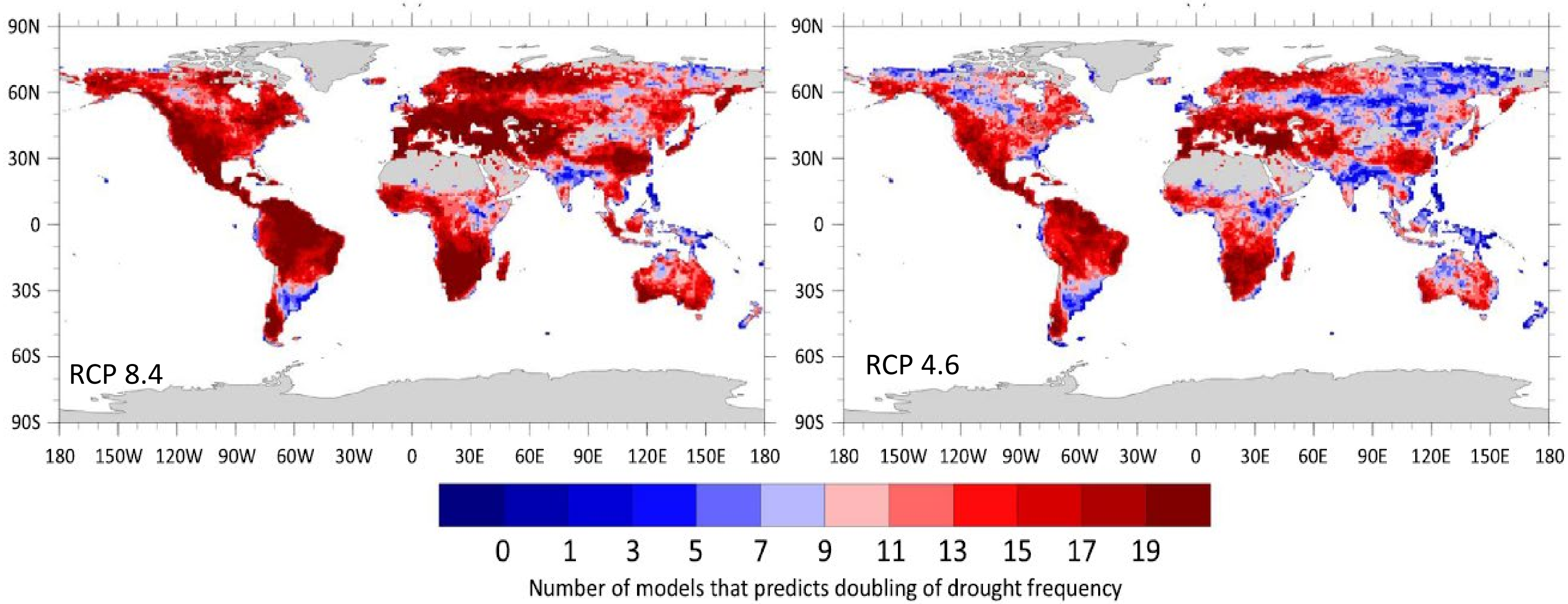


McDowell et al. 2016

In Southwestern USA

And throughout the northern temperate zone

VPD overwhelms CO_2 water savings?
Decreasing soil moisture, e.g. 'soil drought', is likely



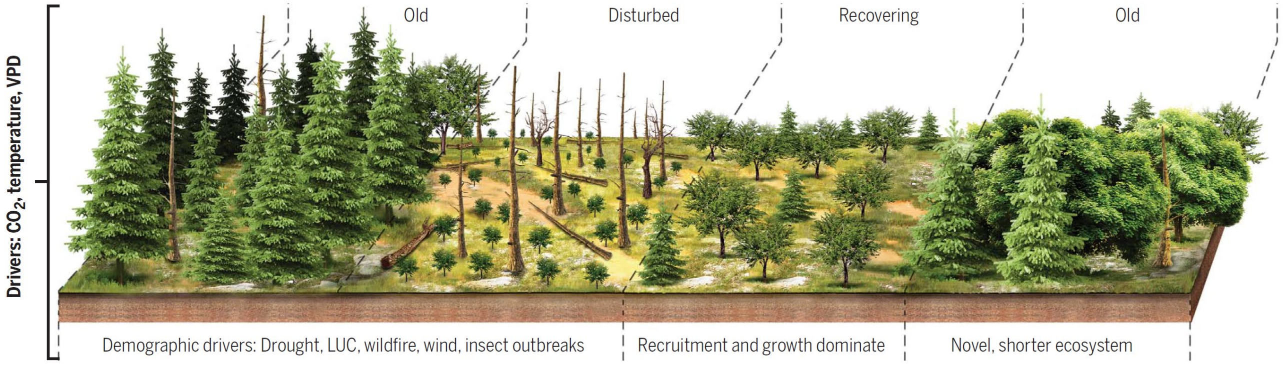
The number of models that predict doubling of *severe* ***soil moisture*** *drought* as predicted by 22 CMIP5 models. Top 10cm and root zone-weighted estimates are similar.

McDowell et al. 2017
Xu et al. 2019
Also see USGCRP November 2017

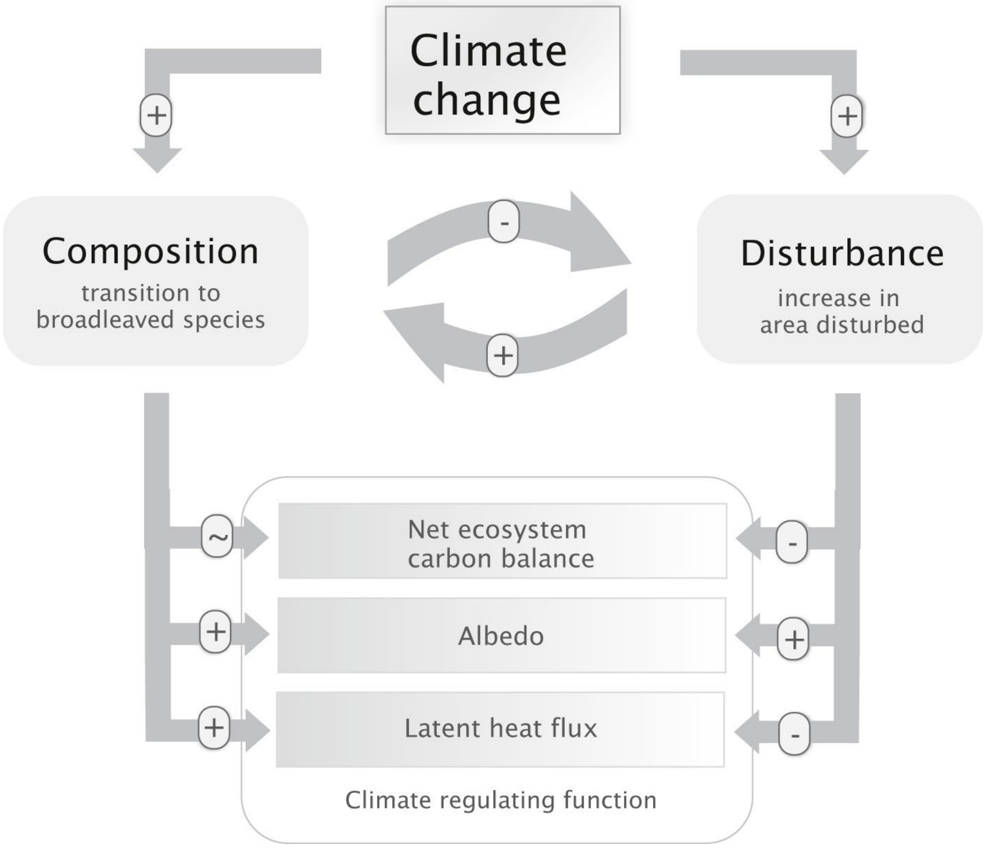
What are the impacts of these VPD-driven disturbances on surface energy, carbon, and water budgets?

Disturbance causes:

- Dynamic changes in transpiring leaf area
- Large decline in root water uptake
- Large change in albedo
- Large changes in surface energy budget



McDowell et al. 2020



Thom et al. 2017

What are the net impacts of rising VPD and rising CO_2 on climate?

The Amazon forest, Manaus, Brazil

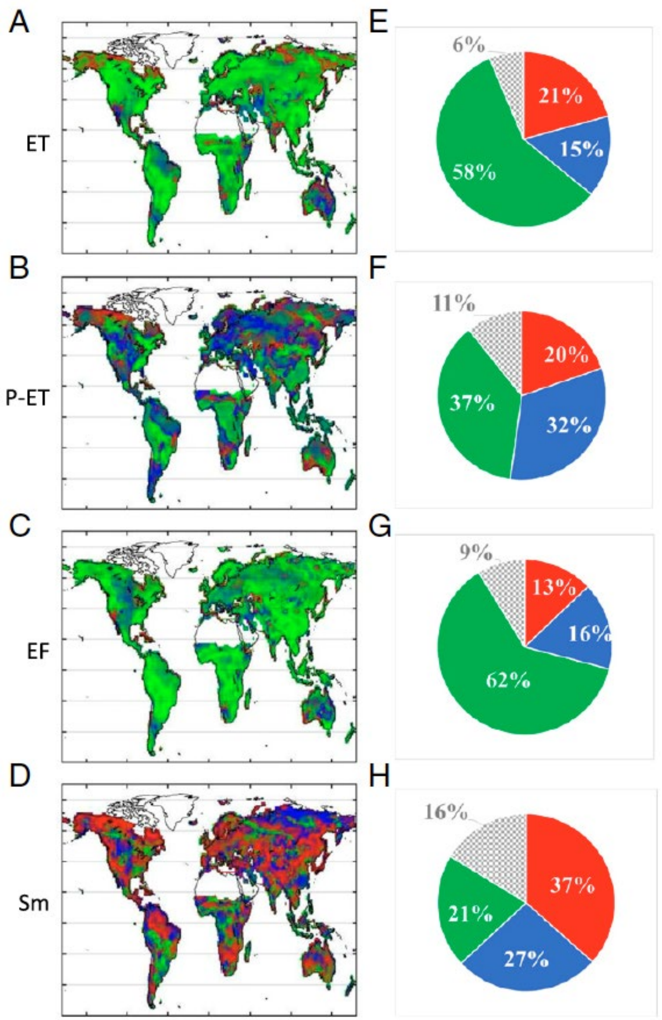
Predictions suggest transpiration is decreasing due to rising CO_2

- Physiological effects of **reduced transpiration**
  - increase global warming (Sellers et al. 1996 Science; Cao et al. 2010)
  - increase streamflow (Cao et al. 2010)
  - increase runoff (Lemordant et al. 2018)
  - increase flooding (Fowler et al. 2019)
  - reduce drought stress (Swann et al. 2016)

- Reduced transpiration influences
  - zonally asymmetric changes in tropical rainfall (Kooperman et al. 2018)
  - modulate global land monsoon and water resources (Cui et al. 2020).

- Substantial regional variation in CO_2-driven vegetation responses and feedbacks
  - increased LAI and transpiration (McDermid et al. 2021)
  - reduced stomatal conductance and transpiration (McDermid et al. 2021)

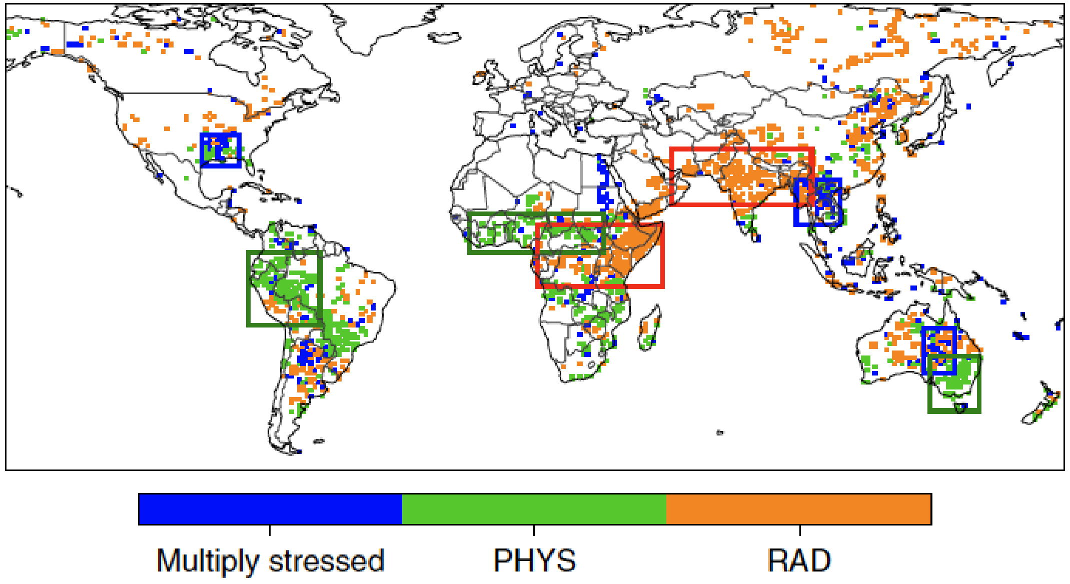
Models suggest physiology has a significant impact on the global hydrologic cycle



Physiological effects (green fractions of the circle plots) have a dominant role on A) transpiration, B) precipitation-transpiration, C) evaporative fraction, and D) soil moisture.

(Lemordant et al. 2018 PNAS)

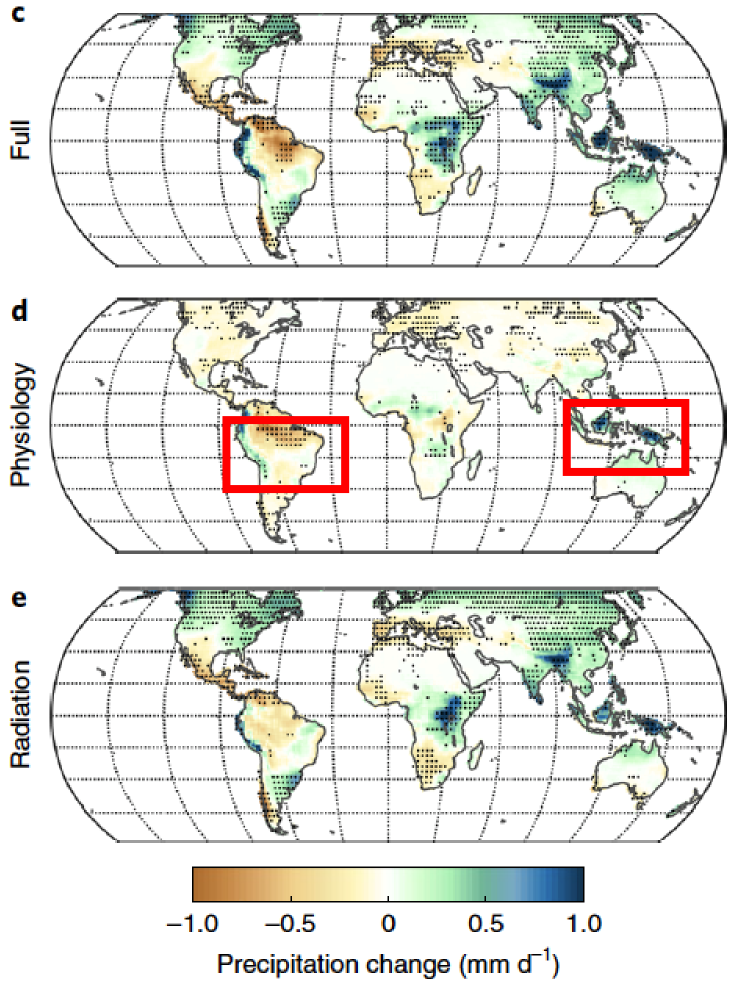
Drivers of 100-yr floods under elevated CO_2: physiological effects dominate in the tropics



(Fowler et al. 2019 NCC)

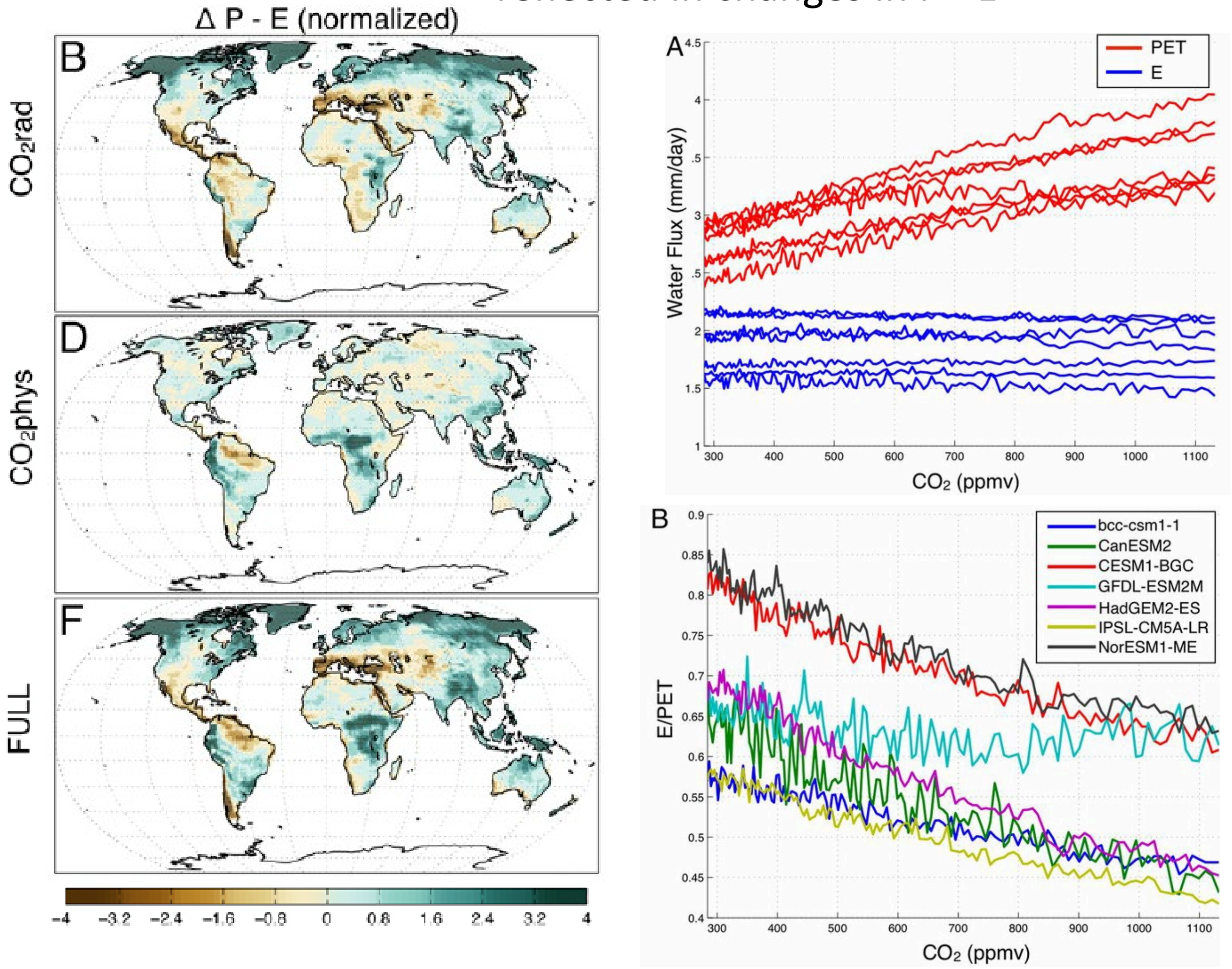
Models suggest significant impacts on climate and on vegetation drought stress

Physiological response dominates the increased zonally asymmetric rainfall change in tropical land



(Kooperman et al. 2018 NCC)

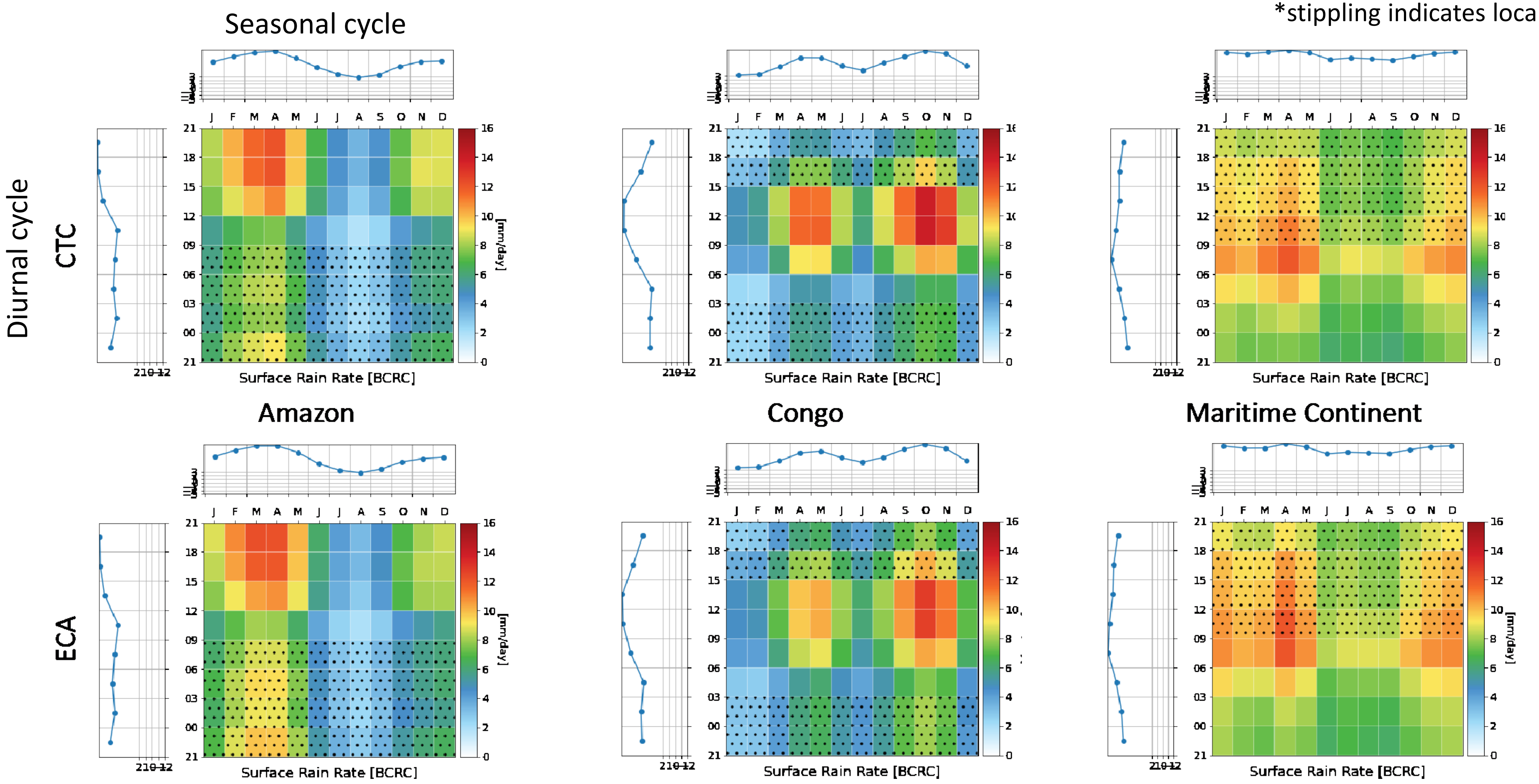
Physiological response reduces drought stress as reflected in changes in P - E



(Swann et al. 2016 PNAS)

Radiative and physiological effects on tropical precipitation in E3SM: changes in diurnal and seasonal cycles

*stippling indicates local nighttime



Bryce Harrop, PNNL

A robust damping of diurnal amplitude of rainfall: (1) radiative damping comes from storage changes and (2) physiological damping comes from local evaporation changes (except over Maritime Continent)

Change in precip diurnal cycle amplitude → base, RAD ΔP

Moisture budget breakdown → RAD STOR, RAD CONV, RAD EVAP

$$P = E - \frac{\partial q}{\partial t} - \nabla \cdot \mathbf{v}q$$

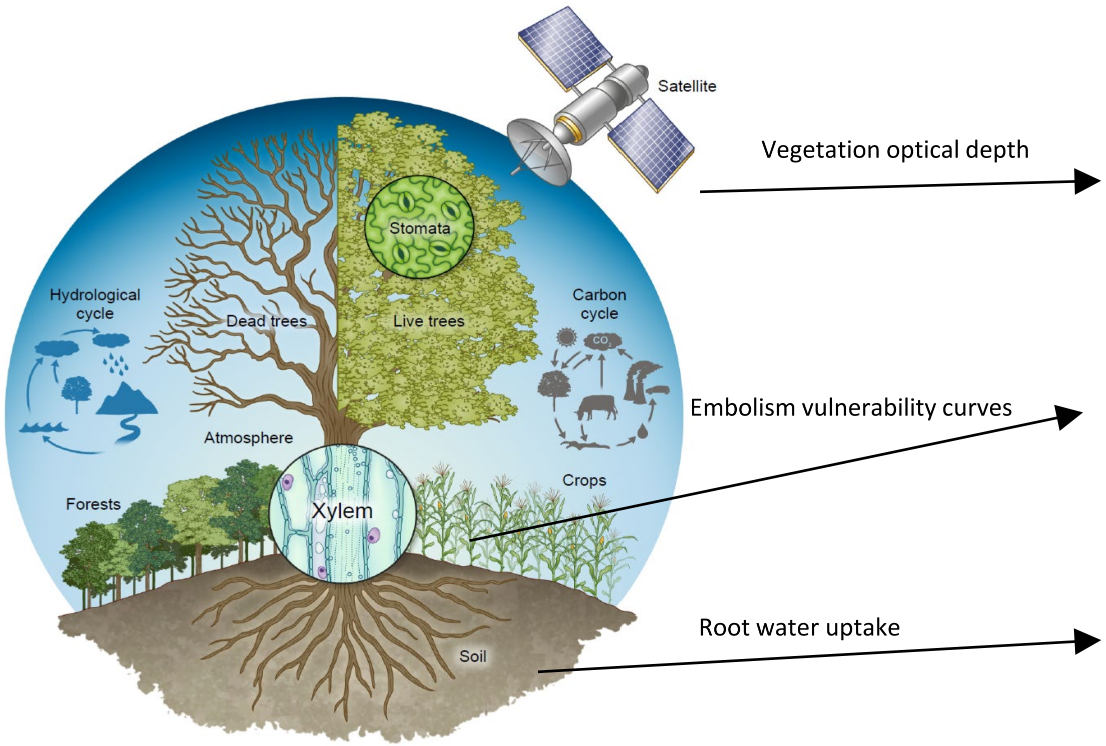
EVAP (E), STOR ($\frac{\partial q}{\partial t}$), CONV ($\nabla \cdot \mathbf{v}q$)

	CTC Amazon	ECA Amazon	CTC Congo	ECA Congo	CTC Maritime Continent	ECA Maritime Continent
base	**0.117**	**0.094**	**0.202**	**0.136**	**0.066**	**0.07**
RAD ΔP	-0.039	-0.021	-0.021	-0.012	-0.015	-0.014
RAD STOR	-0.023	-0.024	-0.053	-0.039	-0.036	-0.024
RAD CONV	0.015	0.042	0.016	0.015	0.024	0.025
RAD EVAP	-0.012	-0.003	0.019	0.024	-0.001	-0.005
PHY ΔP	-0.008	-0.018	-0.008	-0.02	-0.012	-0.011
PHY STOR	0.03	0.022	0.029	0.023	-0.016	-0.016
PHY CONV	-0.009	-0.005	-0.006	-0.012	0.005	-0.005
PHY EVAP	-0.025	-0.028	-0.029	-0.029	0.007	0.016
TOT ΔP	-0.025	-0.034	-0.015	-0.027	-0.023	-0.022
TOT STOR	0.009	0.005	-0.024	-0.012	-0.051	-0.044
TOT CONV	0.032	0.041	0.018	0.009	0.031	0.026
TOT EVAP	-0.015	-0.02	0.006	-0.003	0.001	0.005

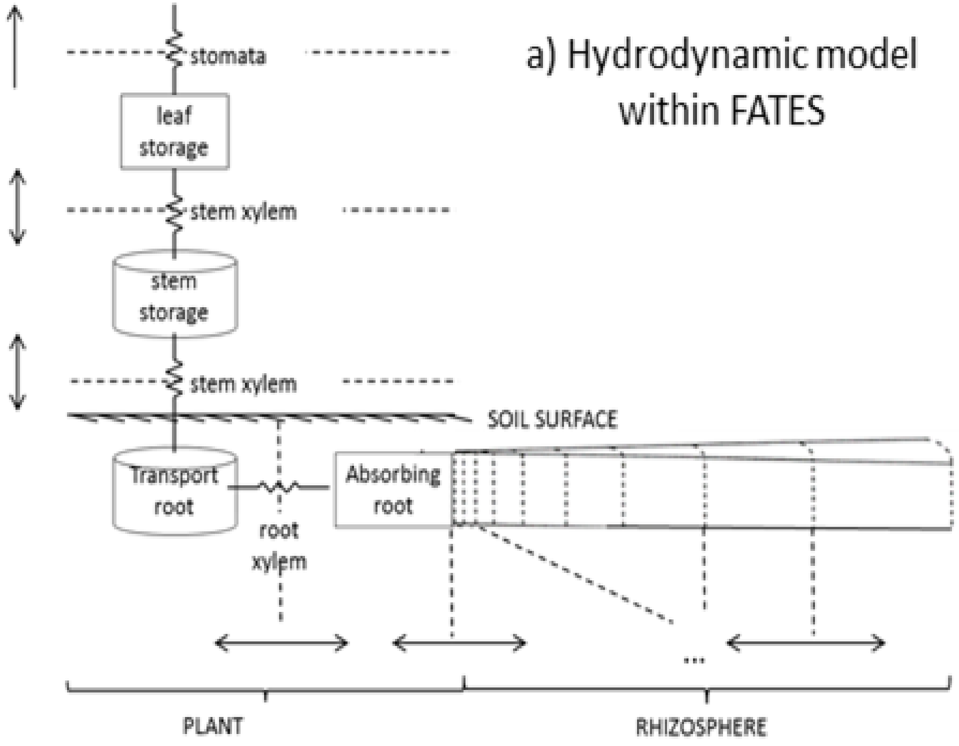
Amplified diurnal cycle ↕ Dampened diurnal cycle

Bryce Harrop, PNNL

Mechanistic representation of plant hydraulics within models. Could this effect the outcomes?



McDowell, Brodribb, Nardini 2019



Christoffersen, Xu, et al *in prep*

e.g. replace the non-mechanistic water stress term (beta) with real hydraulics

VPD vs CO_2 impacts on drought-induced hydraulic failure and subsequent mortality using hydraulically mechanistic models

Modeled hydraulic failure (PLC, percentage loss of conductance) for mature spruce trees in Switzerland

Ensemble means of five models: Sureau, Sperry, TREES, MedFates, CABLE. Gray shading is standard error.

Mortality may not be more likely under future VPD due to water savings benefits of rising CO_2

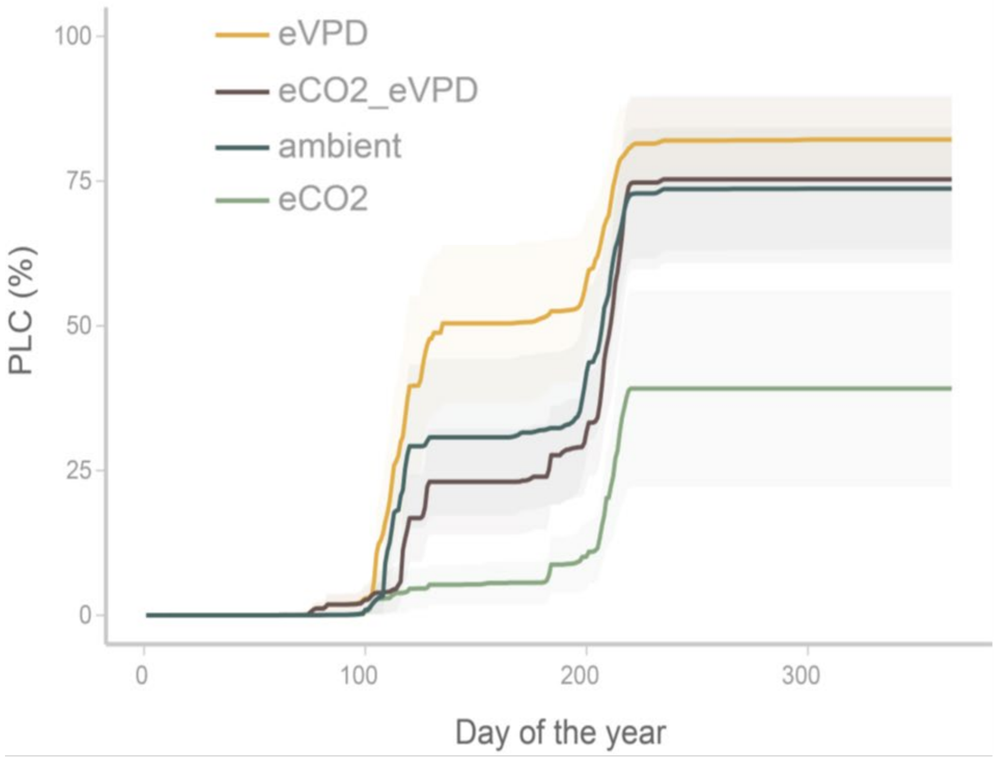


Photo M. Arend

McDowell et al. *in review*

Future challenges

Key fluxes and processes that require more mechanistic understanding under rising VPD and CO_2

- **Leaf to plant**:
  - carbon and water fluxes
  - plant production
  - plant mortality
- **Ecosystem to globe**:
  - Dynamic PFT changes; LAI, disturbances
- **Feedbacks on**
  - surface energy
  - carbon budgets
  - water budgets

Dead spruce from drought and insect attack, Germany

Future solutions

- Determining individual and net impacts of CO_2 and VPD empirically
  - Model development is currently advanced beyond measurements
    - Empirical and numerical manipulative experiments
    - Observations: ground, atmosphere, remote sensing
- Improving models with advanced hydraulics
  - More realistic transpiration simulations
  - Development
  - Benchmarking
- Representing dynamic changes in vegetation PFTs, LAI, disturbances
- Reconciling data and observations with simulations
  - Model-experiment and model-observation integration is essential

Conclusions

- The net impact of rising VPD and CO_2 upon plant carbon and water fluxes, growth, and mortality is unknown.
- VPD and CO_2 have conflicting impacts on plant fluxes of carbon and water
  - Changing decreased stomatal conductance, leaf area, etc.
- VPD-driven disturbances add additional uncertainty
- To reduce predictive uncertainty of global land-surface and climate models, we may need to capture these antagonistic processes at the scales of stomata to Earth system feedbacks.

Acknowledgement

This research was supported as part of the Next Generation Ecosystem Experiments-Tropics, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research.

NGEE–TROPICS
NEXT-GENERATION ECOSYSTEM EXPERIMENTS–TROPICS

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