

Functional diversity in land surface modeling: where and when does it matter for the terrestrial carbon cycle?

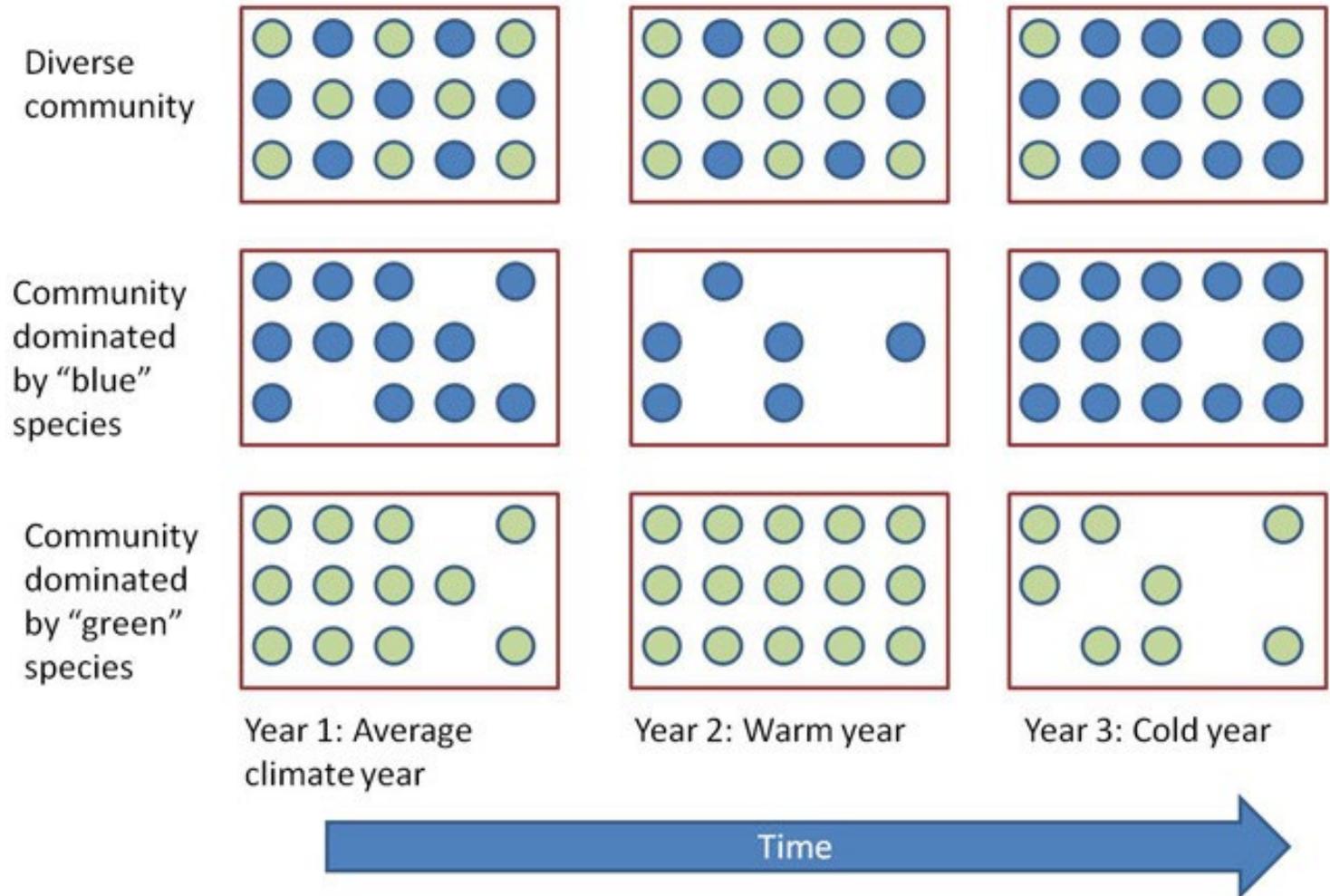
Evan Margiotta, Daniel
Kennedy, Linnia
Hawkins, Anna Trugman

*LMWG Meeting
February 24th, 2026*



Plant diversity plays a key role in buffering ecosystems to disturbance

- Ecosystems with multiple strategies to respond to stress are more likely to have some organisms survive
- This “diversity-stability” effect may be an important mechanism regulating carbon fluxes during disturbance



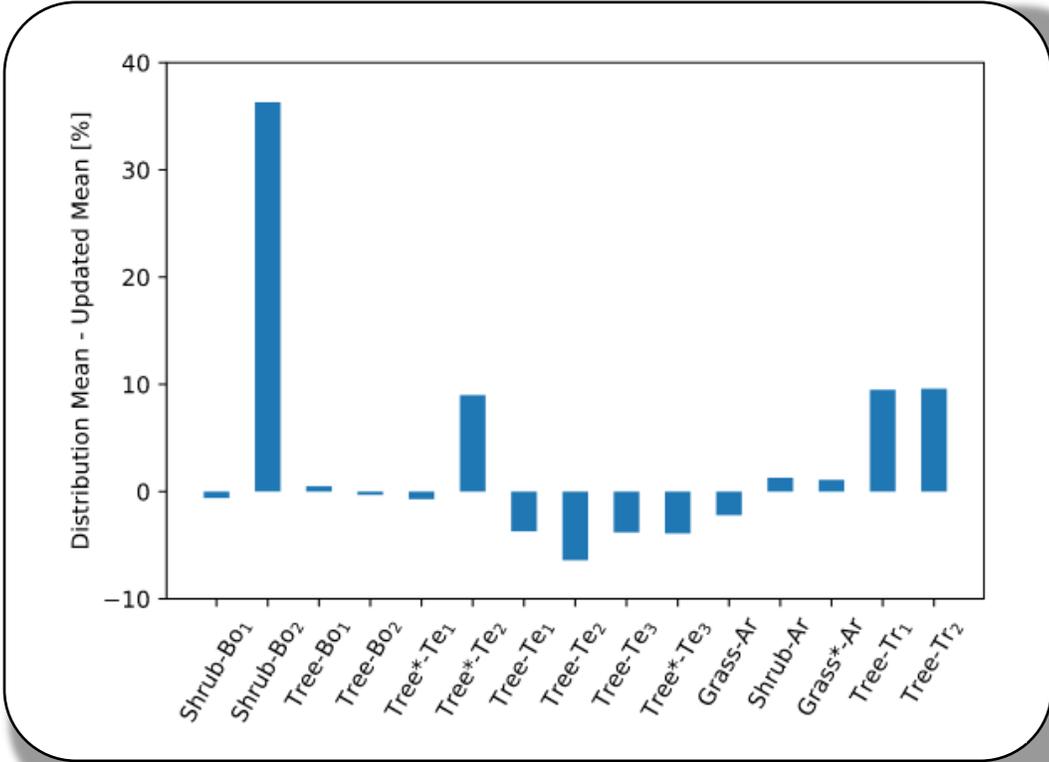
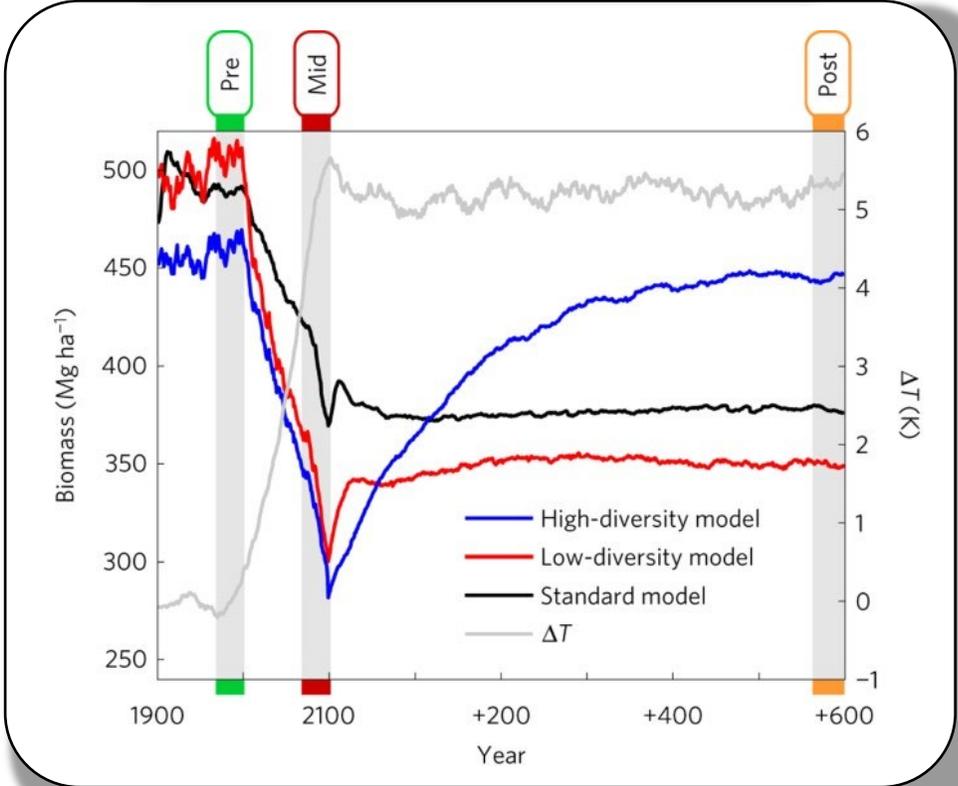
From Cleland (2011)



Literature examining effect of functional diversity in LSMs are sparse and suggest diversity effects may vary across ecosystem types

Letter | Published: 29 August 2016
Resilience of Amazon forests emerges from plant trait diversity
[Boris Sakschewski](#)  [Werner von Bloh](#), [Alice Boit](#), [Lourens Poorter](#), [Marielos Peña-Claros](#), [Jens Heinke](#), [Jasmin Joshi](#) & [Kirsten Thonicke](#)
Nature Climate Change **6**, 1032–1036 (2016) | [Cite this article](#)
 9759 Accesses | 251 Citations | 198 Altmetric | [Metrics](#)

Increasing Functional Diversity in a Global Land Surface Model Illustrates Uncertainties Related to Parameter Simplification
 Ethan E. Butler  Kirk R. Wythers, Habacuc Flores-Moreno, Daniel M. Ricciuto, Abhirup Datta, Arindam Banerjee, Owen K. Atkin, Jens Kattge, Peter E. Thornton, Madhur Anand, Sabina Burrowscano, Chaeho Byun, J. H. C. Cornelissen, Estelle Forey, Steven Jansen, Koen Kramer, Vanessa Minden, Peter B. Reich ... [See fewer authors](#) ^
 First published: 06 March 2022 | <https://doi.org/10.1029/2021JG006606> | Citations: 8



Research Questions

1. At the grid cell scale, does trait diversity, not just mean trait values, affect the sensitivity of carbon fluxes to drought?
2. Do observed diversity-stability effects, where increased diversity reduces ecosystem sensitivity to drought, emerge in simulations with higher functional diversity? If so, how do diversity-stability effects vary with climate?
3. What mechanism underlies any observed diversity effects? Is there emergent behavior responding to competition between PFTs?



Experimental Design: Varying diversity through parameter perturbation

CLM5-PFT-PPE

- Linnia's wave 1 simulations
- 500 member ensemble
- Perturbation of 32 traits
- Selected 8 for this analysis, 5 of which vary independently for each PFT

Output metric

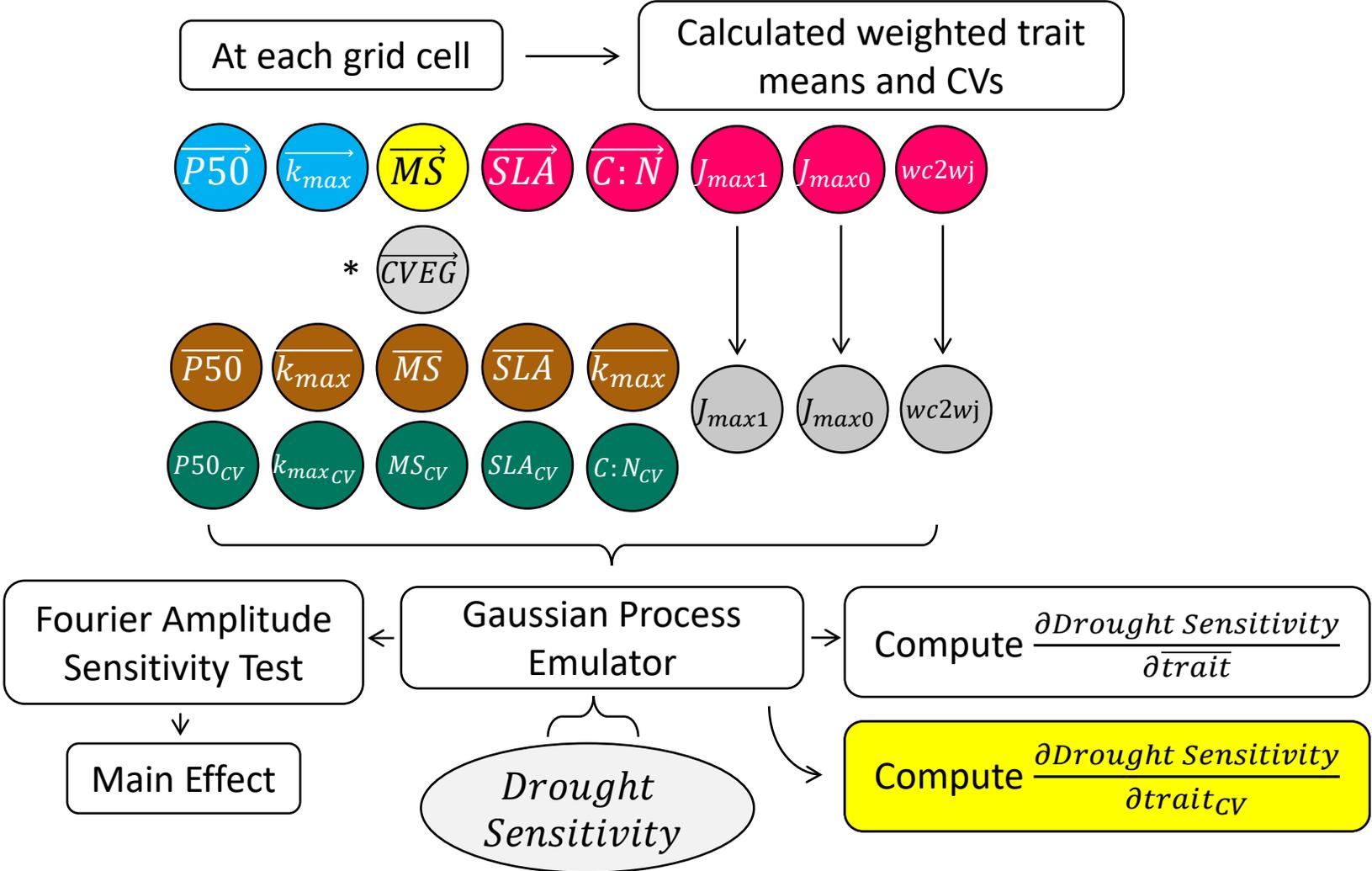
- Drought Sensitivity

Trait	Classification
Water potential at 50% loss in conductance (P50)	Hydraulic
Maximum hydraulic conductance (k_{max})	Hydraulic
Medlyn Slope	Stomatal
Specific Leaf Area (SLA)	Carbon Economy
Leaf carbon: nitrogen target (Leaf C:N)	Carbon Economy
LUNA Traits: J_{maxb0} , J_{maxb1} , and $wc2wjb0$	Carbon Economy

$$\text{Drought Sensitivity} = \frac{GPP_{3 \text{ most stressed years average}} - GPP_{1985-2014 \text{ average}}}{GPP_{1985-2014 \text{ average}}}$$

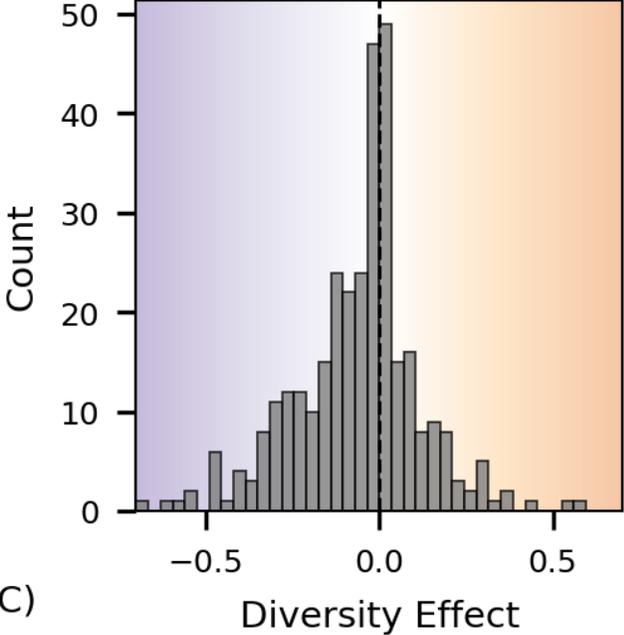
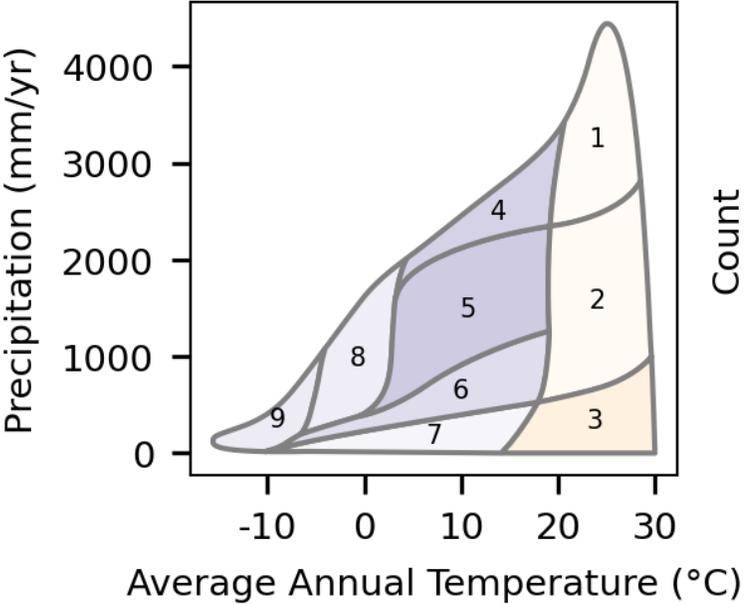
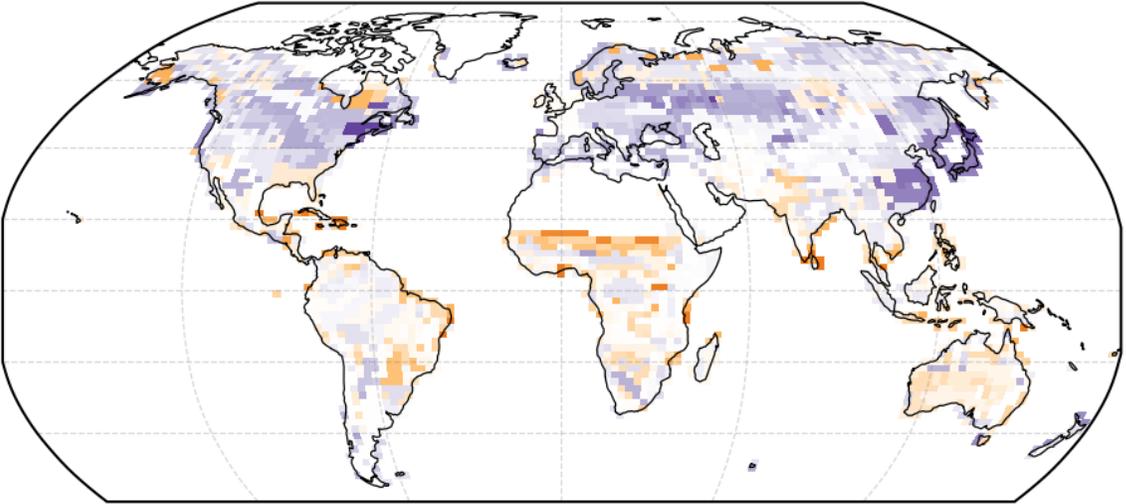
Experimental Design: Varying diversity through parameter perturbation

Ecosystem scale analysis



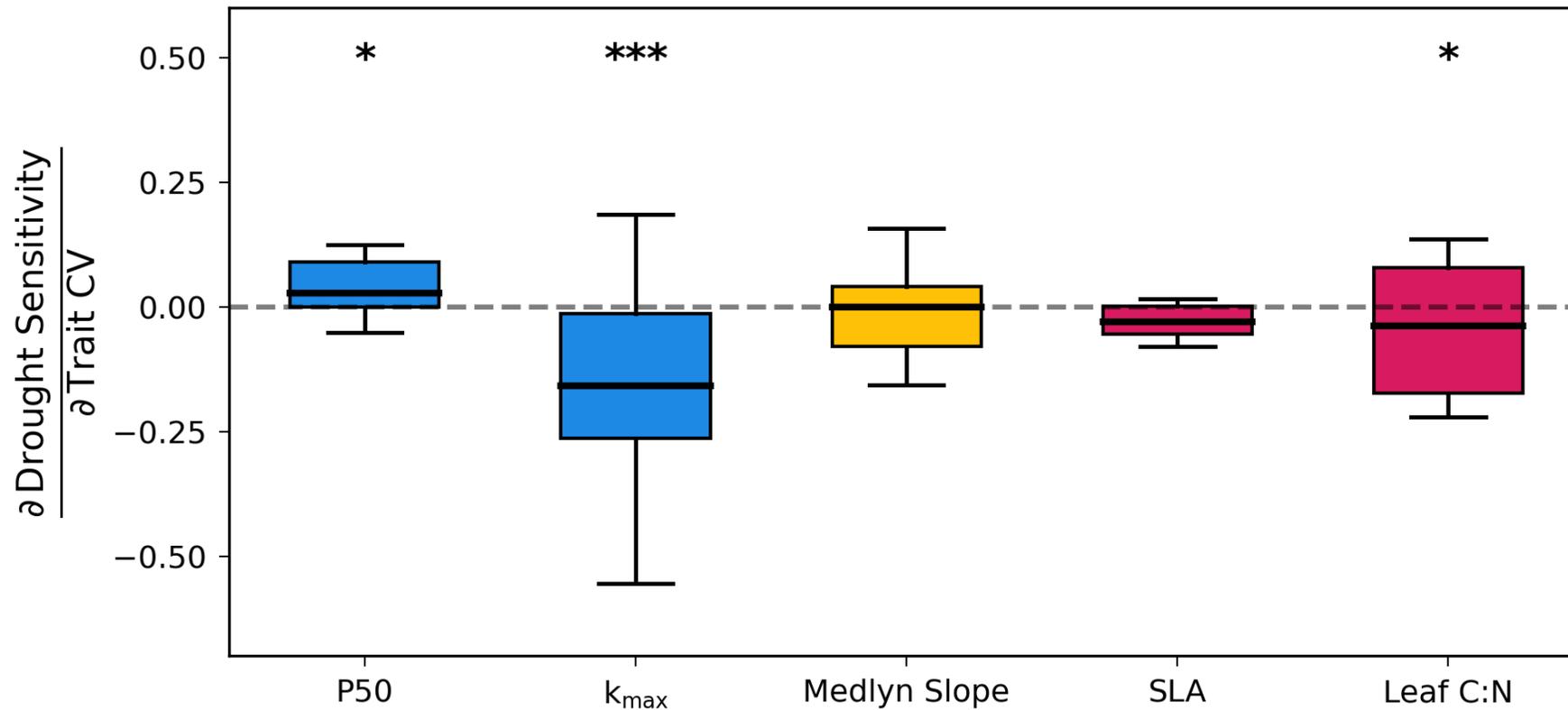
Effect of functional diversity on drought sensitivity varies across the globe

$$\text{Diversity Effect} = \frac{\partial \text{Drought Sensitivity}}{\partial P50 CV} + \frac{\partial \text{Drought Sensitivity}}{\partial k_{max} CV} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{Medlyn Slope CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{Leaf C:N CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{SLA CV}}$$

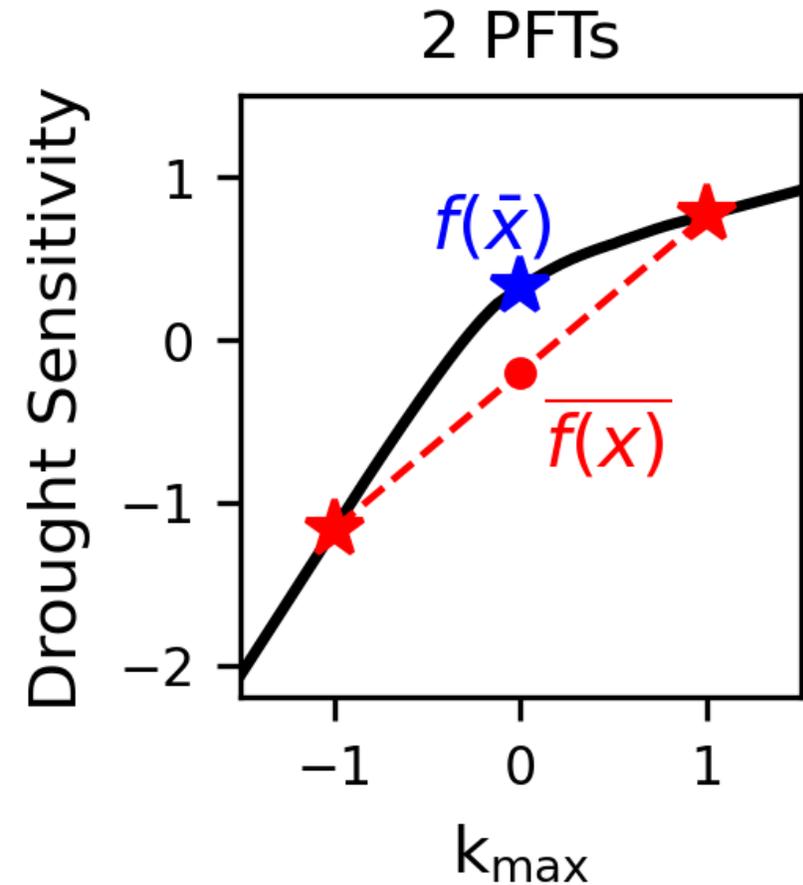
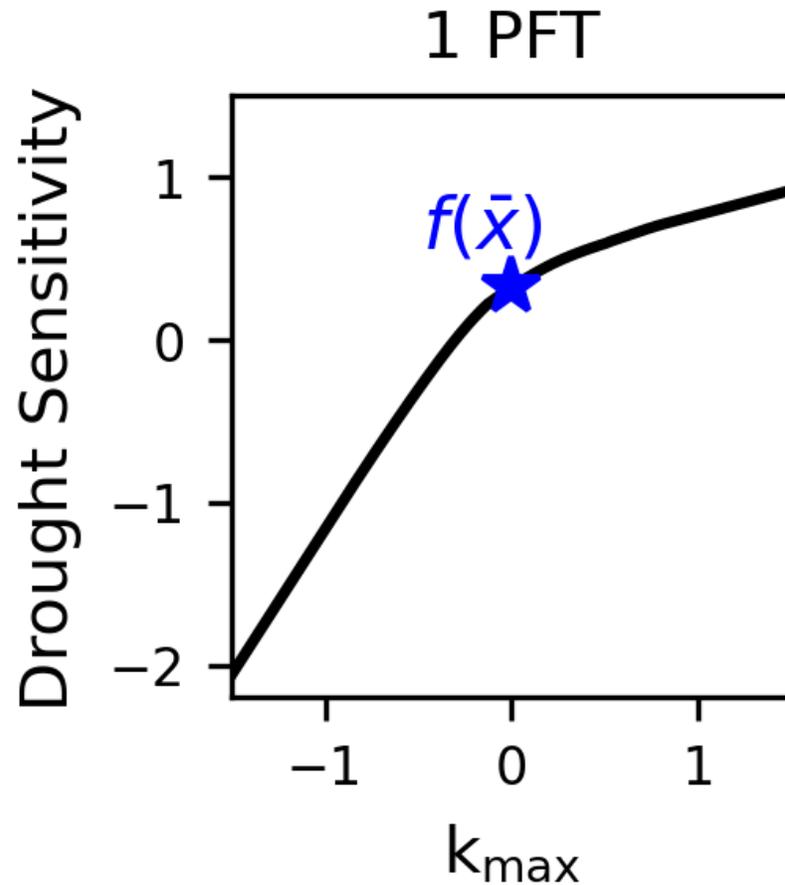
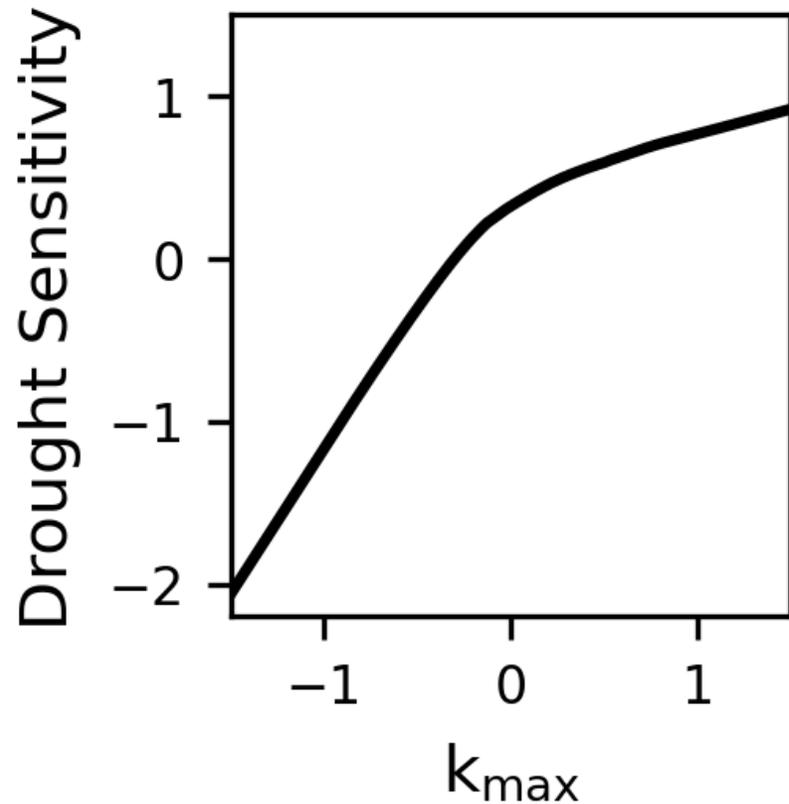


Effect of functional diversity on drought sensitivity driven by kmax

$$\text{Diversity Effect} = \frac{\partial \text{Drought Sensitivity}}{\partial P50 \text{ CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial k_{\max} \text{ CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{Medlyn Slope CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{Leaf C:N CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{SLA CV}}$$

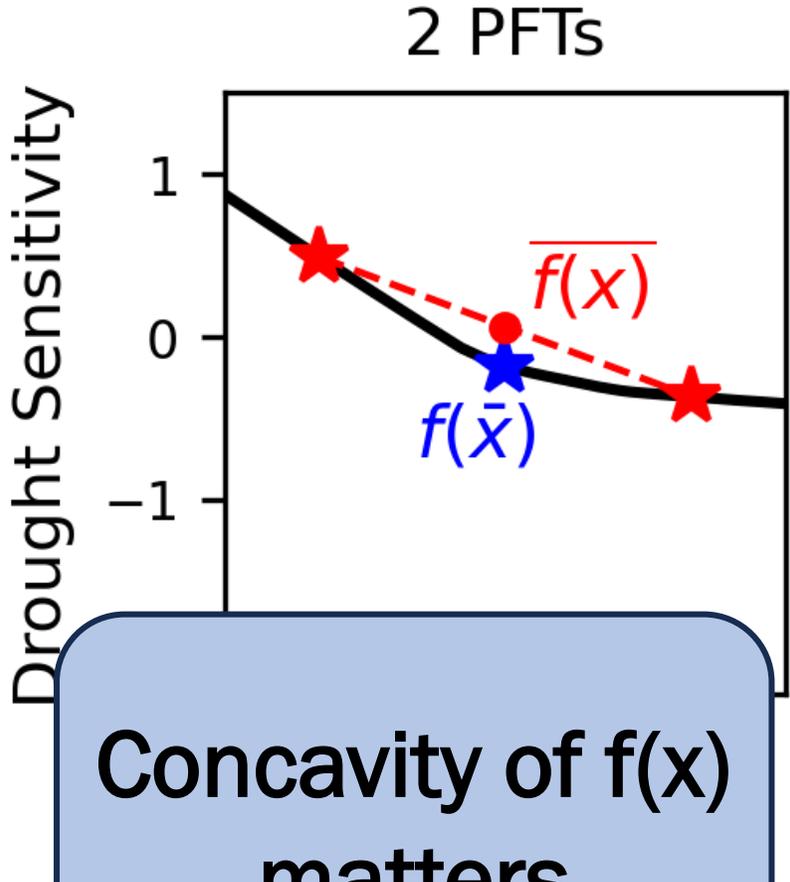
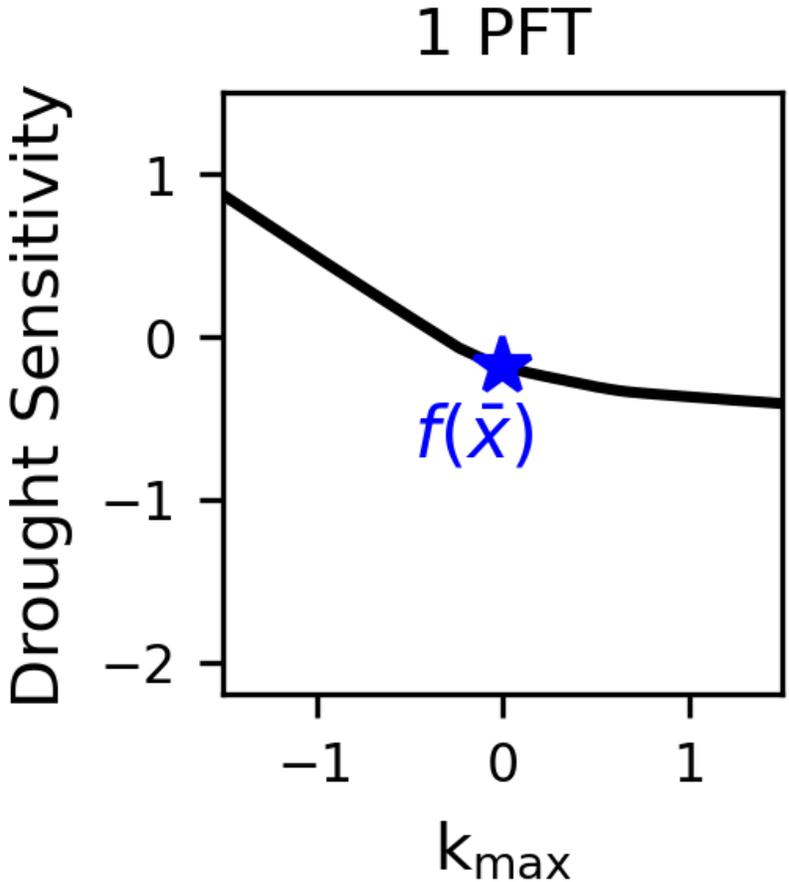
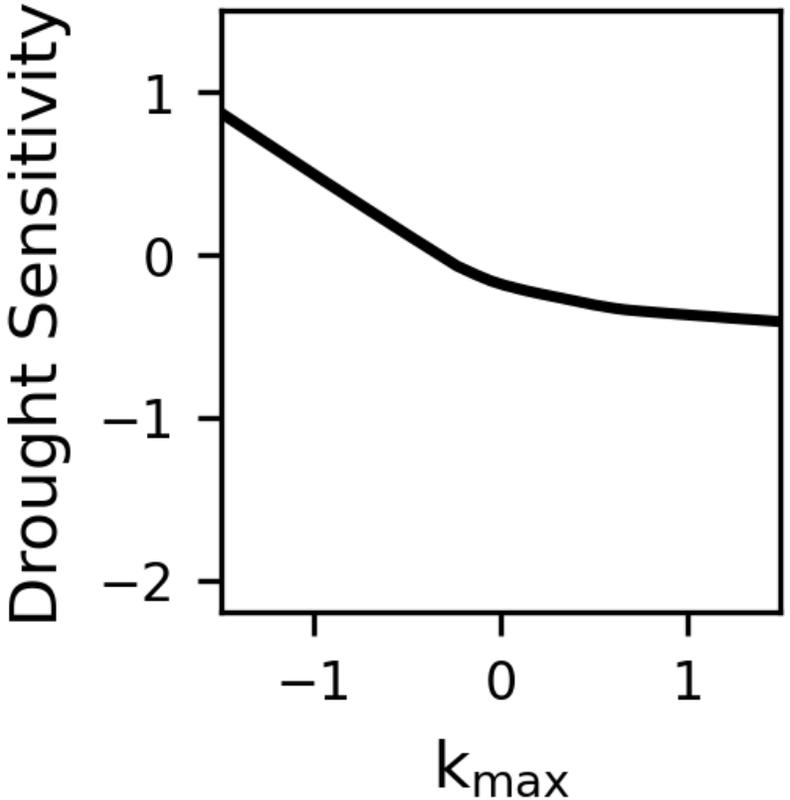


The relationship between k_{max} and Drought Sensitivity is nonlinear



$$\overline{f(kmax_{PFT1}), f(kmax_{PFT2})} \neq f(\overline{(kmax_{PFT1}, kmax_{PFT2})})$$

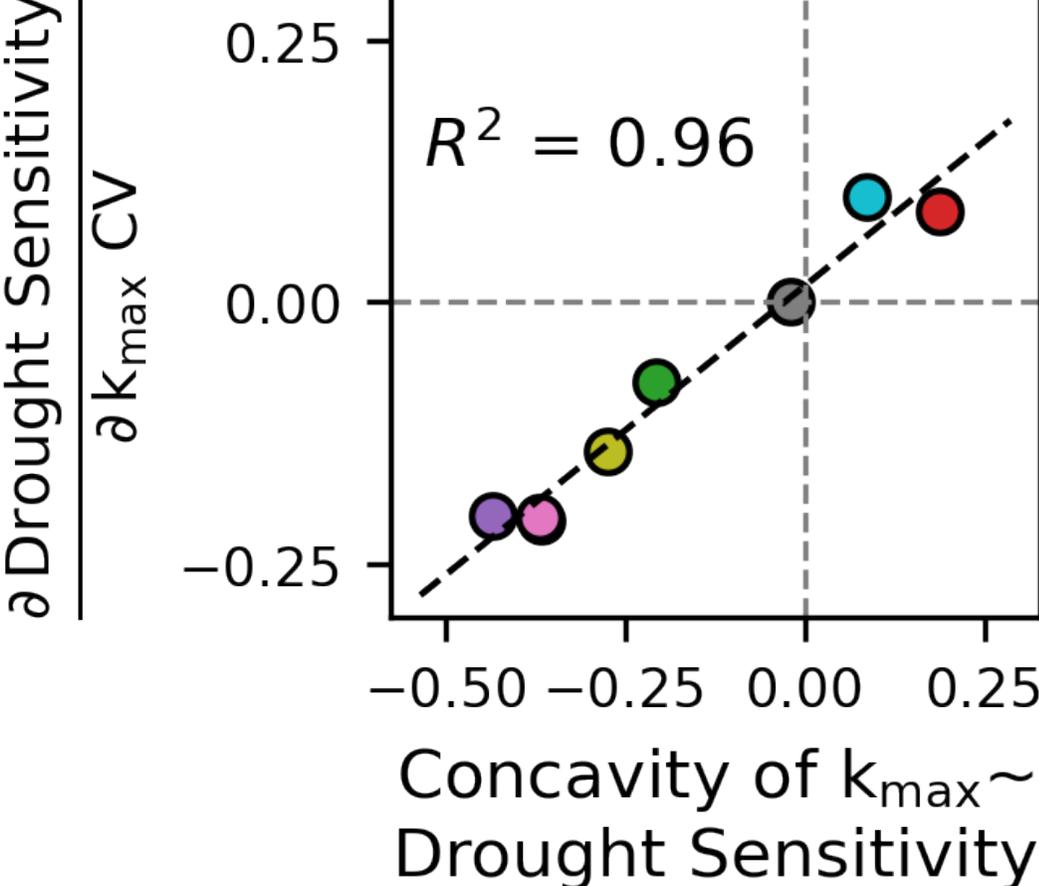
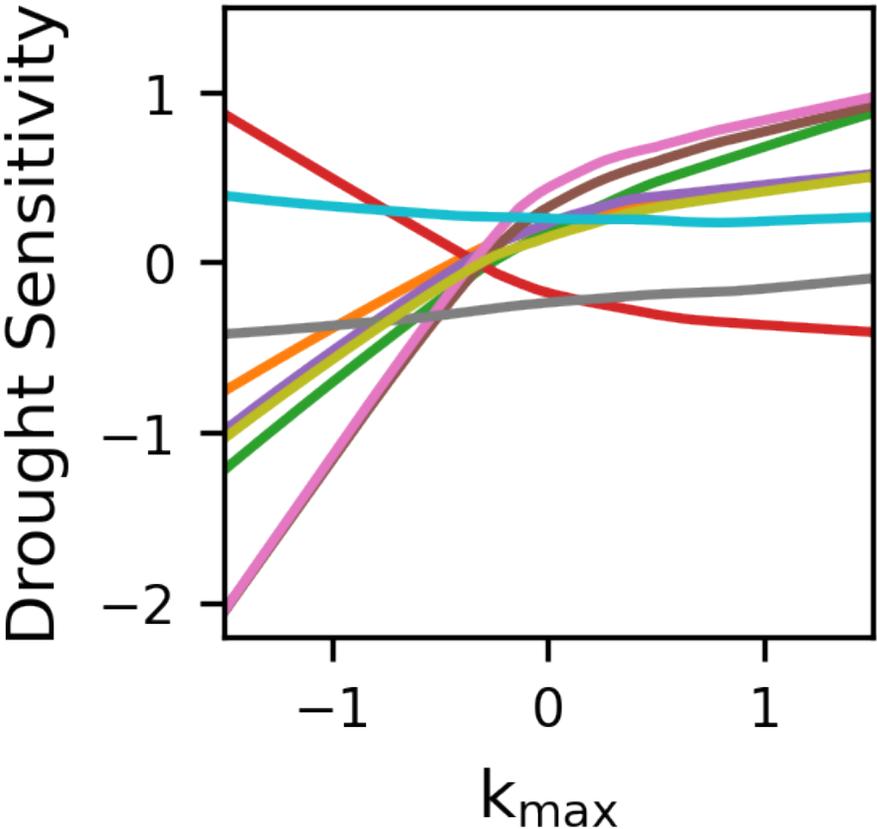
The relationship between k_{max} and Drought Sensitivity is nonlinear



Concavity of $f(x)$ matters

$$\overline{f(kmax_{PFT1}), f(kmax_{PFT2})} \neq f(\overline{(kmax_{PFT1}, kmax_{PFT2})})$$

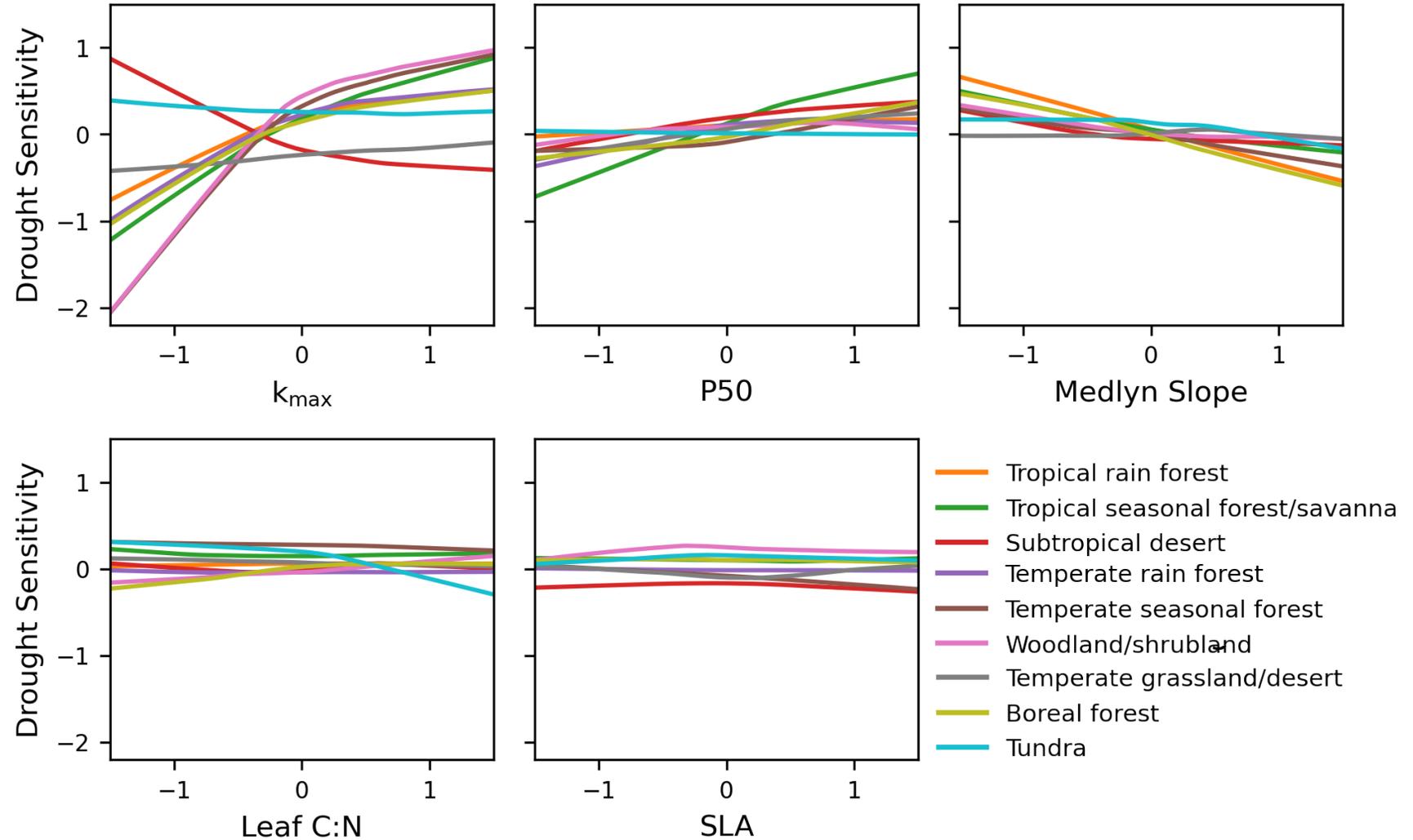
Variation in the effect of diversity in k_{max} diversity is the consequence of sampling from a nonlinear function



- Tropical rain forest
- Temperate rain forest
- Temperate grassland/desert
- Tropical seasonal forest/savanna
- Temperate seasonal forest
- Boreal forest
- Subtropical desert
- Woodland/shrubland
- Tundra

Variation in the effect of diversity in k_{max} diversity is the consequence of sampling from a nonlinear function

None of the other traits have nonlinear relationships with drought sensitivity



Key Takeaways

- The effect of trait diversity is a consequence of sampling from nonlinear functions, and not an emergent effect of competition
- Calibration efforts might only need to consider diversity for a much smaller number of traits
- Will be interesting to redo in FATES, CLM6, and beyond with more avenues for competition



**Accompanying paper in *Global Change Biology*
with Daniel Kennedy, Linnia Hawkins, and Anna
Trugman**

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Global Change Biology
Research Article

Functional diversity in land surface modeling: where and when
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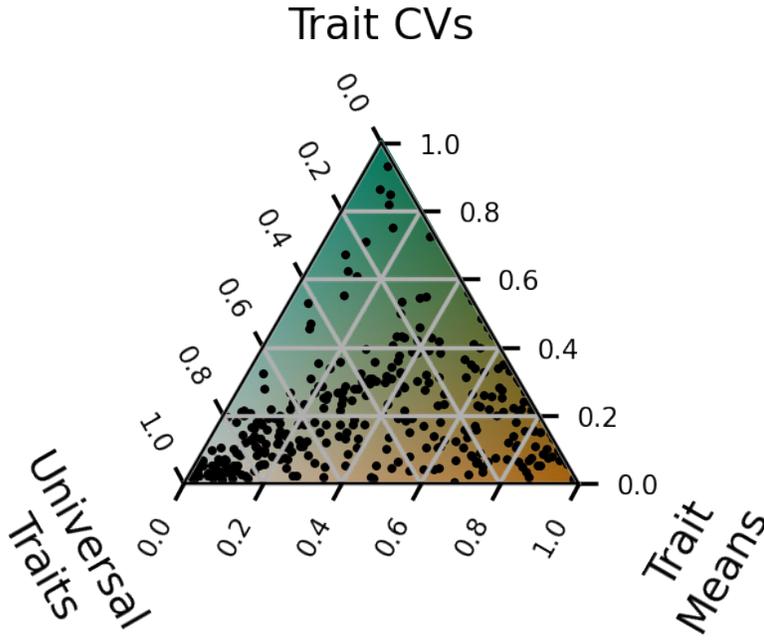
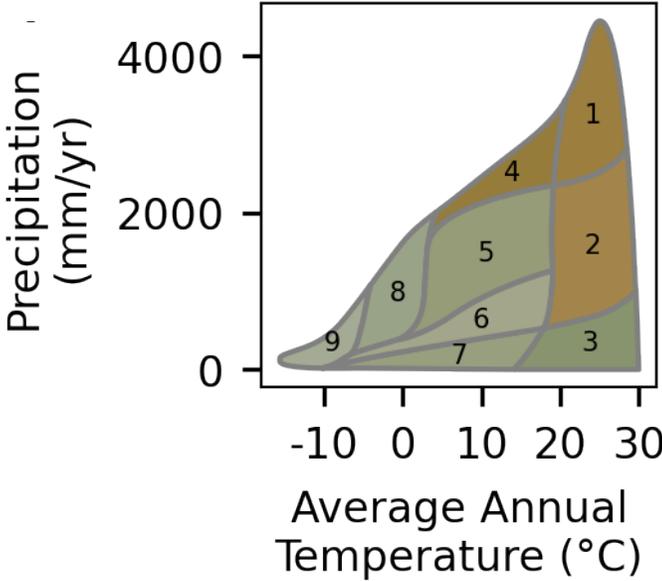
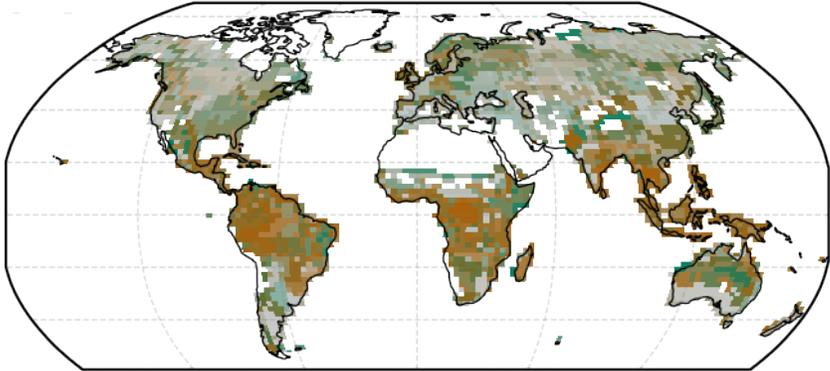
This submission is under
consideration and cannot be edited.
Further information will be emailed to
you by the journal editorial office.

[Submission overview →](#)

A vibrant, detailed forest scene. The foreground is filled with green grass and numerous small purple flowers. Several large, brown logs lie on the ground. The middle ground is dominated by tall, slender evergreen trees with dense green foliage. The background shows more trees and a clear blue sky with a few white birds flying. The overall atmosphere is bright and natural.

Supplemental Slides

Importance of diversity is constrained by where multiple PFTs are permitted to coexist

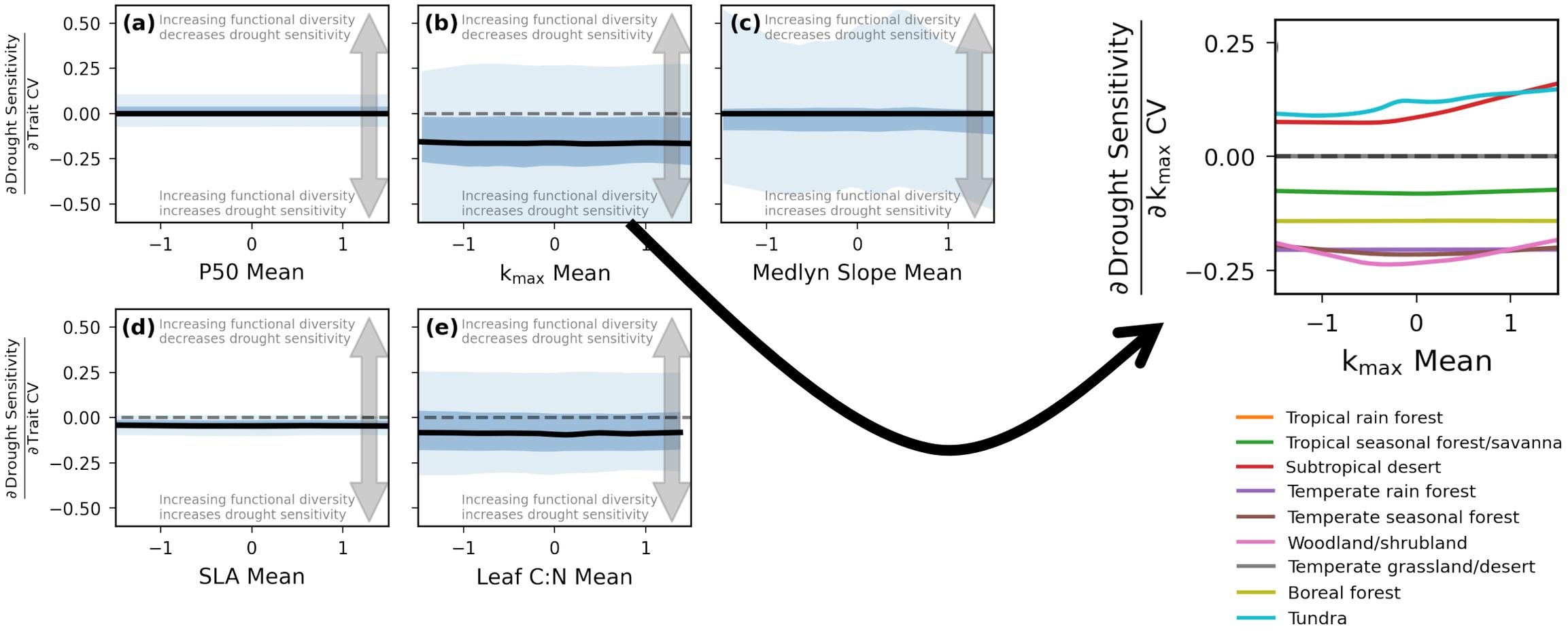


-  = Proportion of Variance Explained by Trait Means
 -  = Proportion of Variance Explained by Trait Coefficients of Variation
 -  = Proportion of Variance Explained by Universal Traits
- Strength of Colors



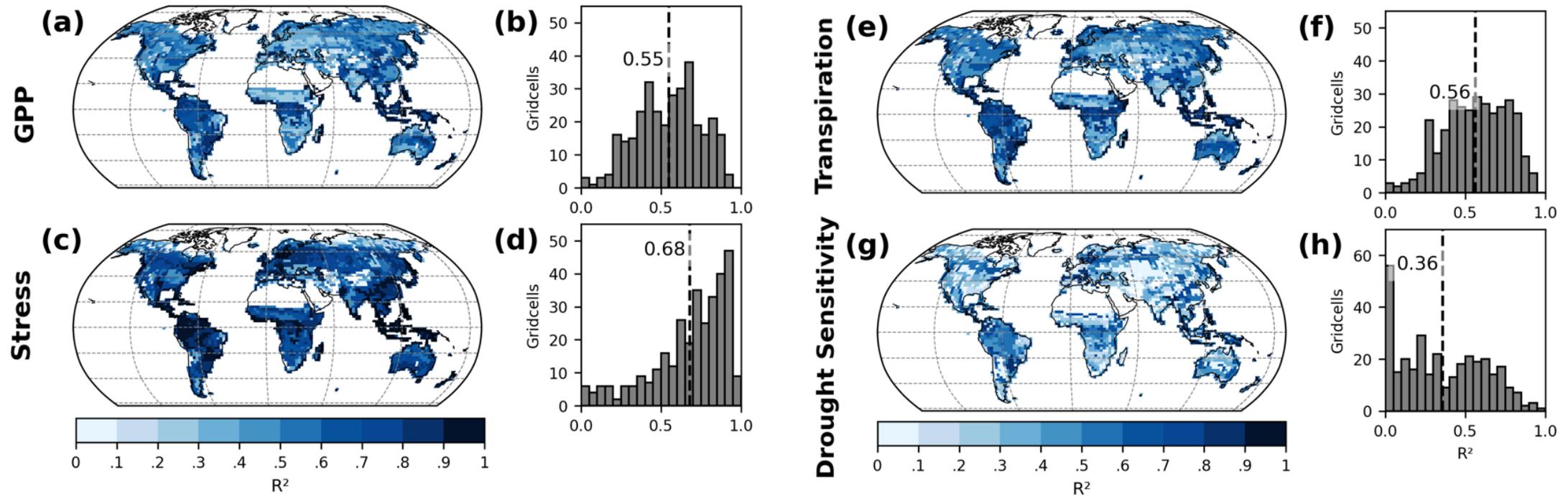
A consistent directional effect of diversity is only present for kmax

$$\text{Diversity Effect} = \frac{\partial \text{Drought Sensitivity}}{\partial \text{P50 CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{kmax CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{Medlyn Slope CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{LeafCN CV}} + \frac{\partial \text{Drought Sensitivity}}{\partial \text{SLA CV}}$$

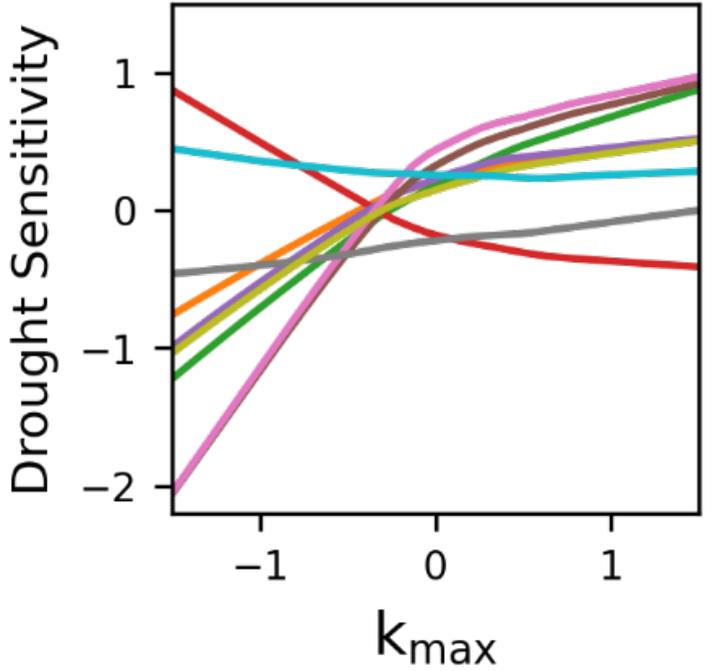
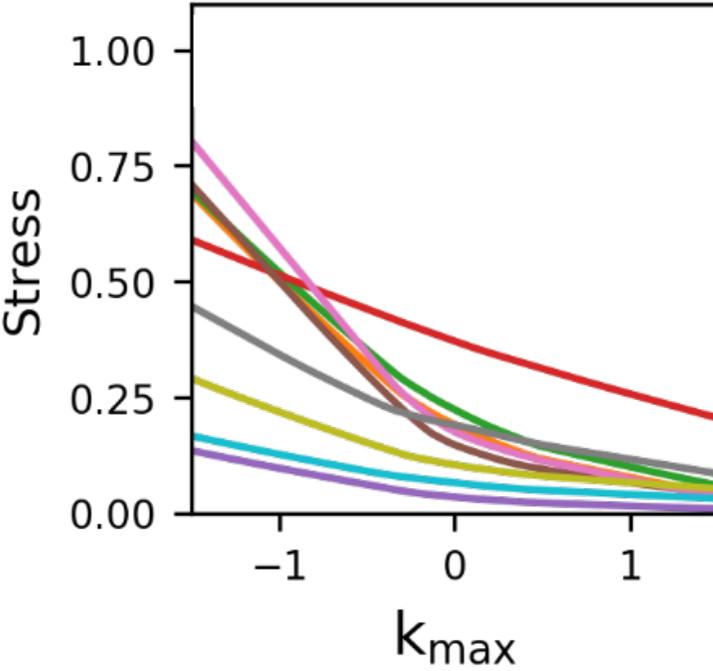
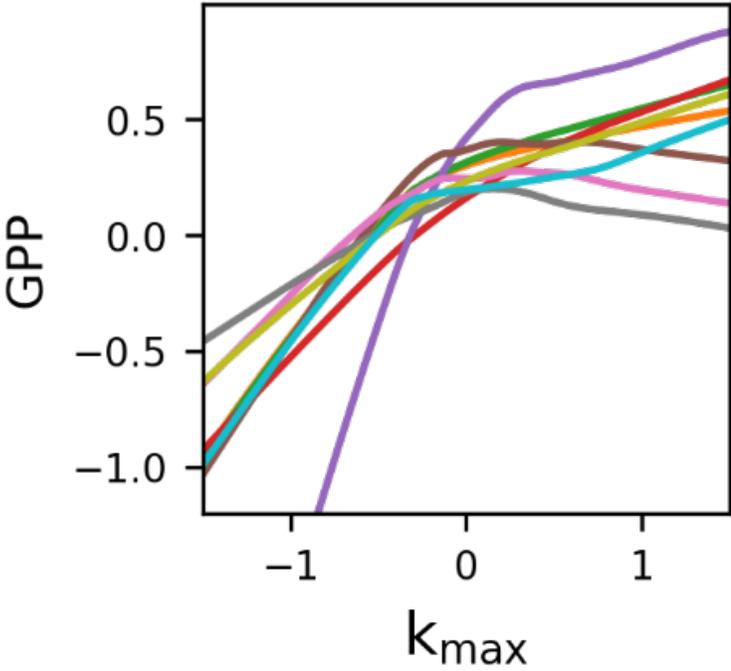


Gaussian Process Emulators perform acceptably in predicting key model outputs

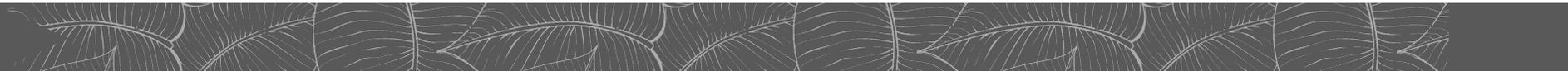
- Goal is not necessarily predictive accuracy
- GPE only sees 8 of 32 perturbed parameters



Maximum hydraulic conductivity shows nonlinear relationships with model outputs

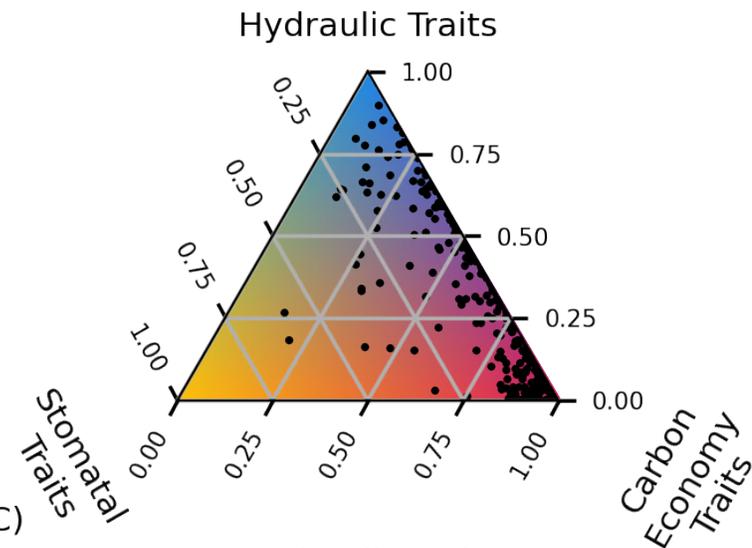
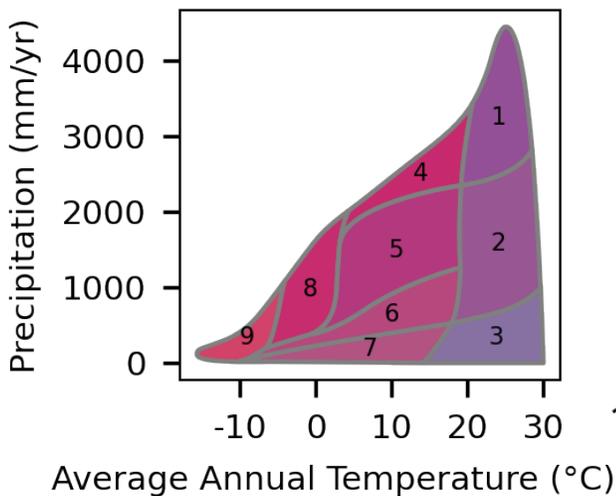
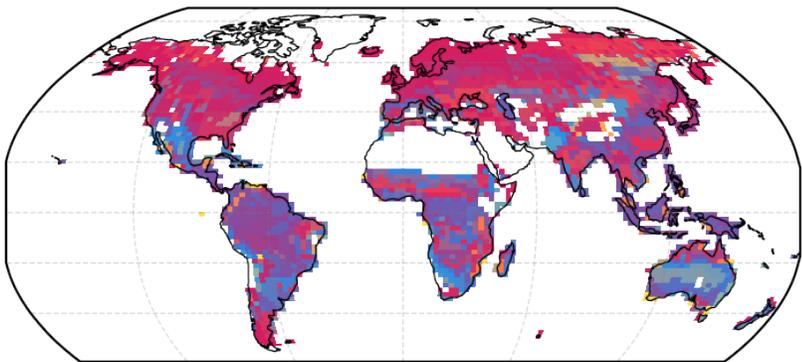


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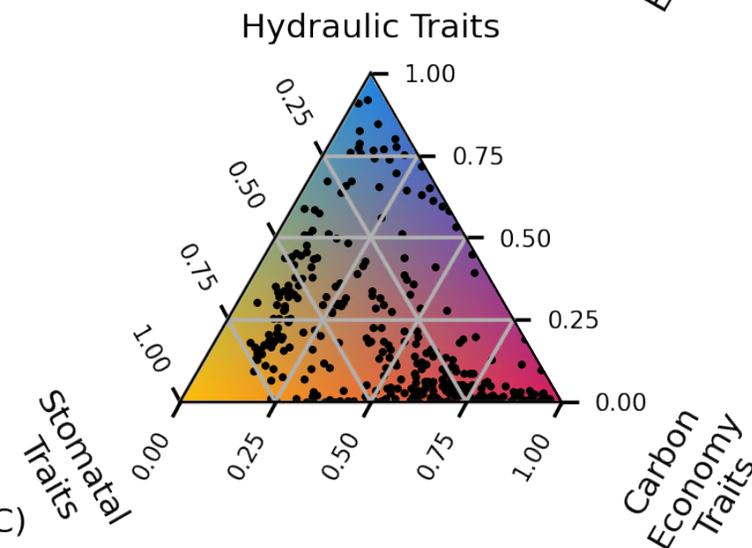
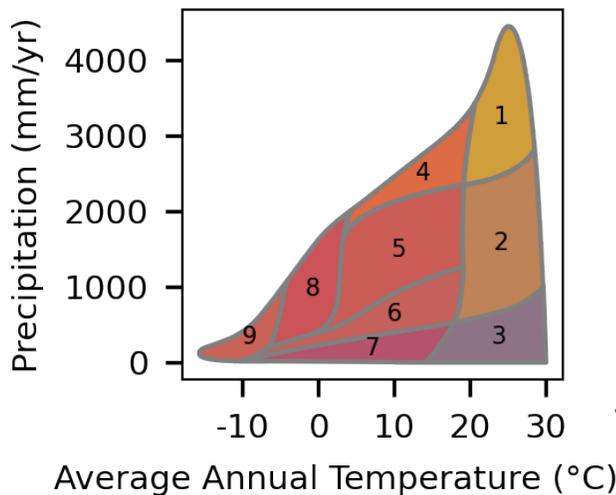
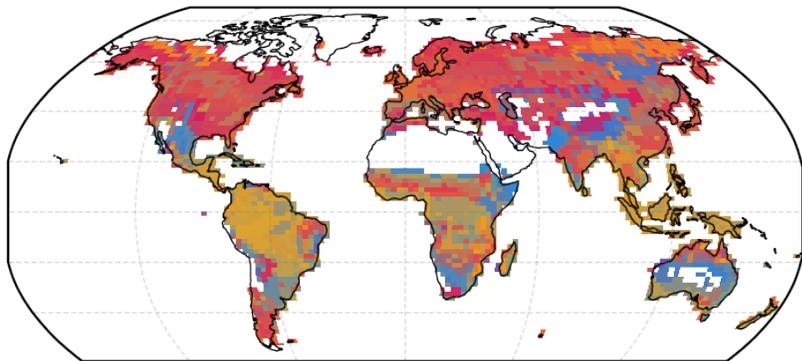


Type of trait, combination of traits, most important for explaining model outcomes vary across space and output metric of interest

GPP

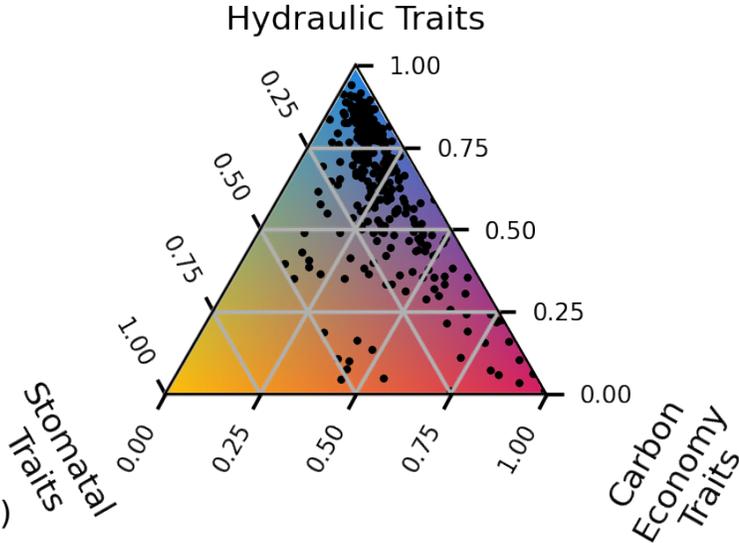
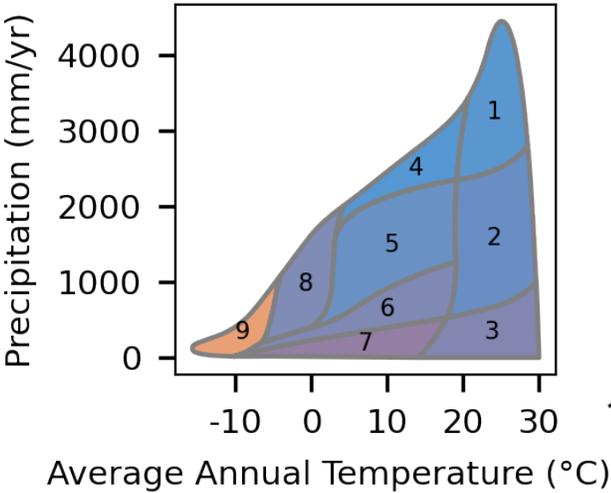
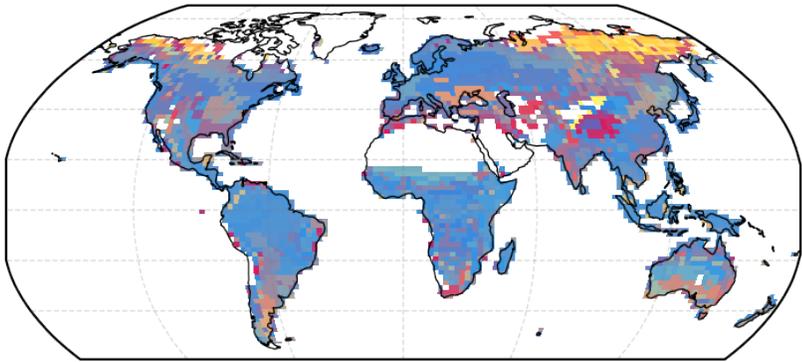


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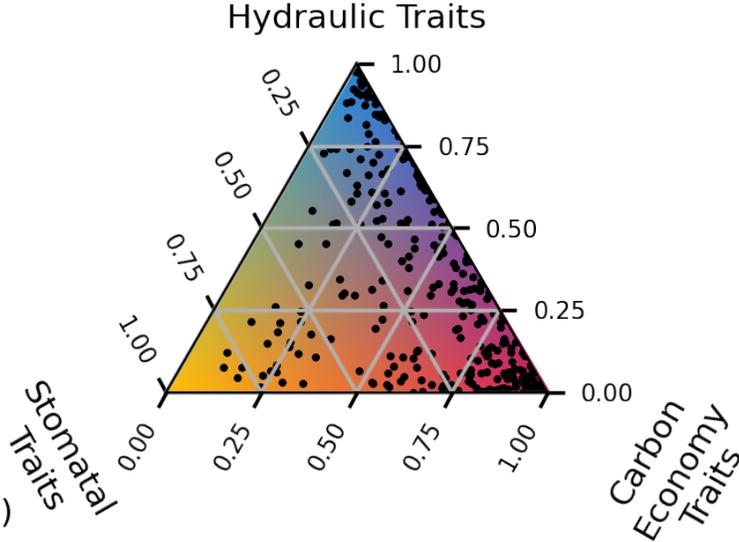
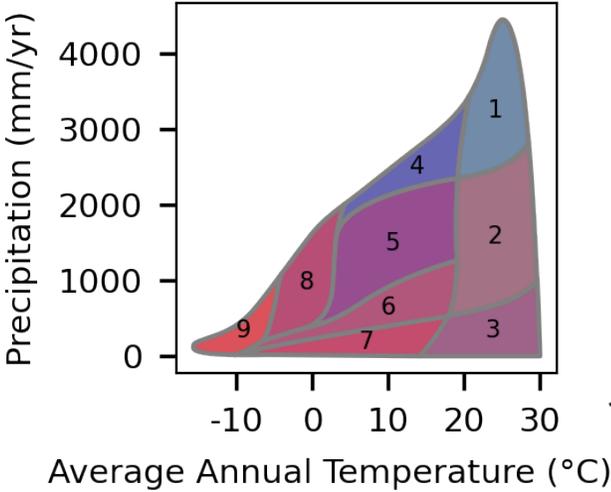
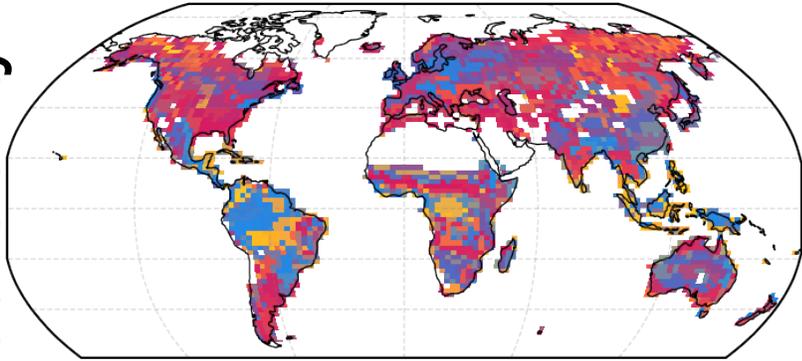


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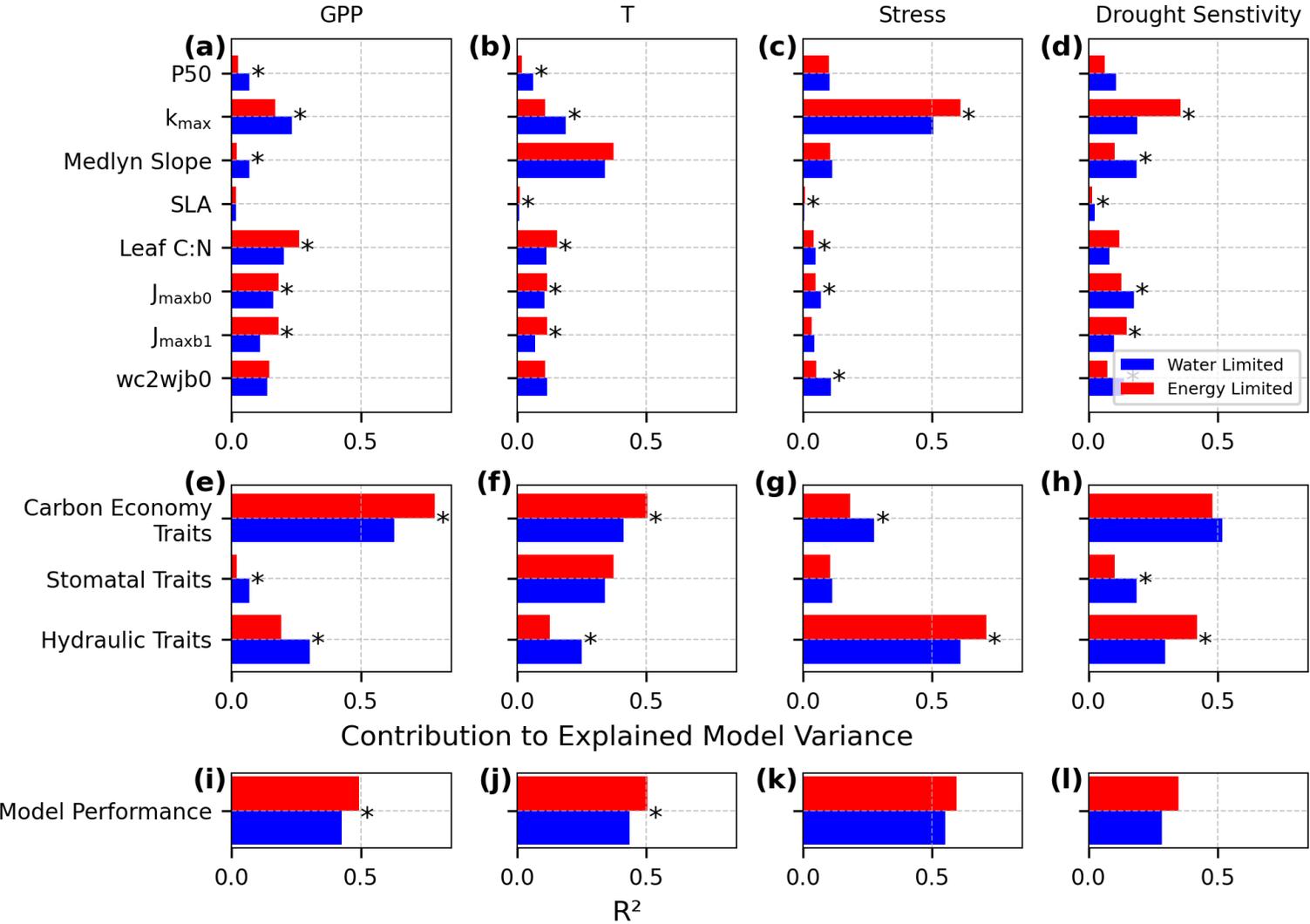
Stress



Drought Sensitivity

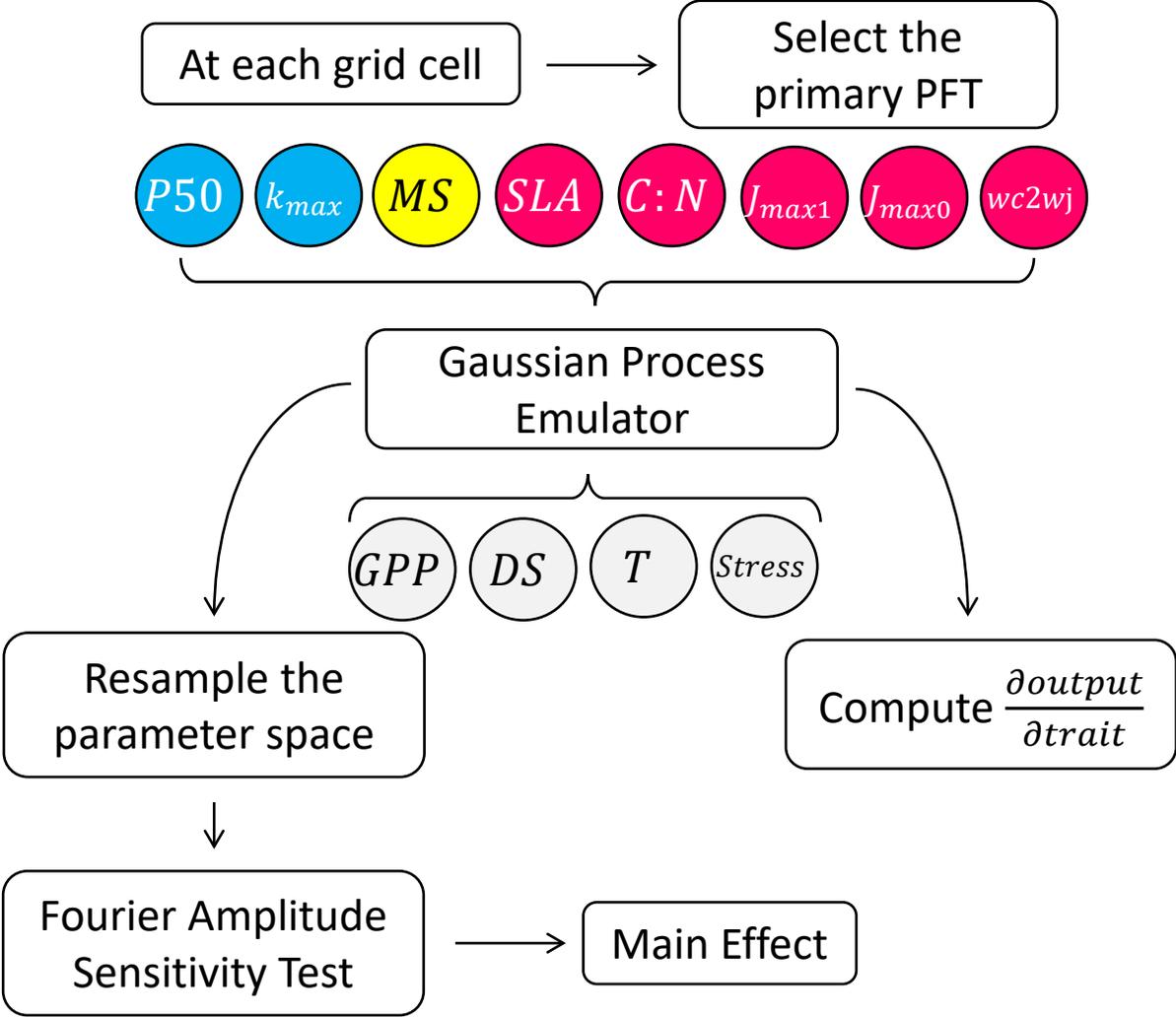


Controls on ecosystem fluxes of water and carbon vary with limiting resource, highlights important role of k_{max}

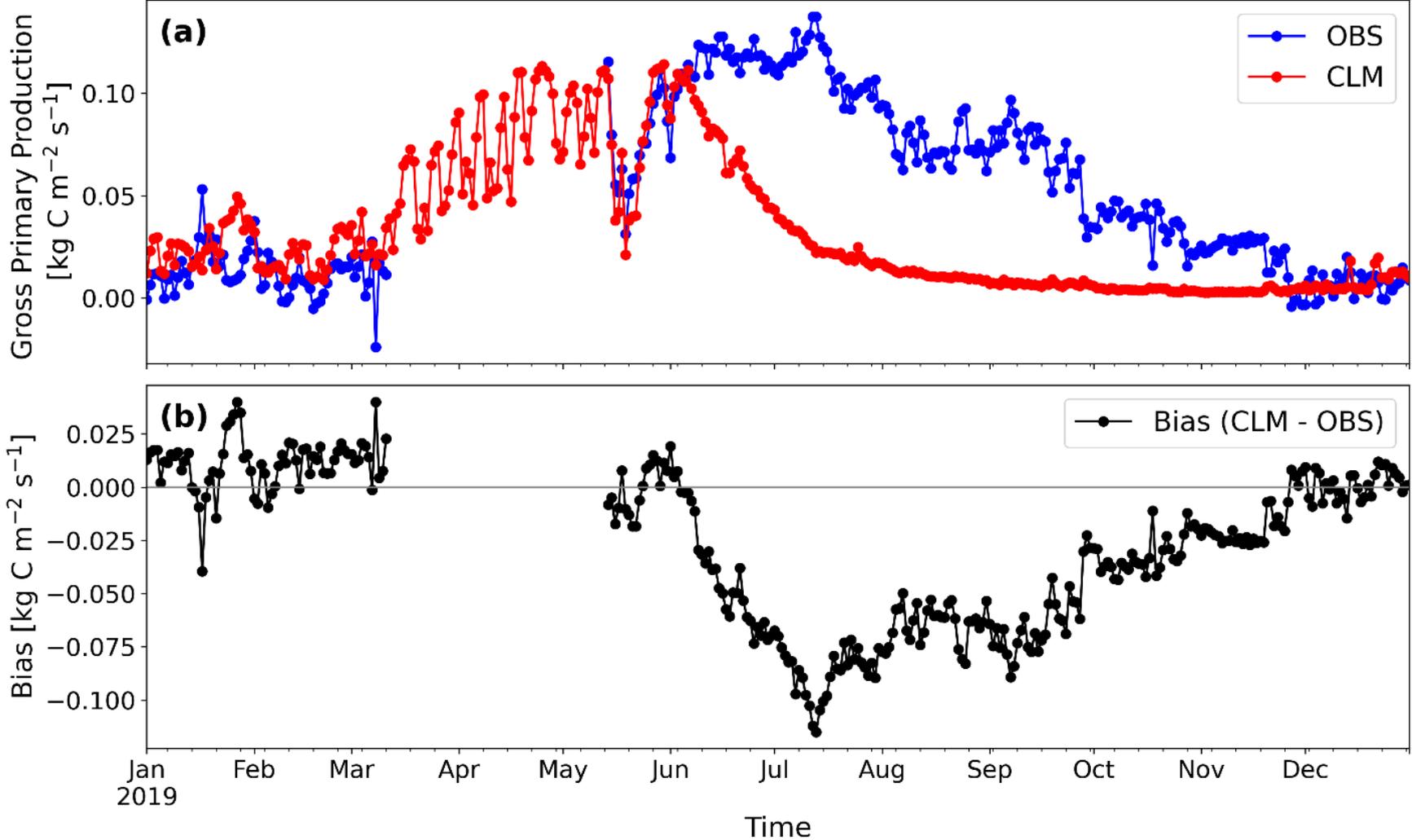


Experimental Design: Varying diversity through parameter perturbation

Organism scale analysis



Initial comparison to observations provide an example of misrepresented end of growing season behavior

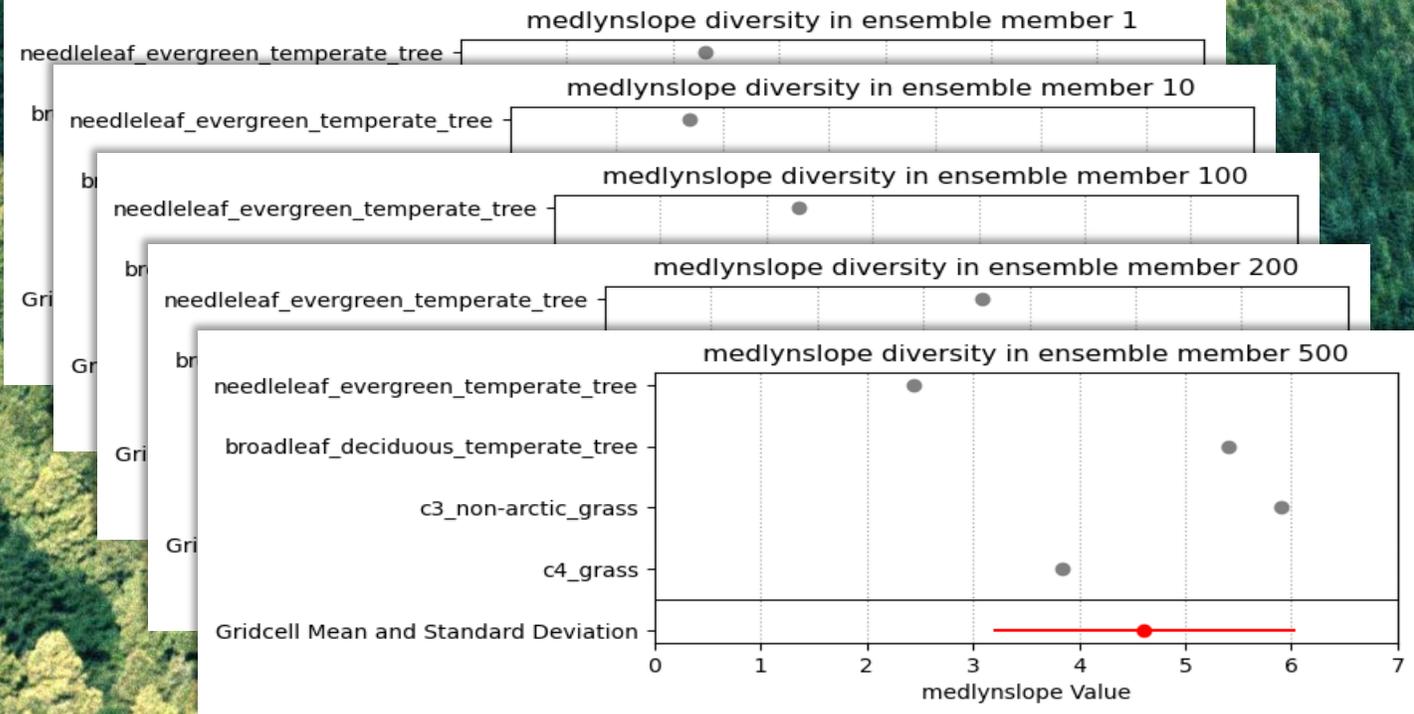
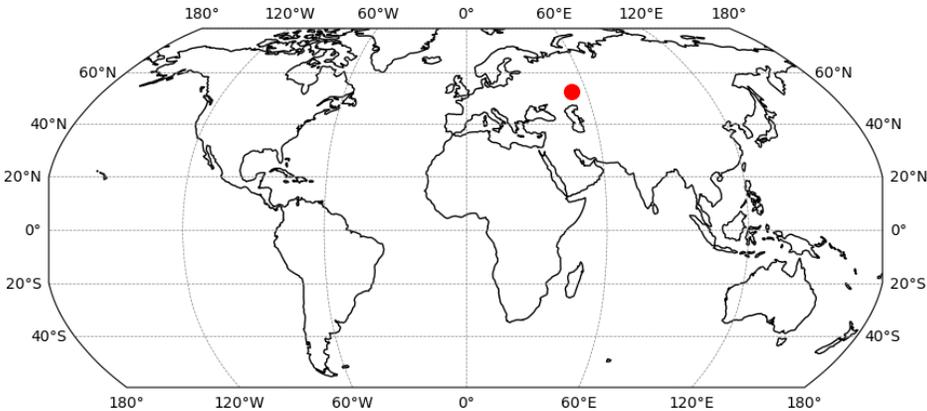


Experimental Design: Varying diversity through parameter perturbation

CLM Parameter Perturbation Experiment

- Perturbation of 32 traits associated with plant hydraulics, photosynthesis, and stomatal regulation across 500 ensemble member
- **12 traits are perturbed separately for each PFT**
- Across ensemble members, grid cell level trait means and trait diversity can vary

Temperate Forest Site (1 of 400 grid cells)



GPP/Stress/
Transpiration/
Drought Sensitivity

$$\sim \text{Trait}_i\text{-Mean} + \text{Trait}_i\text{-SD}$$

Diversity Effect

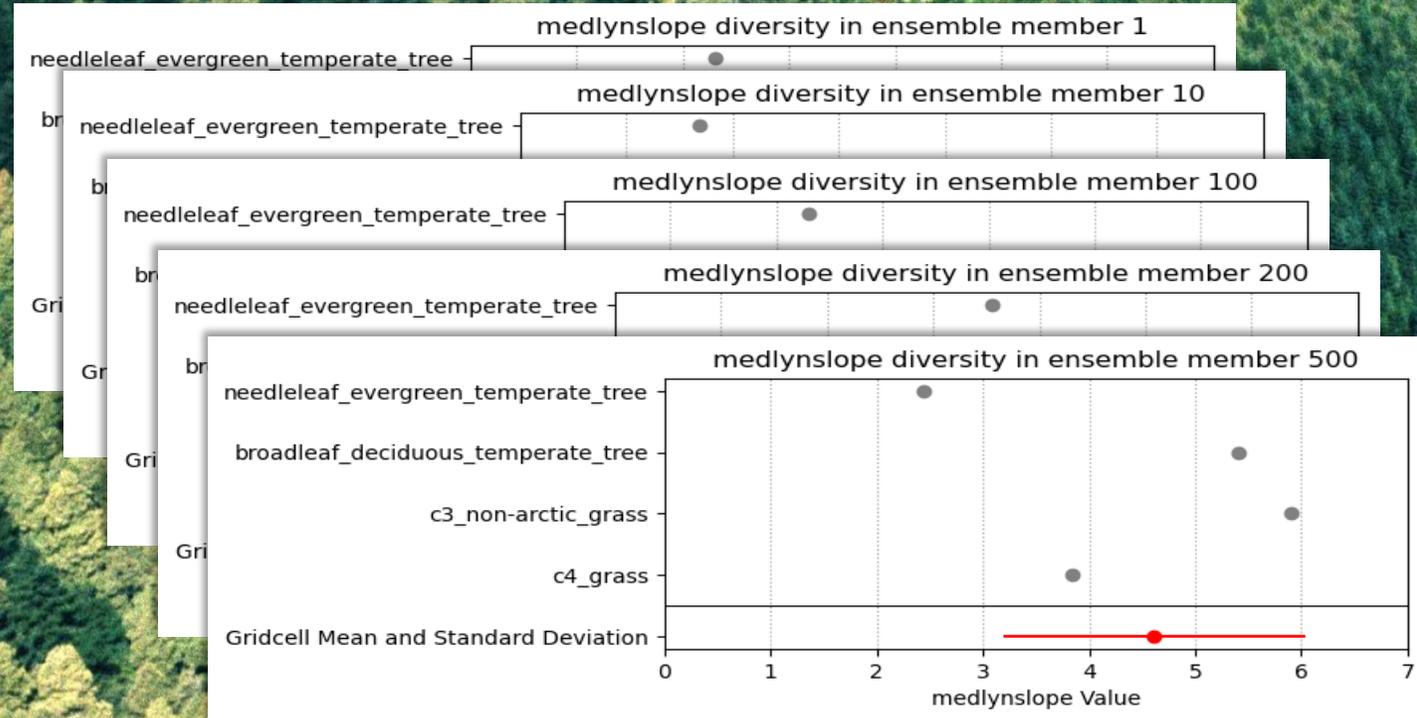
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Partitioning of Model Variance

- Gaussian process emulator to partition model variance in drought sensitivity between trait means and trait standard deviations
- Partition variance procedure at every grid cell
- Novel use of the CLM-PPE for understanding competition processes which emerge from grid cell scale interaction between parameters

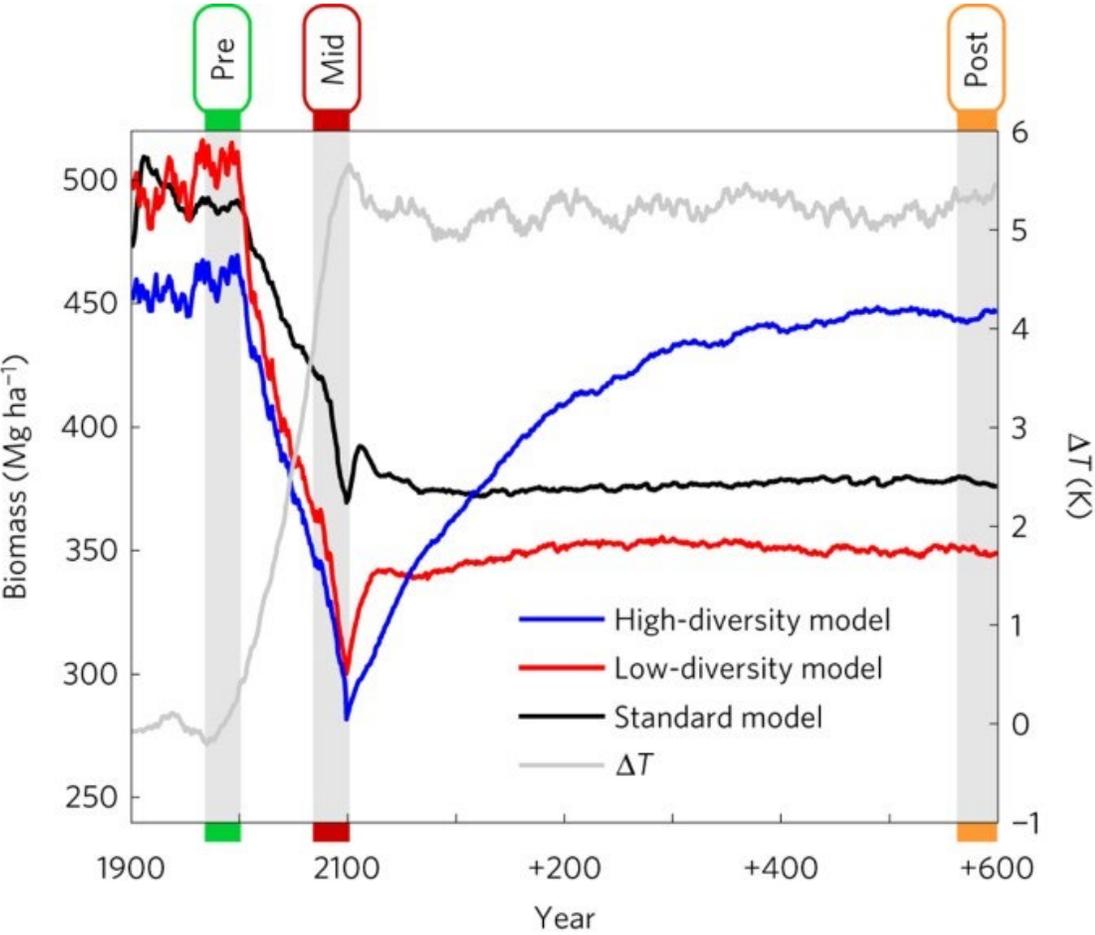


GPP/Stress/
Transpiration
Drought Sensitivity

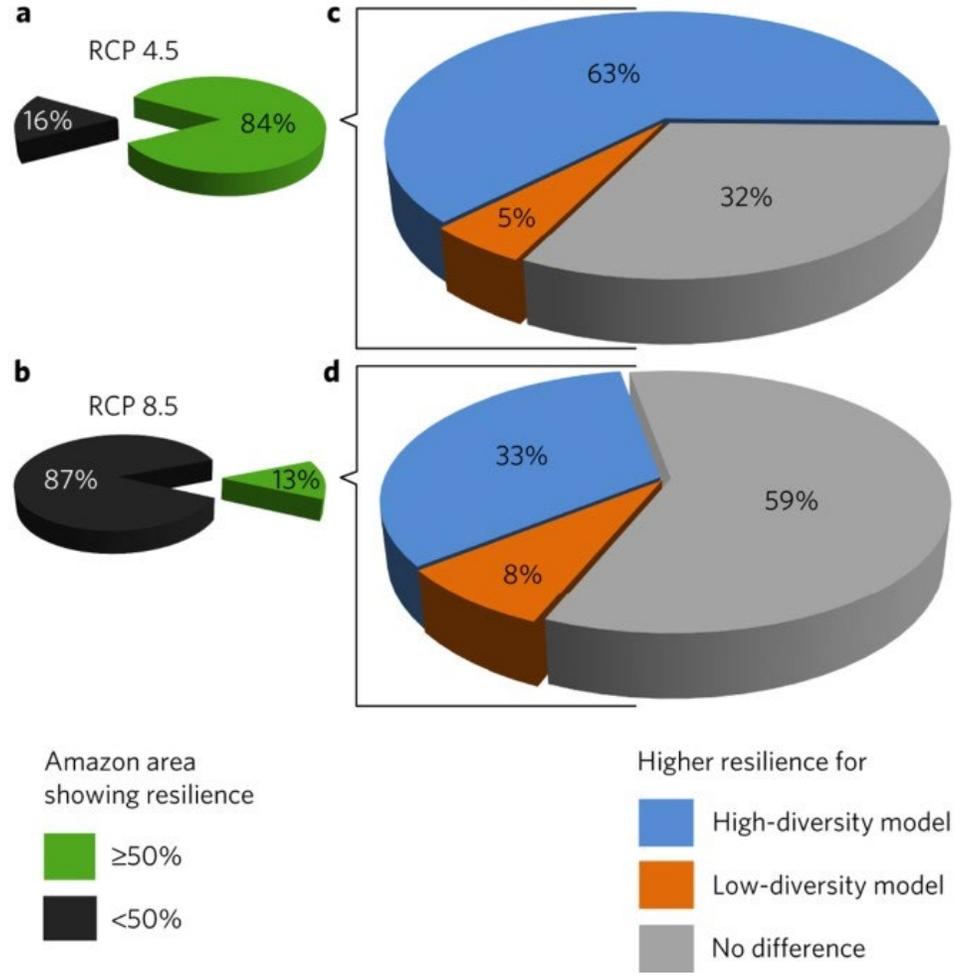
$$\sim \text{Trait}_i\text{-Mean} + \text{Trait}_i\text{-SD}$$

Diversity Effect

Other experiments evaluating diversity impacts in land surface models show mixed effects of diversity on ecosystem processes



Sakschewski *et al.* (2016)



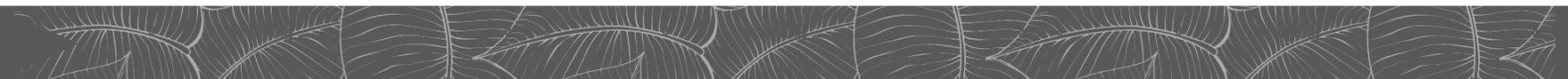
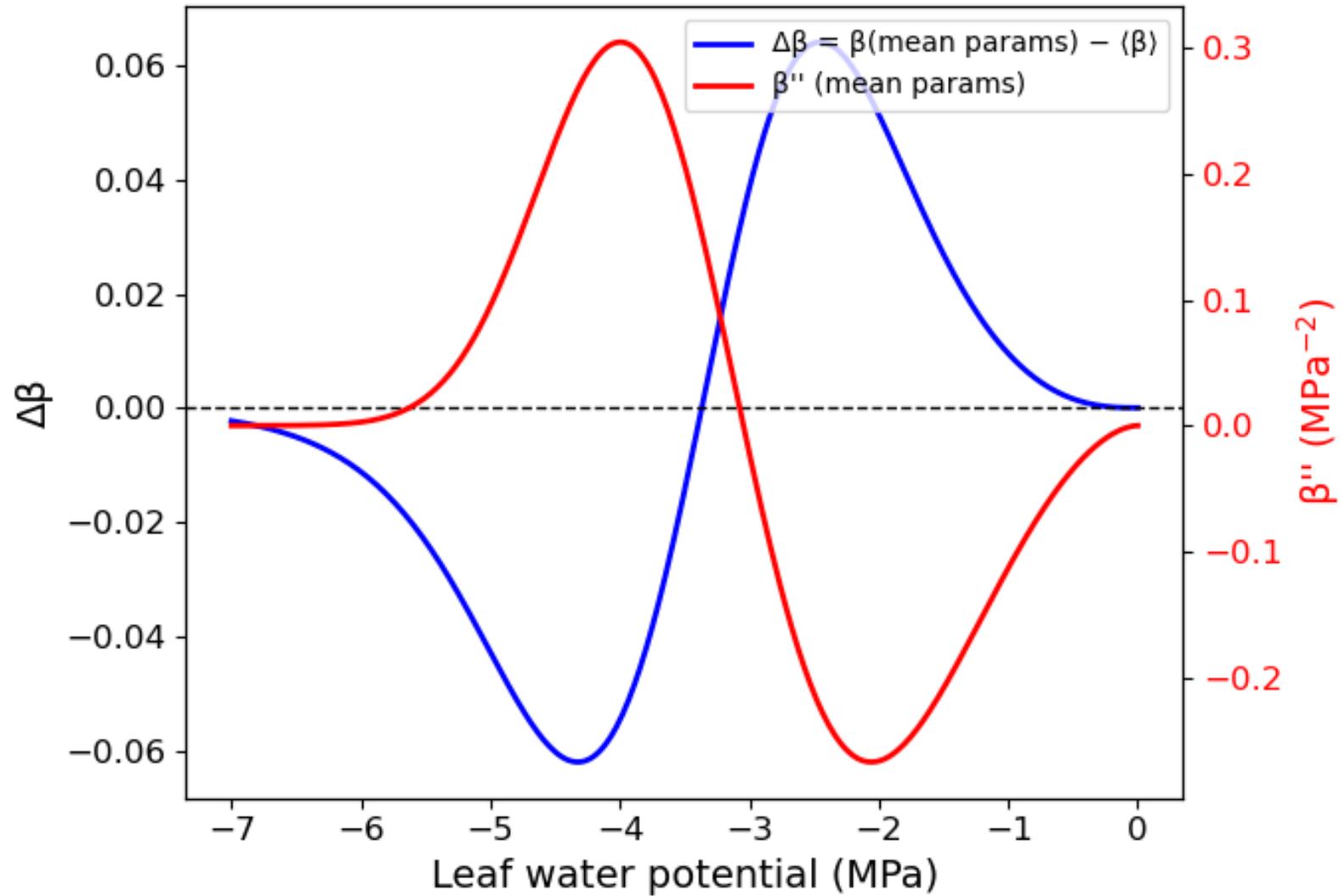
Amazon area showing resilience

- Green: ≥50%
- Black: <50%

Higher resilience for

- Blue: High-diversity model
- Orange: Low-diversity model
- Grey: No difference

Effects of nonlinear functions on model bias when simplifying vegetation heterogeneity



Sparse Grid Sampling Design

