BG3.13

D458

Aliénor Lavergne[1,*]

Heather Graven[1], Iain Colin Prentice[2]

& David Sandoval[2], Vincent Hare[3]

Soil water stress impacts on the stomatal limitation of photosynthesis: a meta-analysis

[1] Carbon Cycle Research Group, Department of Physics, Imperial College London (UK)
[2] Prentice's Climate Group, Department of Life Sciences, Imperial College London (UK)
[3] Stable Light Isotope Laboratory, University of Cape Town (South Africa)

*a.lavergne@imperial.ac.uk

Imperial College London

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Coupling carbon and water cycles

- Atmospheric aridity and drought impacting physiological function in plant leaves
- However, their relative contributions on changes in **ratio of leaf-internal (c_i) to ambient (c_a) partial pressure of CO_2 (also known as χ)** still difficult to disentangle

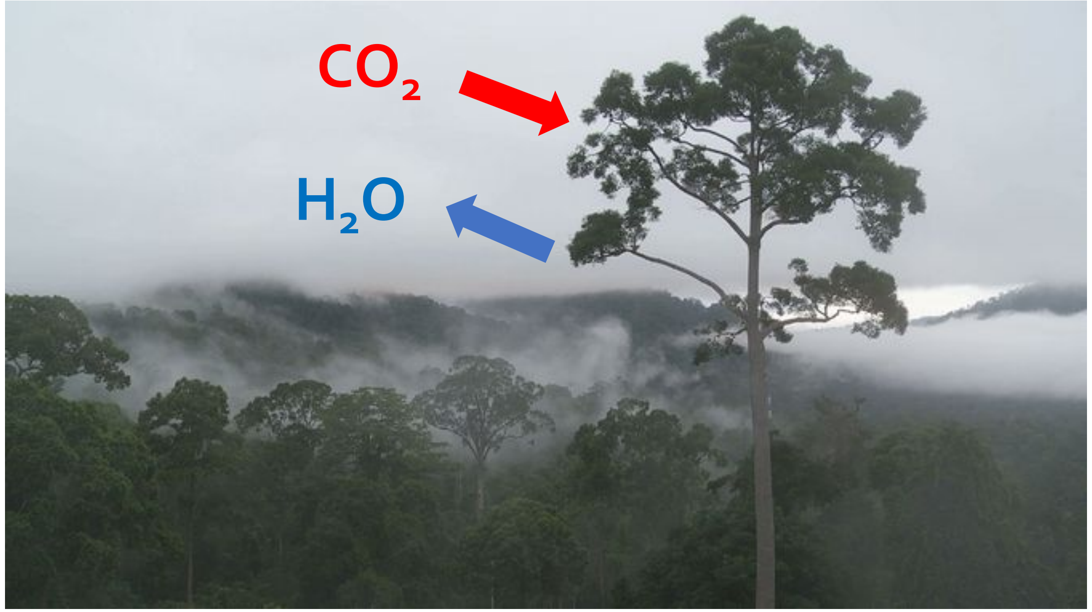
Many stomatal models predicting χ include the effect of only one of these drivers

$$\text{WUE} = \frac{CO_2}{H_2O}$$

Water use efficiency

χ = index of adjustments in both leaf stomatal conductance and photosynthetic rate to environmental conditions

- Key variable for the study of **carbon uptake**
- Provides insight into **(intrinsic) WUE**



Optimal χ: predictions

Least-cost optimality hypothesis: leaves minimize the summed unit costs of transpiration (a_E) and carboxylation (b_v):

$$a_E \frac{\partial(E/A)}{\partial\chi} + b_V \frac{\partial(V_{cmax}/A)}{\partial\chi} = 0$$

Prentice et al. (2014) *Ecol. Lett.*
Wang et al. (2017) *Nature Plants*
Stocker et al. (2020) *Geosc. Mod. Dev.*

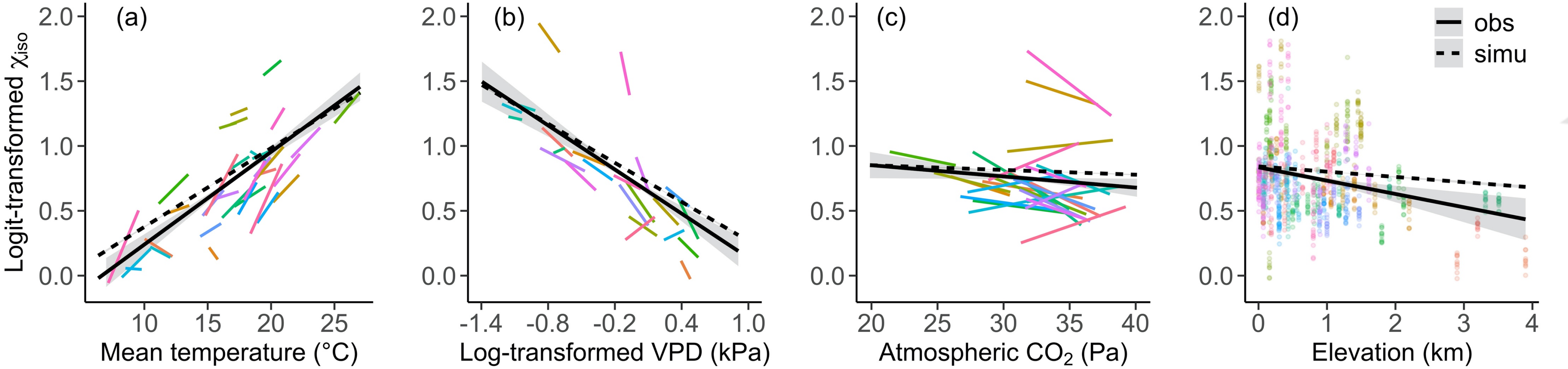
$$\chi = \frac{\Gamma^*}{c_a} + \left(1 - \frac{\Gamma^*}{c_a}\right)\frac{\xi}{\xi + \sqrt{D}}$$

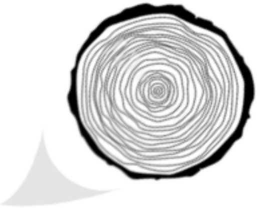
$$\xi = \sqrt{\beta \frac{K+\Gamma^*}{1.6\eta*}}$$

E: transpiration (mol m^{-2} s^{-1}), *A:* net assimilation rate (µmol m^{-2} s^{-1})
V_{cmax}: photosynthetic capacity (µmol m^{-2} s^{-1})
D: leaf-to-air vapour pressure deficit (Pa)
$\eta*$: viscosity of water relative to its value at 25°C (unitless)
K: effective Michaelis constant for Rubisco-limited photosynthesis (Pa)
Γ^*: CO_2 photorespiratory compensation point (Pa)
β = ratio of b_v and ($a_E/\eta*$)

χ depends on temperature, vapor pressure, atmospheric CO2 and atmospheric pressure (indexed by elevation)

Optimal χ: consequences on trends in iWUE





> 100 $\delta^{13}C_{tree\text{-}ring}$ chronologies

Lavergne et al. (2020) *New Phytol.*

→ Broadly constant χ over long timescales after integrating environmental effects

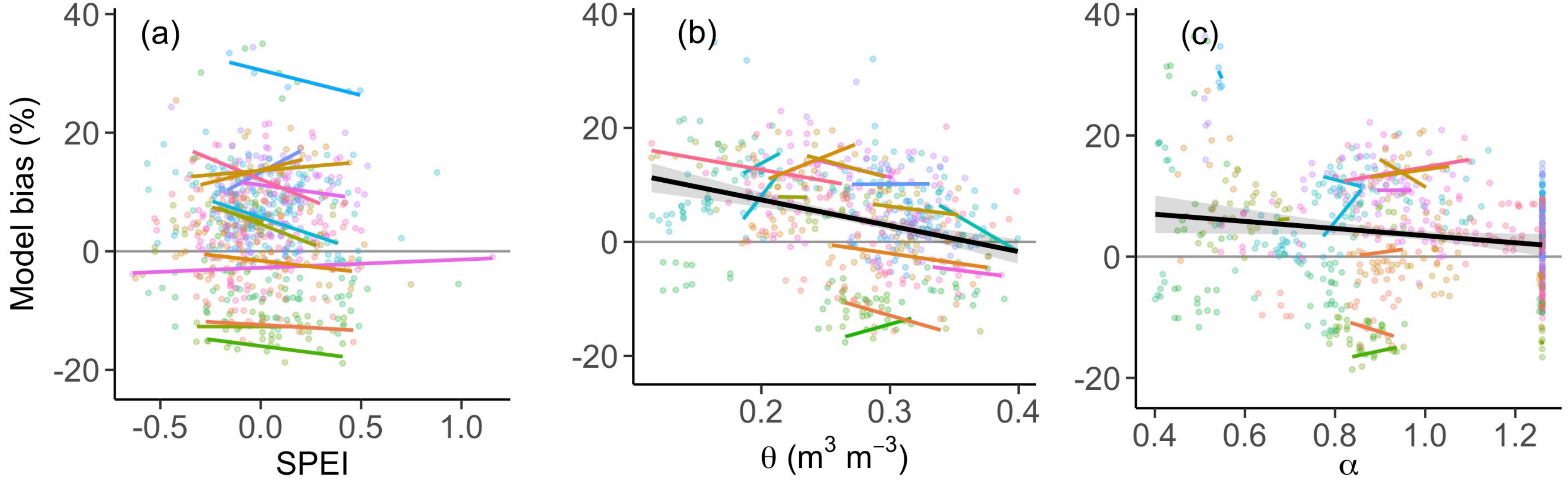
Implications for iWUE:

1. increase in iWUE with rising c_a **can be offset** by increasing mean T and decreasing VPD
2. for the same increase in CO_2, iWUE increase with decreasing P_{atm} (increasing elevation)

Optimal χ: limitations of LC theory

But LC model **does not predict how dry soils** with reduced soil water availability **further influence χ**

→ overestimation of χ under dry conditions and underestimation of χ under moist conditions (Lavergne et al. 2020 *New Phytol.*)



Standardized Precipitation-Evapotranspiration Index

ESA CCI v4.4 volumetric soil moisture

SPLASH model AET/PET*

*AET/PET = ratio of actual to potential evapotranspiration

Is β sensitive to soil water availability?

β = unit costs of carboxylation and transpiration modulated by water viscosity

Standard model: β constant (~170-190 for full model vs ~200-240 for simple model)

Questions

1) Is there any difference in the response of β to soil water between angiosperms and gymnosperms? s10
2) Can β be predicted from soil moisture data? s11
3) Does the inclusion of β as a function of soil moisture improve χ predictions compared to those from the original LC model? s12-s13

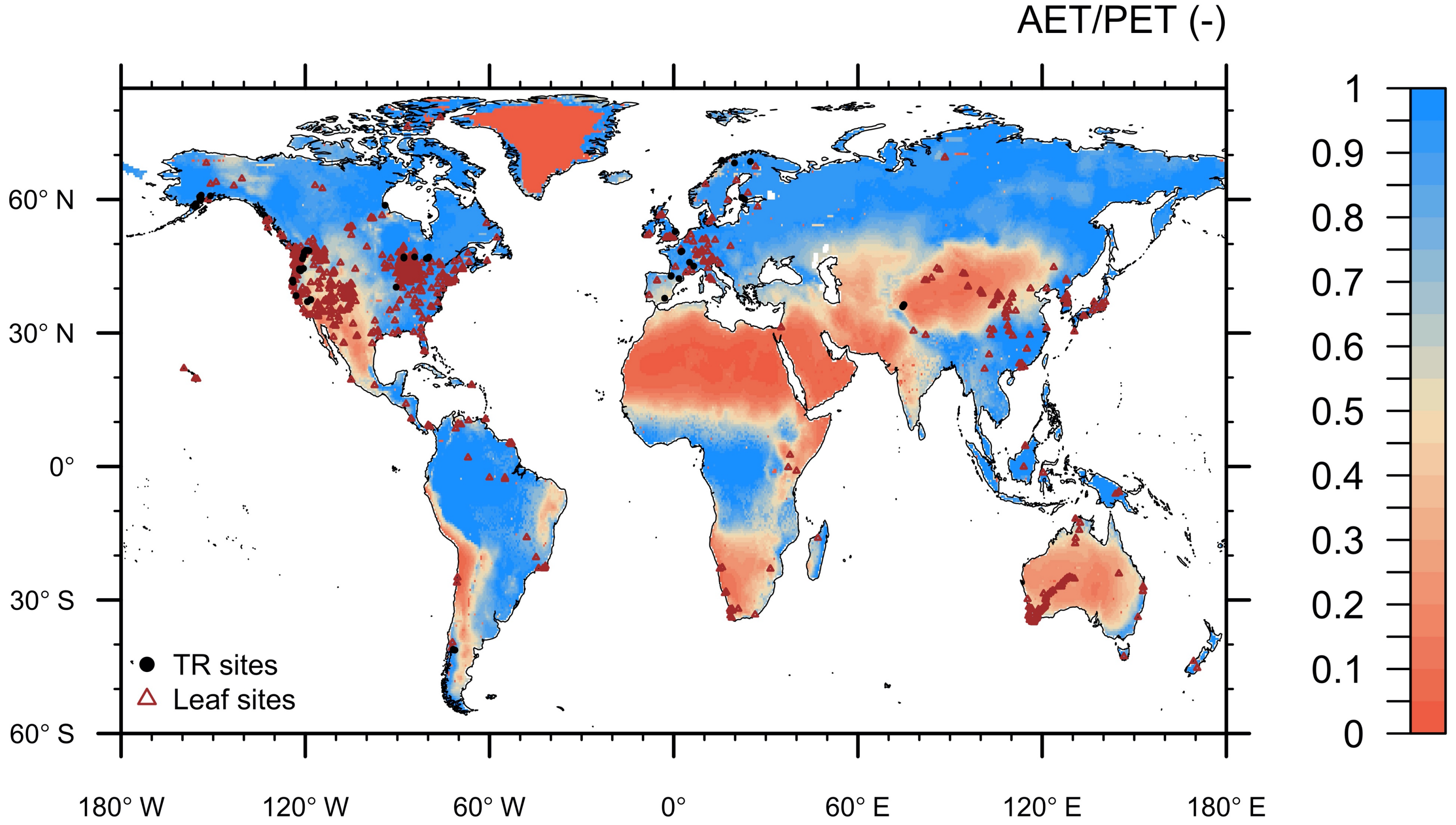
We hypothesize that:

1. $\beta_{angio} > \beta_{gymno}$ ($\chi_{angio} > \chi_{gymno}$) due to higher sapwood permeability in angiosperms
2. β decrease with reduction in soil moisture due to changes in whole plant hydraulic conductivity → decrease of χ

Lavergne et al. (submitted)

1. Compiling stable carbon isotopes ($\delta^{13}C_{plant}$) data

- **leaf level:** $\delta^{13}C_{leaf}$ for C3 woody plants from Diefendorf et al. (2010) *PNAS* + Cornwell et al. (2018) *Global Ecol. Biogeo.* + Sheldon et al. (2020) *Global Plan. Change*
- **plant level:** tree-rings $\delta^{13}C_{TR}$ at 75 sites from Lavergne et al. (2020) *New Phytol.*



*AET/PET = ratio of actual to potential evapotranspiration

2. Predicting β from χ and environmental data

χ inferred from $\delta^{13}C_{plant}$ assuming **infinite mesophyll conductance**:

$$\chi_{iso} = \frac{\left(\frac{\delta^{13}CO_2 - (\delta^{13}C_{plant} - d)}{1 + (\delta^{13}C_{plant} - d)/1000}\right) + f\,\frac{\Gamma^*}{c_a}}{b - a_s}$$

a_s = 4.4 ‰ fractionation due to diffusion of CO_2 in air
b = 28‰ fractionation due to carboxylation
f = 12 ‰ fractionation due to photorespiration
d = 2.1 ‰ post-photosynthetic fractionation (for TR only)
Γ^* and K: calculated from temperature and atmospheric pressure using parameter values at 25˚C derived from Bernacchi et al. (2001) *Plant, Cell & Env.*

LC optimality model

$$\chi = \frac{c_i}{c_a} = \frac{\Gamma^*}{c_a} + \left(1 - \frac{\Gamma^*}{c_a}\right)\frac{\xi}{\xi + \sqrt{D}} \qquad (1)$$

$$\xi = \sqrt{\beta\,\frac{K + \Gamma^*}{1.6\eta^*}} \qquad (2)$$

Expected β

$$\beta = 1.6\eta^* D\,\frac{\left(\chi_{iso} - \frac{\Gamma^*}{c_a}\right)^2}{(1 - \chi_{iso})^2 (K + \Gamma^*)}$$

+ CRU climate dataset as input: 0.5 x 0.5 spatial resolution over 1901-2018
+ Atmospheric CO_2 from SCRIPPS
+ $\delta^{13}CO_2$ from Graven et al. (2017) *Geosc. Mod. Dev.*

3. Comparing inferred β values with soil water data

soil moisture cci ~ 0.5 cm soil depth

ESA CCI v4.4 product (1979-2018)
Dorigo et al. (2017) *Rem. Sens. Env.*

gleam ~ 1 m soil depth

GLEAM v3.3a product (1980-2018)
Martens et al. (2017) *Geosci. Mod. Dev.*

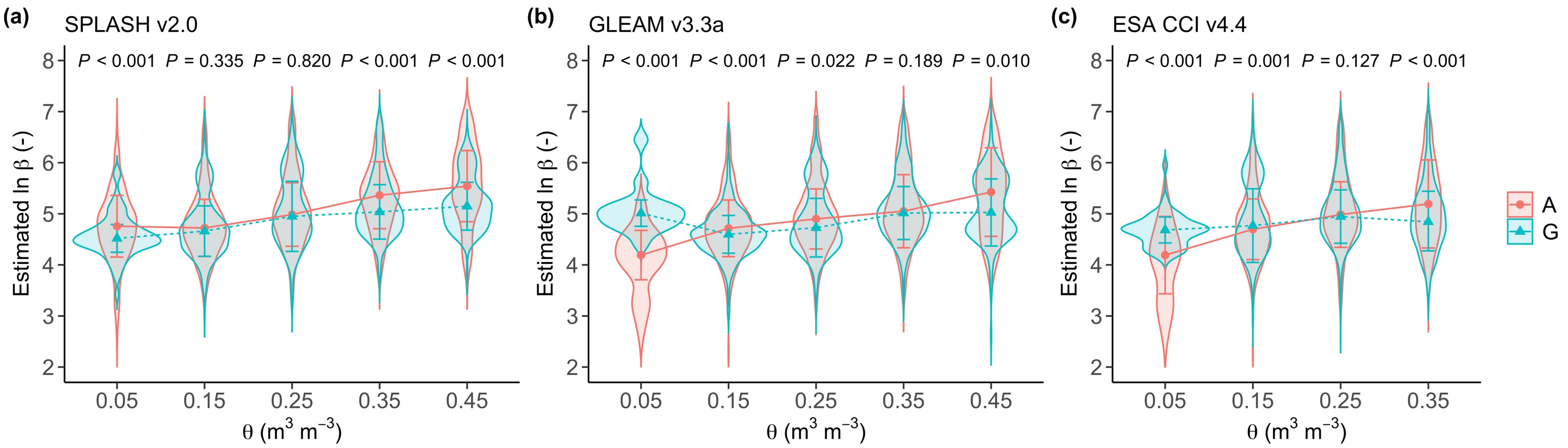
SPLASH model **1 m soil depth**
Davis et al. (2017) *Geosc. Mod. Dev.*

v2.0 from Sandoval et al. (in prep)*
https://github.com/dsval/rsplash

*see Session HS2.2.1 - 5073: https://meetingorganizer.copernicus.org/EGU2020/EGU2020-5073.html

Sensitivity of β to soil water: across plant groups

Question 1



1 m soil depth

~ 1 m soil depth

~ 0.5 cm soil depth

> 4,050 measures over 1980-2018

→Higher sensitivity of β to changes in soil water content for angiosperms than for gymnosperms

→ Crossover at around 0.35 ± 0.05 $m^3\ m^{-3}$

A: angiosperm
G: gymnosperm

Question 2

Sensitivity of β to soil water: within & across bins

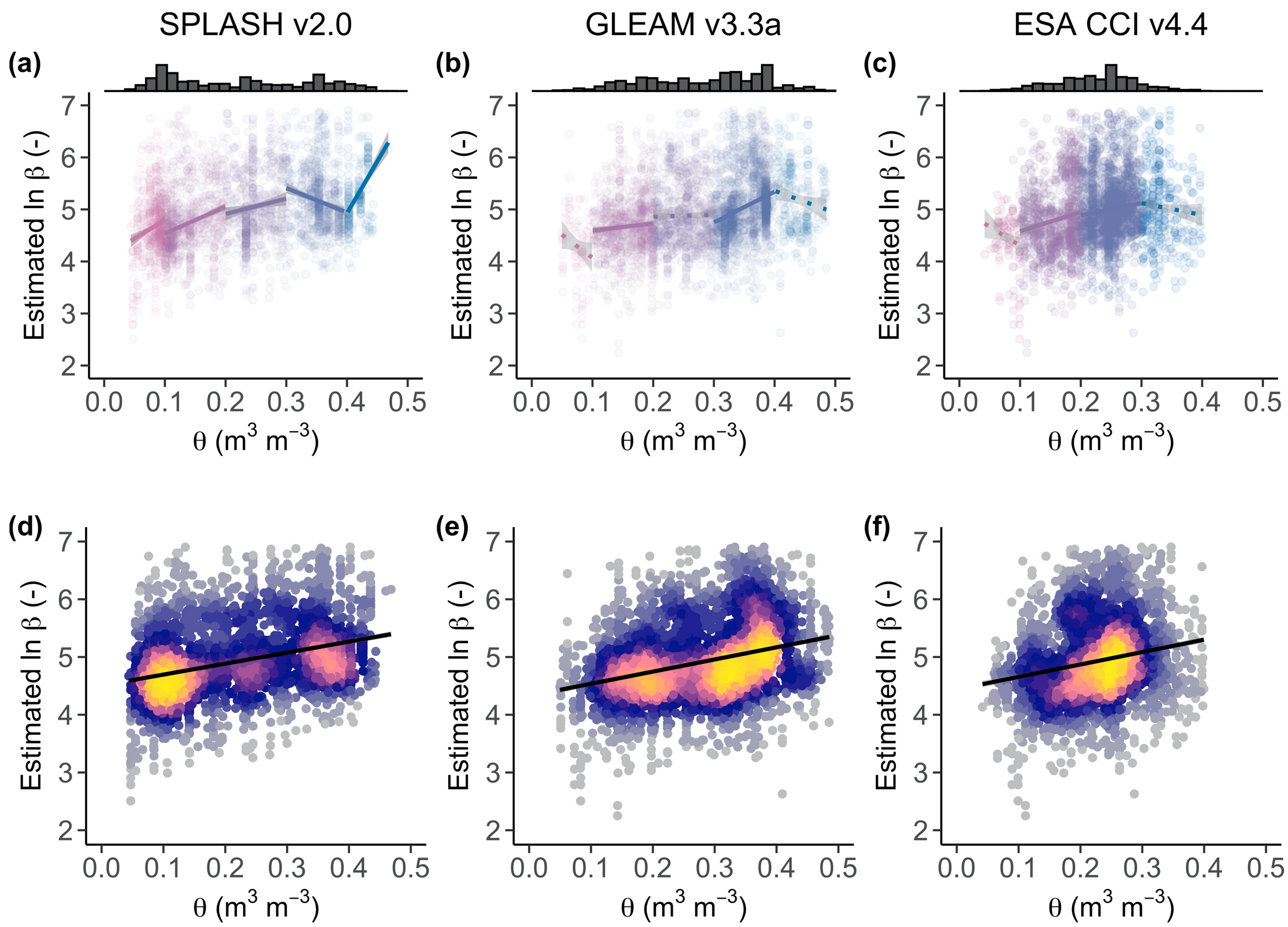
→ Increase of β within bins of soil water
Saturation at high soil moisture?

→ β increase relatively linearly over the whole range of soil water conditions

$$\ln\beta = a_\beta\theta + b_\beta$$

a_β= 2.0 ± 0.1

b_β= 4.4 ± 0.1

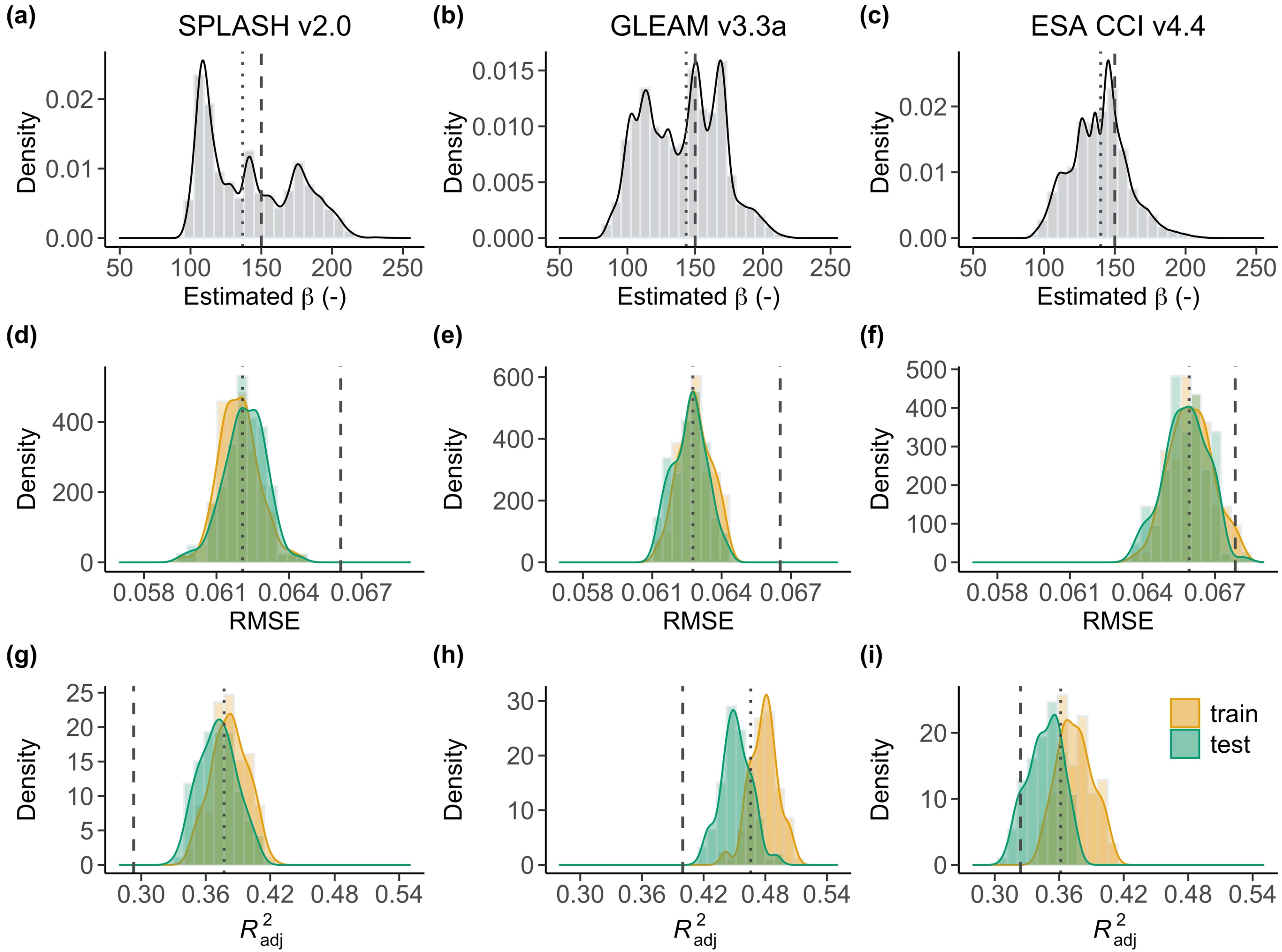


Question 3

Predicting β with soil moisture: calibration

Cross-validation tests:
100 training/testing subsets

Bootstrapping (100 replicates)



⋯⋯ Median values for modified model

– – – Original model

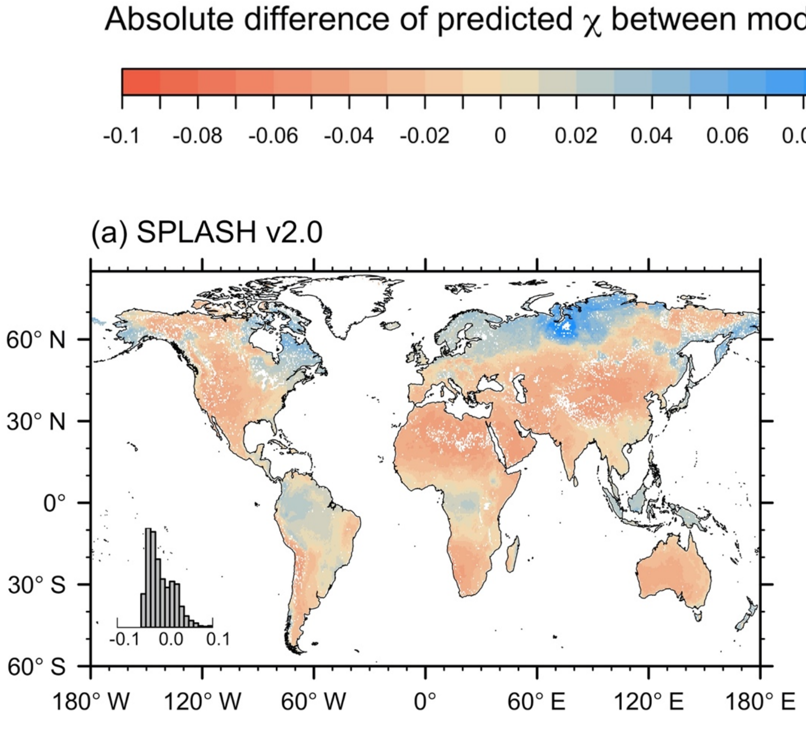
RMSE = root mean square error

R^2_{adj} = adjusted R^2

→ Higher predictive skill for the modified than for the original models

Optimal χ: modified versus original LC model

Modified - original model

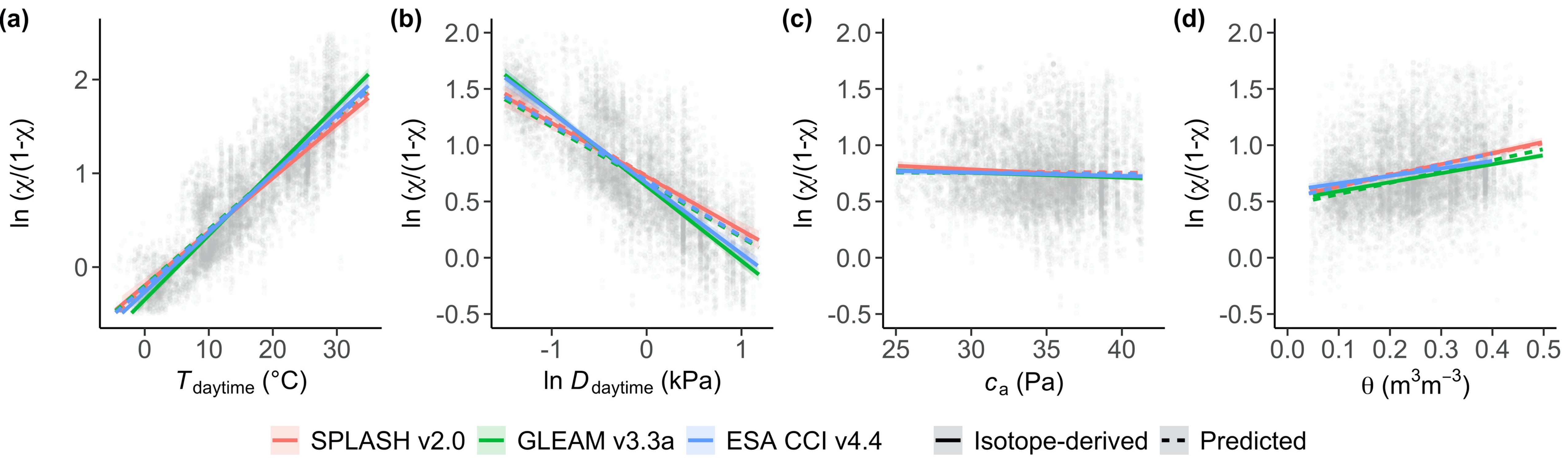


→ Soil moisture effect reducing on average predicted χ values by 1.4 $\pm$ 3.9% over the globe

→ **But** higher predicted χ values in modified than in original model in dense vegetation areas (e.g., boreal or tropical rainforests)

Optimal χ: environmental dependencies

Partial residual regressions of isotope-derived and predicted χ with environmental drivers



→ Good predictions of environmental dependencies from LC model

→ Larger effects of temperature and vapor pressure deficit on χ

Towards an improvement of optimal χ predictions

- Only **partial support for our first hypothesis**: $\beta_{angio} > \beta_{gymno}$ solely under well-watered upper- to mid-soil conditions

- Higher sensitivity of β to soil water for angiosperms than for gymnosperms

  → **contrasting trait-based hydraulic strategies** for the two plant vascular groups: larger diameter of xylem conduits / narrower hydraulic safety margins / lower water potential for angiosperms than for gymnosperms **maximizing hydraulic conductance of angiosperms**

- Simple empirical function for β to represent χ responses to soil drought improving predictions by 6.2 ± 2.4% (mean ± sd of adjusted R^2) over 1980-2018

- **But approach** does not provide insights into underlying processes → need to incorporate plant hydraulics and information about trait-environment dependencies into the model*

*see Jadeep Joshi presentation beyond the 'β approach' Session BG3.6: https://meetingorganizer.copernicus.org/EGU2020/EGU2020-9687.html

Thank you

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More information:
a.lavergne@imperial.ac.uk

github.com/Alielav

Twitter: @AlienorLavergne

http://www.imperial.ac.uk/people/a.lavergne
http://www.sp.ph.ic.ac.uk/~hgraven/people.html
https://prenticeclimategroup.wordpress.com/lab-members/

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