Predicting eco-evolutionary adaptations of plants to drought and rainfall variability

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Part 1

The P-hydro model of plant photosynthesis and hydraulics

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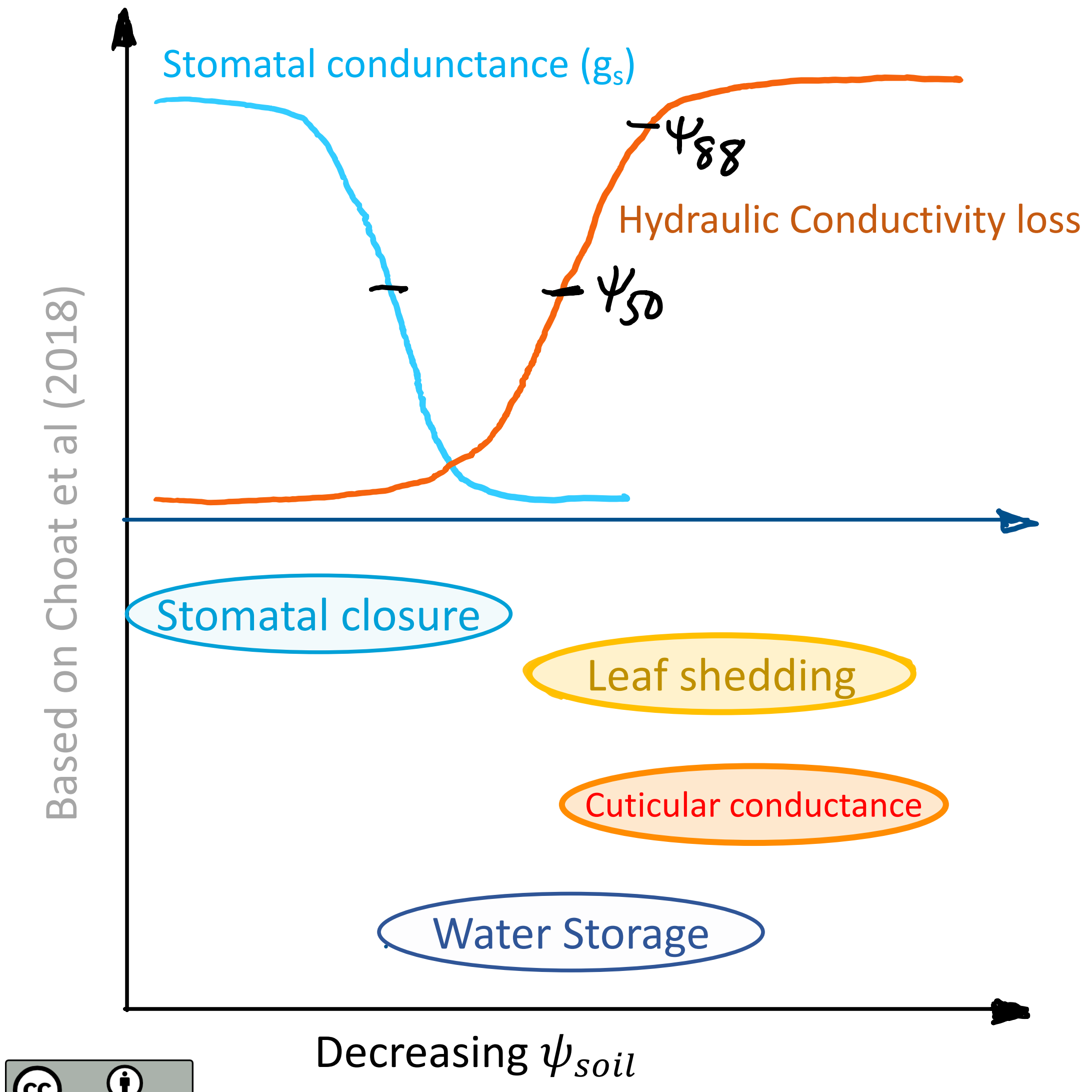
Need a unified theory to explain plant responses to soil moisture

1. Decline of GPP and transpiration with decreasing soil moisture (Stocker et al, 2018)
2. Short term decline of V_{cmax} with soil moisture (Zhou et al 2013, 2014) and subsequent recovery (Zhou et al 2017)
3. Linear relationship between logit(c_i/c_a) and log(D) with a slope of -0.76 ± 0.15 (Dong et al., 2020)
4. Stomatal closure before substantial xylem embolism (Choat et al 2018)
5. Global convergence towards low hydraulic safety margins (Choat et al 2012)
6. Differential (trait-dependent) response of different species to soil moisture (Isohydric – Anisohydric spectrum)

Don't forget to see notes for more information.

Assimilation and drought response - timescales



Variable (Regulating process)	Time scale
g_s, c_i/c_a (Stomatal regulation)	Seconds - hours
Jmax, Vcmax (Biochemical acclimation)	Weeks
Huber Value (Whole plant acclimation)	Months

Proposed theory of water limited photosynthesis

Principles *(building upon Prentice et al (2014) and Wang et al (2017)):*

1. **Water balance:** Water supply from stem equals atmospheric demand from leaves

$$-\frac{K_0 \nu_H}{H\eta}\int_{\psi_s}^{\psi_s-\Delta\psi} P(\psi)\,d\psi = 1.6 g_s D \qquad P(\psi) = 0.5^{\left(\frac{\psi}{\psi_{50}}\right)^b}$$

2. **Photosynthetic coordination**: Carboxylation capacity (V_{cmax}) and electron transport ($J_{\max}$) capacity are coordinated

$$V_{\mathrm{cmax}}\frac{c_i-\Gamma^*}{c_i+K} = \phi_0 I_{\mathrm{abs}}\frac{1}{\sqrt{1+\left(\frac{4\phi_0 I_{\mathrm{abs}}}{J_{\max}}\right)^2}}\frac{c_i-\Gamma^*}{c_i+2\Gamma^*}$$

3. **Profit Maximization**: Plants optimize $J_{\max}$ and $\Delta\psi$ such that the net assimilation is maximized

$$A-\alpha J_{\max}-\gamma\Delta\psi^2 = \max$$

Testing the model

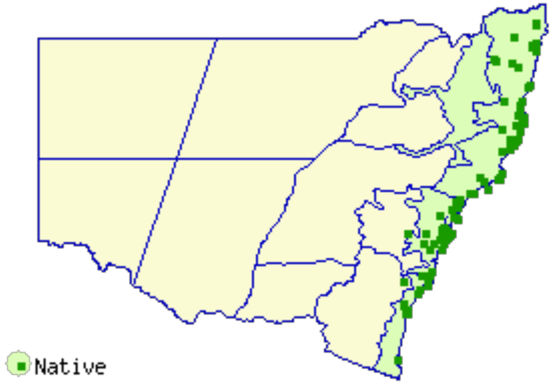
Meta-analysis of published drydown experiments

- Data from 18 species spanning diverse plant functional types
  - Gymnosperms 2
  - Malacophyll angiosperms 3
  - Schlerophyll angiosperms 9
  - Shrubs 2
  - Herbs 2
- Progressive soil drydown under otherwise natural conditions (in glasshouses)
- Data:
  - Triplets of Assimilation rate, stomatal conductance, predawn leaf water potential: $\{A, g_s, \psi_s\}$.
  - Leaf water potentials for some species

Drought response of two Eucalyptus species

Eucalyptus pilularis

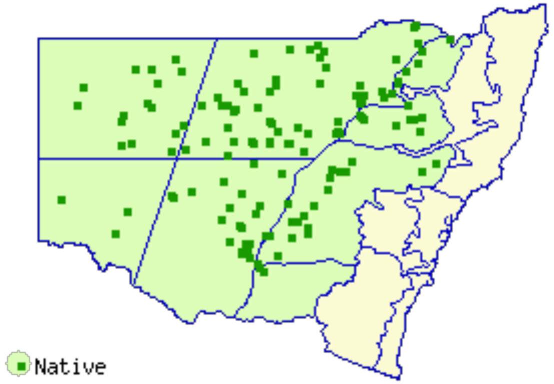
Widespread and often dominant, in wet sclerophyll or grassy coastal forest (PlantNET)



Peter Woodard

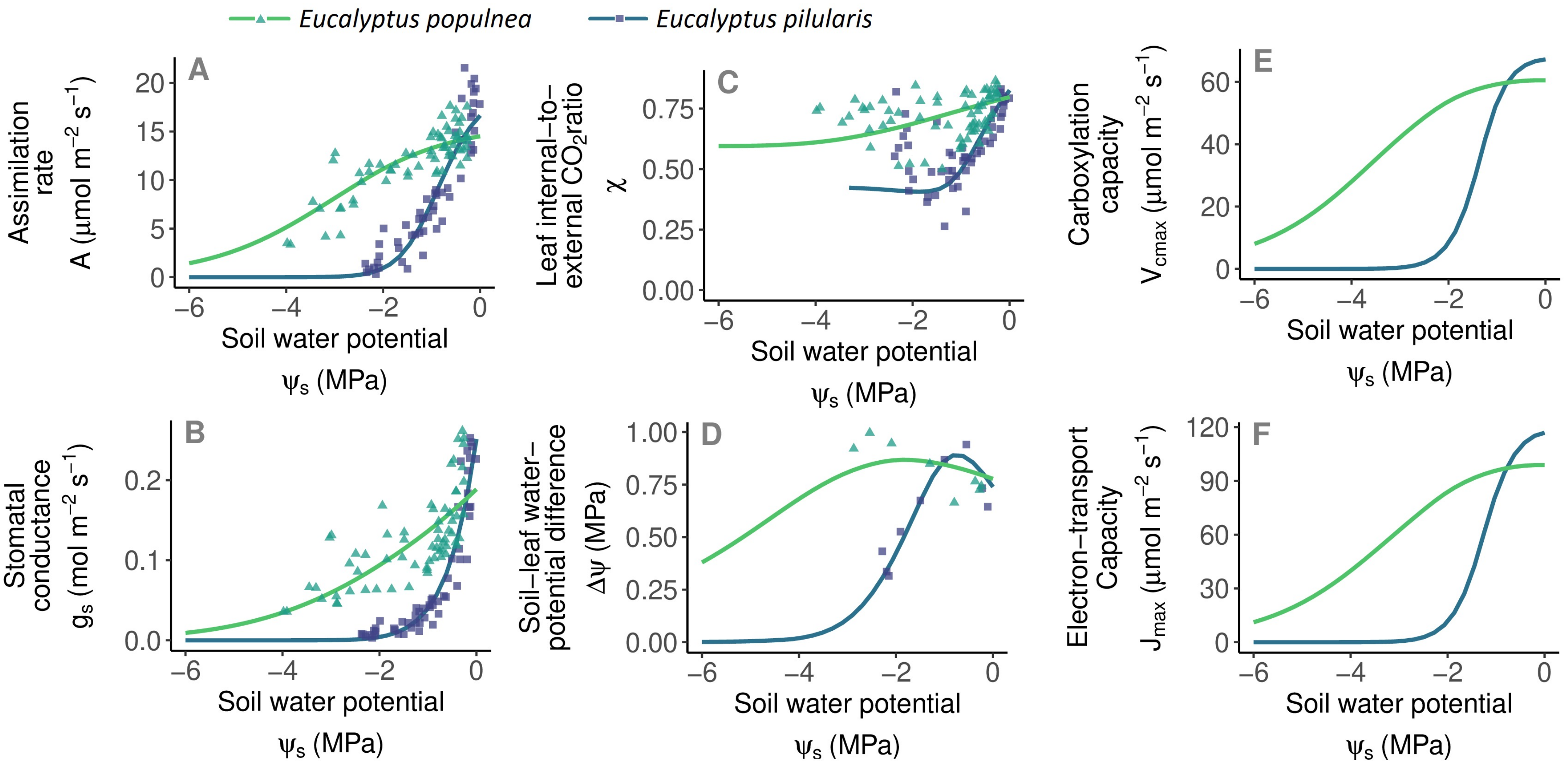
Eucalyptus populnea

Widespread, often dominant, in grassy semi arid climates

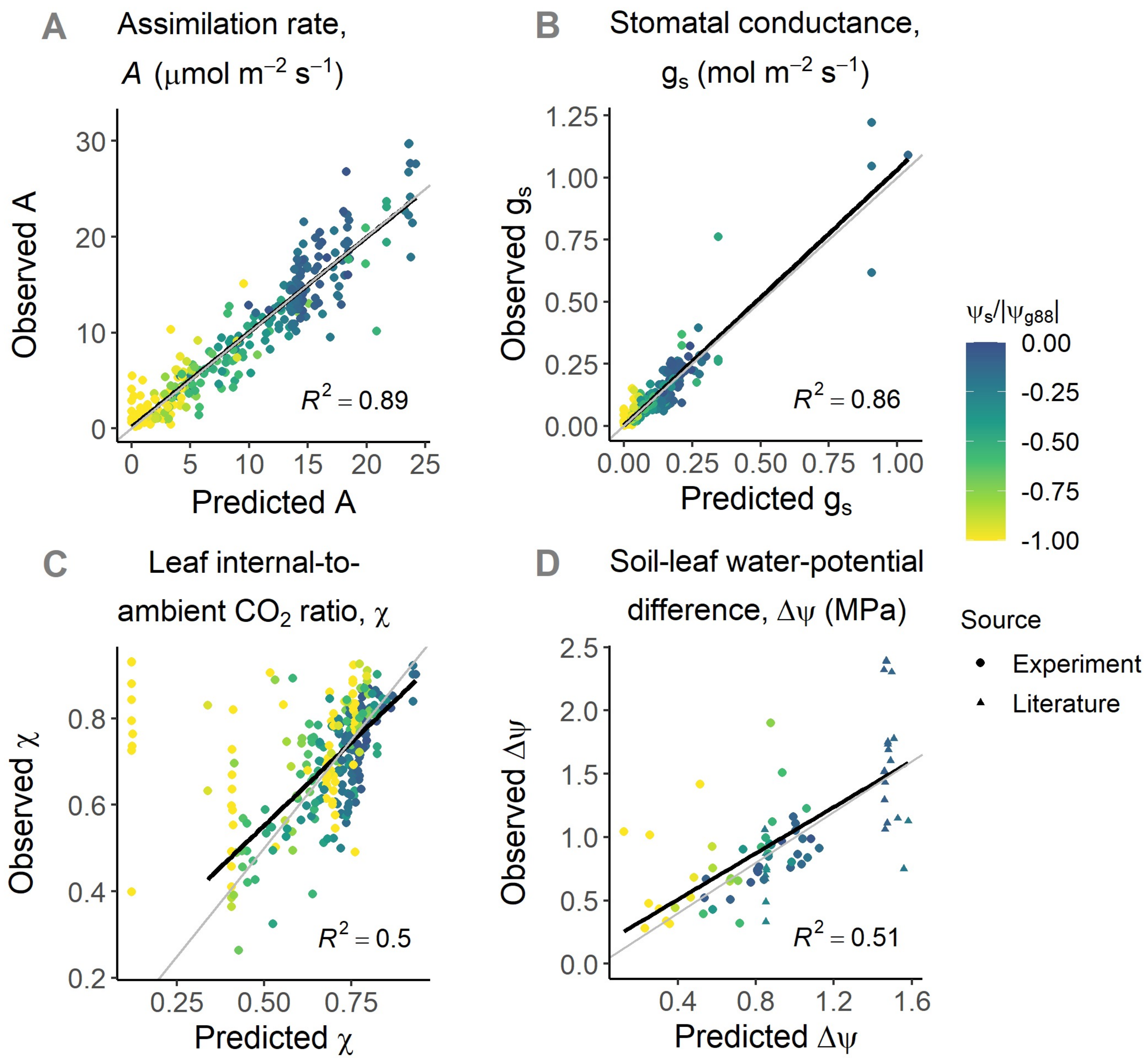


Ethel Aardvark

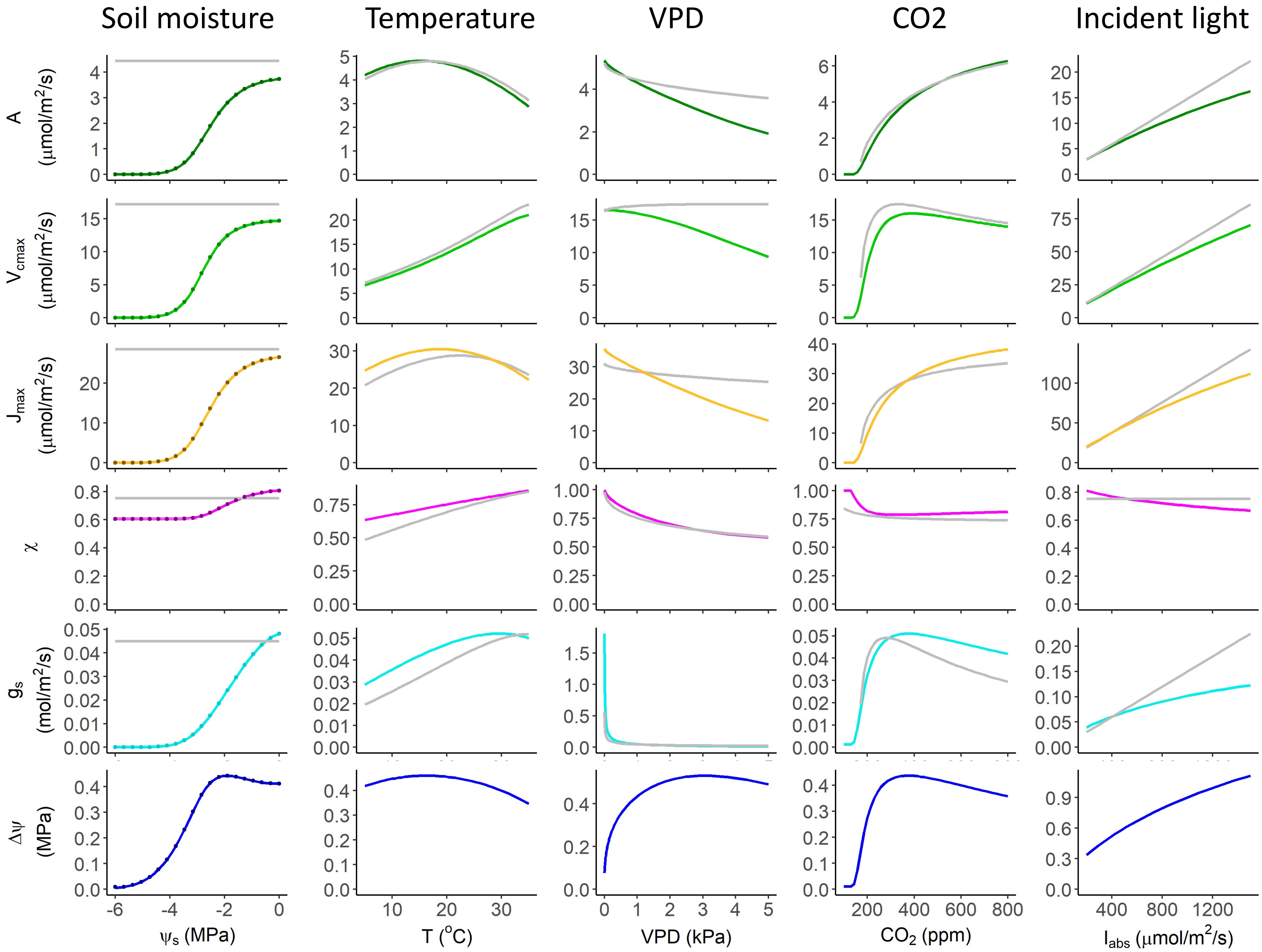
Drought response of two Eucalyptus species



Predictions vs observations for all 18 species



Responses to environmental variables



Grey – Wang et al. (2017)

Coloured – This study

Summary

- We use the optimality framework to develop a unified model of plant photosynthesis and hydraulics
- The model requires hydraulic traits and two parameters to predict photosynthetic responses to the environment at multiple timescales
- The model accurately predicts responses of assimilation, ci, Vcmax, Jmax, gs, and leaf water potential under a wide range of atmospheric conditions

Part 2

Predicting hydraulic adaptations with an eco-evolutionary vegetation model
(Proof of concept analysis)

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Trait-height-patch structured vegetation model

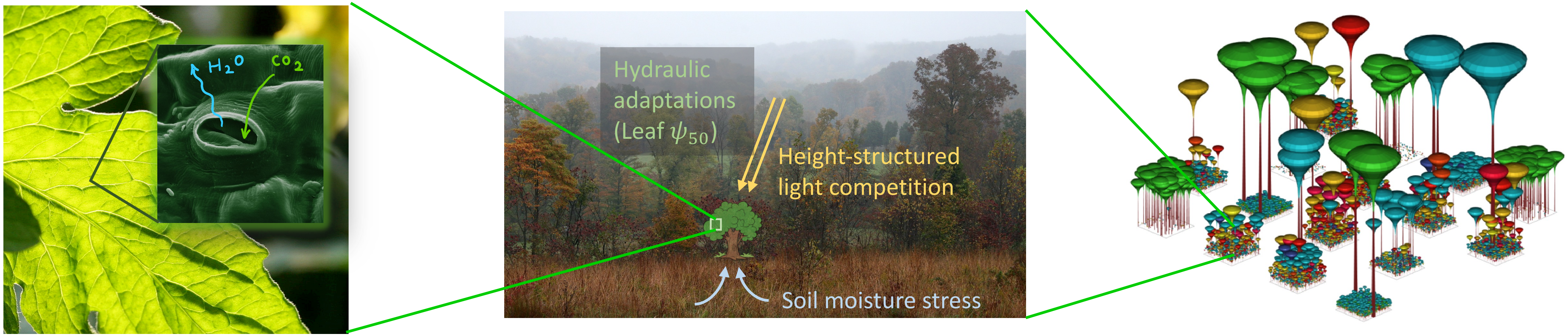
Photosynthesis, growth, response to water stress

(P-Hydro Model; Joshi et al. preprint)

Competition for light and water, mortality and seed production

Patch structure, succession, disturbance; Adapted communities

(Plant-FATE Model based on Falster et al. 2011, 2017)



Days - Months

Years - Decades

Centuries - Millenia

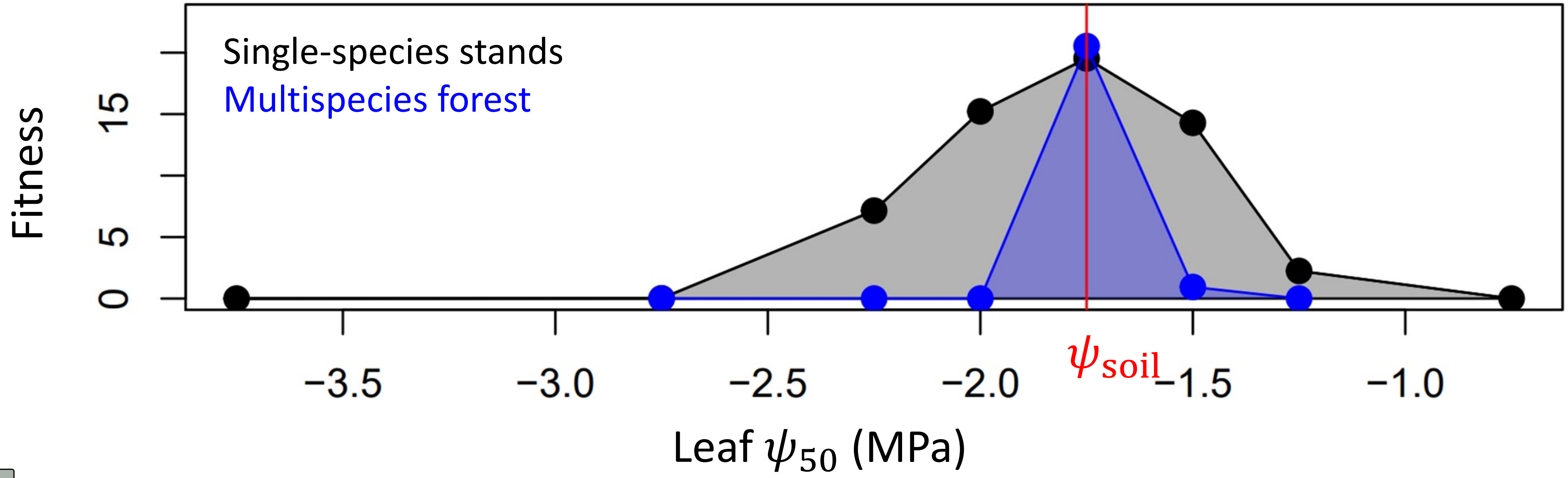
Image Credits: Muffet, Huw Williams, Falster et al. (2017)

Proof of Concept: Modelling the evolution of leaf hydraulic capacity

- Species defined by Leaf-ψ_{50} (related to turgor loss point)
- Costs and benefits of ψ_{50}
  - **Benefits**: High ψ_{50} = ability to keep stomata open during drier soil conditions
  - **Costs**: High ψ_{50} = Added costs of leaf construction and maintenance
- Effects of ψ_{50} in the Plant-FATE model:
  - Additional term $\sim\psi_{50}^2$ in leaf respiration to account for costs
  - P-Hydro accounts for ψ_{50}-dependent stomatal responses
- Model inputs
  - Soil water potential ψ_{soil} set at -1.75 MPa
  - T = 25 ^{o}C, VPD = 1 kPa, PPFD = 1000 μmol m^{-2}s^{-1}
  - Other traits: LMA = 0.18 kg m^{-2}, K = 1e-16 m

ψ_{50} adapts to prevailing soil moisture regime

- Species with ψ_{50} = ψ_{soil}
  - has greatest fitness (seed production rate) in single-species stands
  - Outcompetes all others in a multispecies forest



Summary and next steps

- **Summary**: We showed how a multispecies eco-evolutionary vegetation model can be used to predict adaptations of Leaf ψ_{50} to prevailing moisture regimes

- **Next steps**
  - Use adaptive dynamics to predict evolved trait mixtures
  - Allow LMA and ψ_{50} to coevolve
  - Model plant mortality from xylem cavitation to predict evolution of xylem-ψ_{50} and hydraulic safety margins

Thank you!