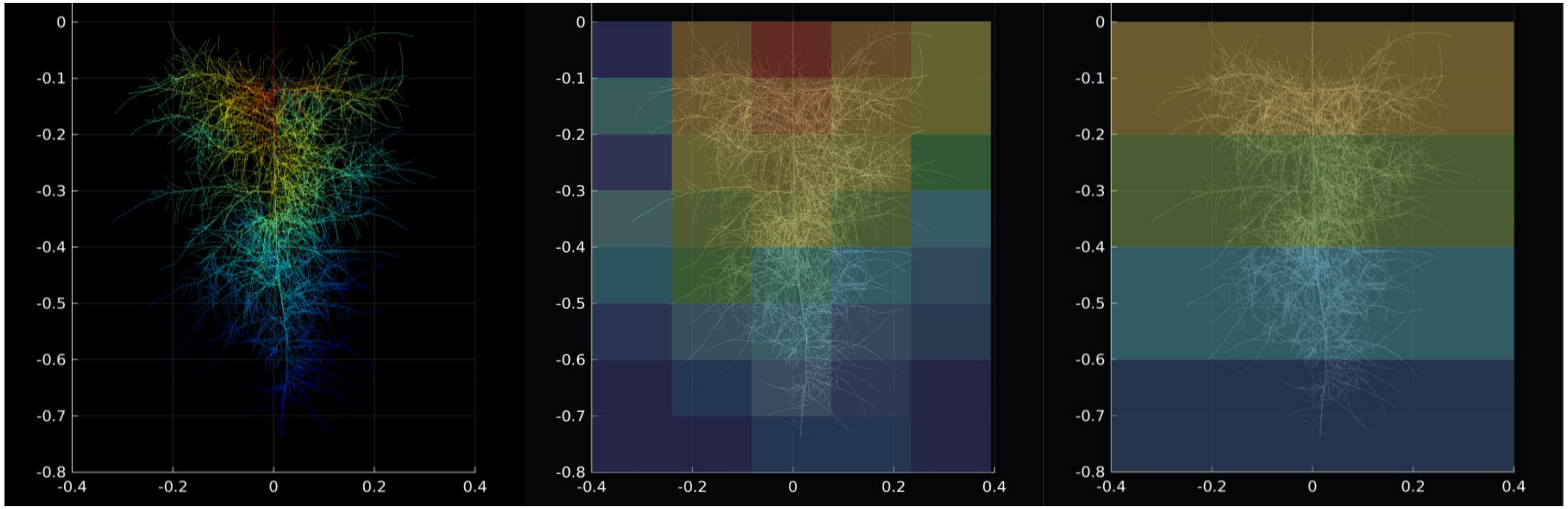
Predicting plant water limitation in heterogeneously drying soils:

the upscaling approach to improving soil-plant hydrodynamics in ESMs



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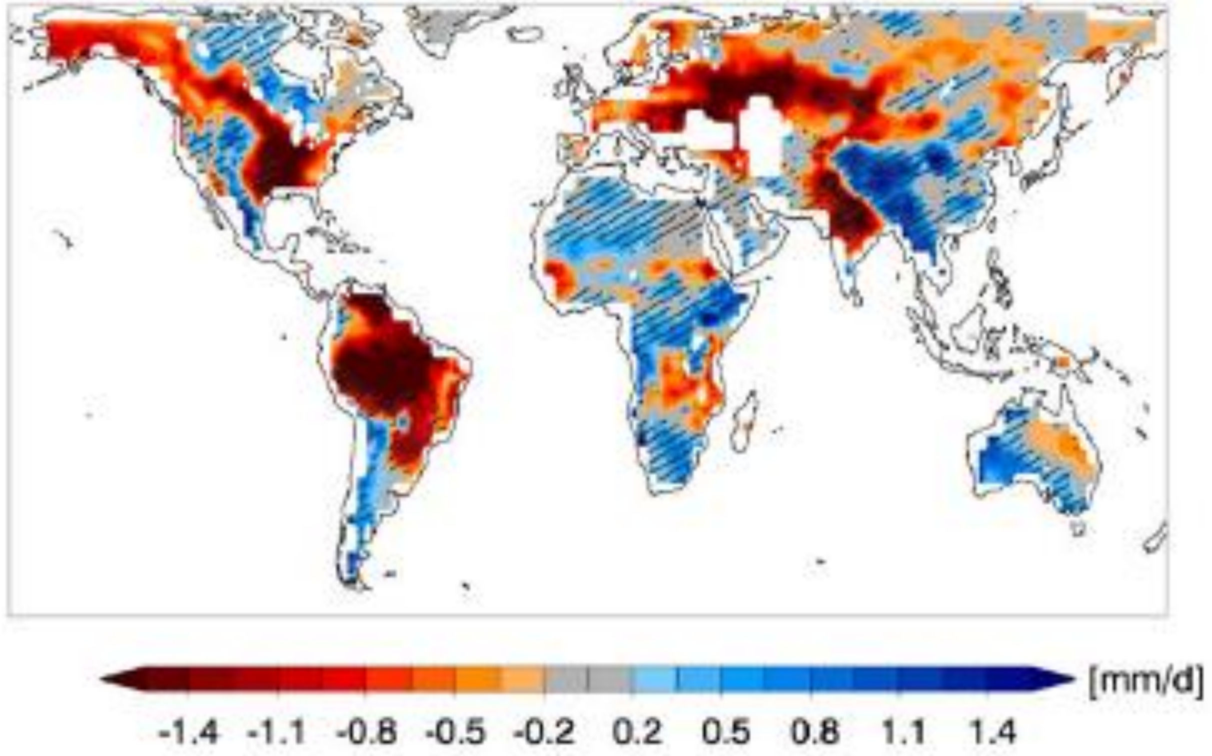
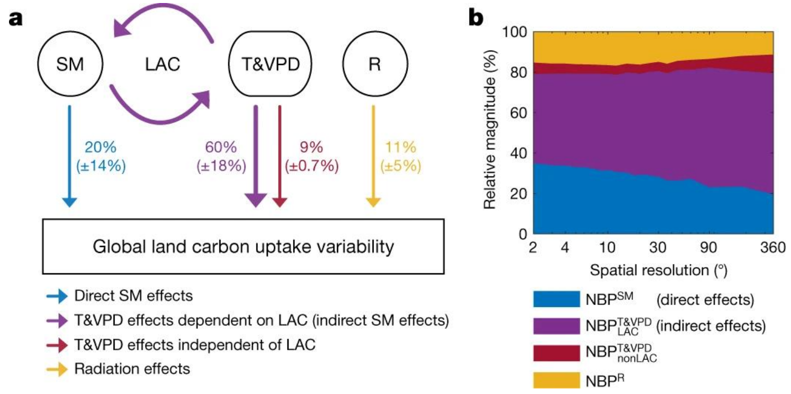
Predicting ET & soil moisture is important, but we’re not always great at it.

Prediction bias in IPCC model evapotranspiration



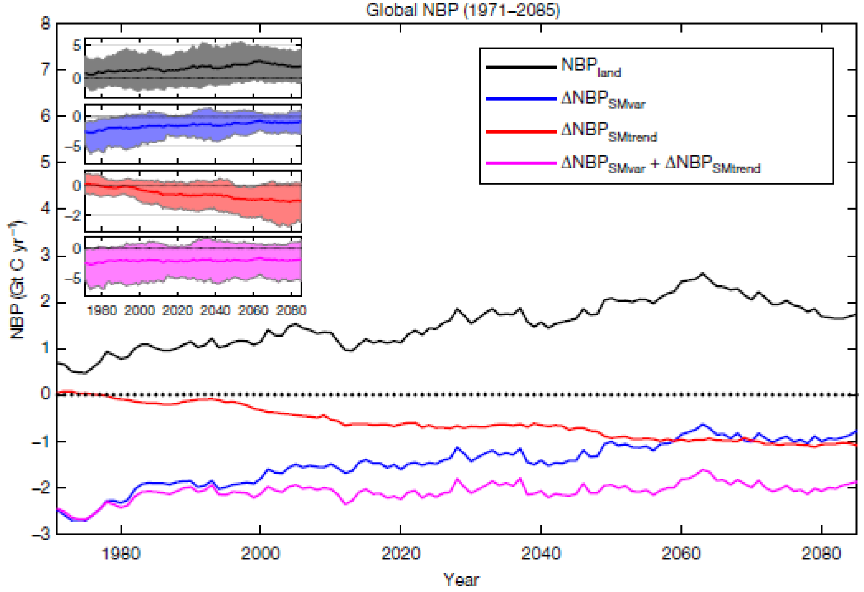
Mueller & Seneviratne (2014) Geophys Res Lett 41:128-134.

80% of interannual land carbon sink variability



Humphrey et al. (2021) Nature 592:65-69.

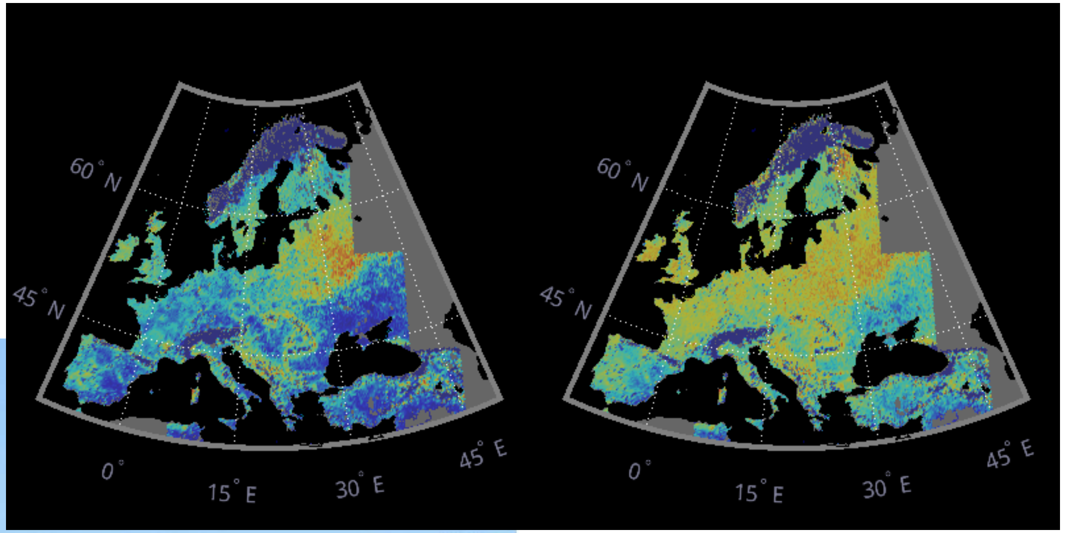
90% of land carbon sink uncertainty



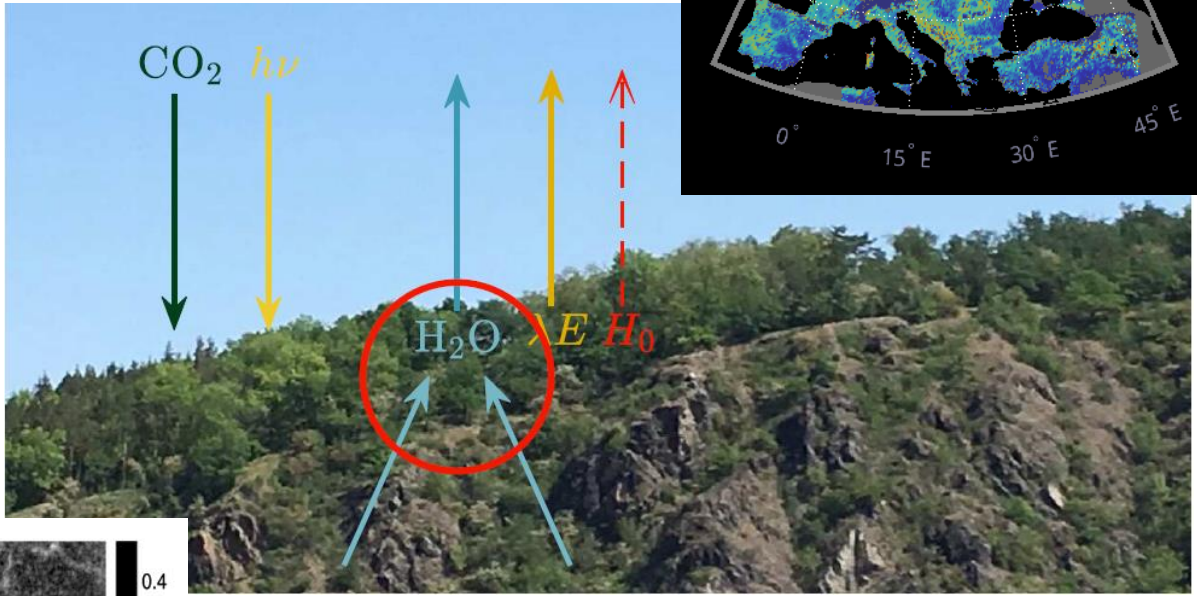
Lawrence et al. (2019) Nature 565:476-479.

Mismatched scales of cause and effect

Earth system processes (e.g. carbon cycle)
100+ km

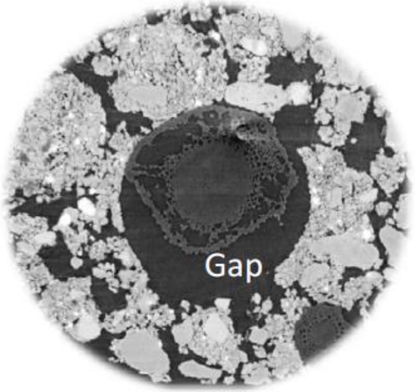


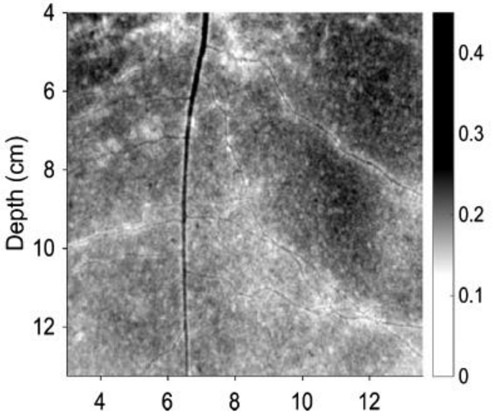
Land-atmosphere feedback:
10m-10km



Integrates to

Root Water Uptake: mm-m

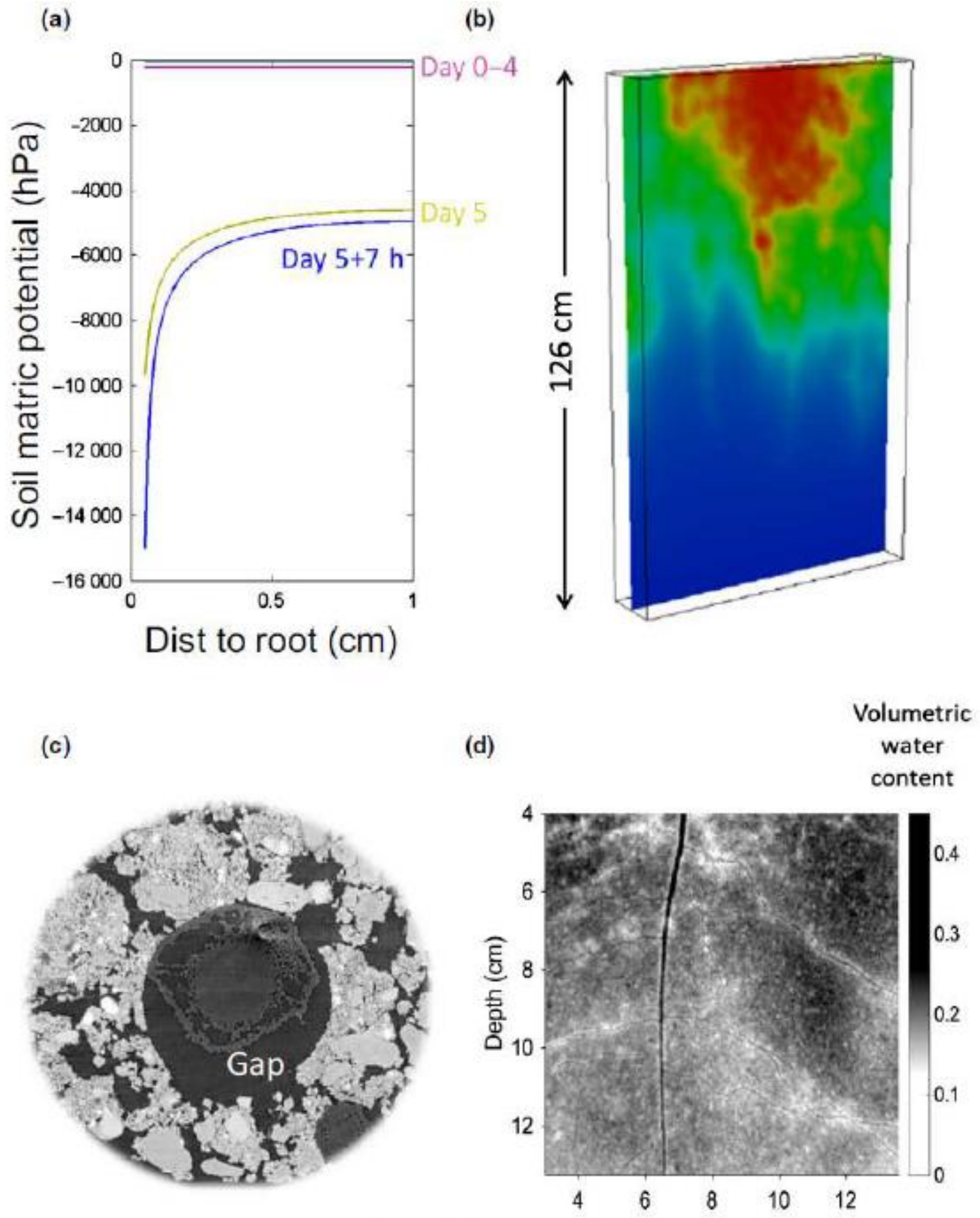




Limits

Carminati et al. (2020) New Phytol. 226: 1541-1543.

Soil Moisture Heterogeneity



Carminati et al. (2020) *New Phytologist* 226(6):1541-1543.

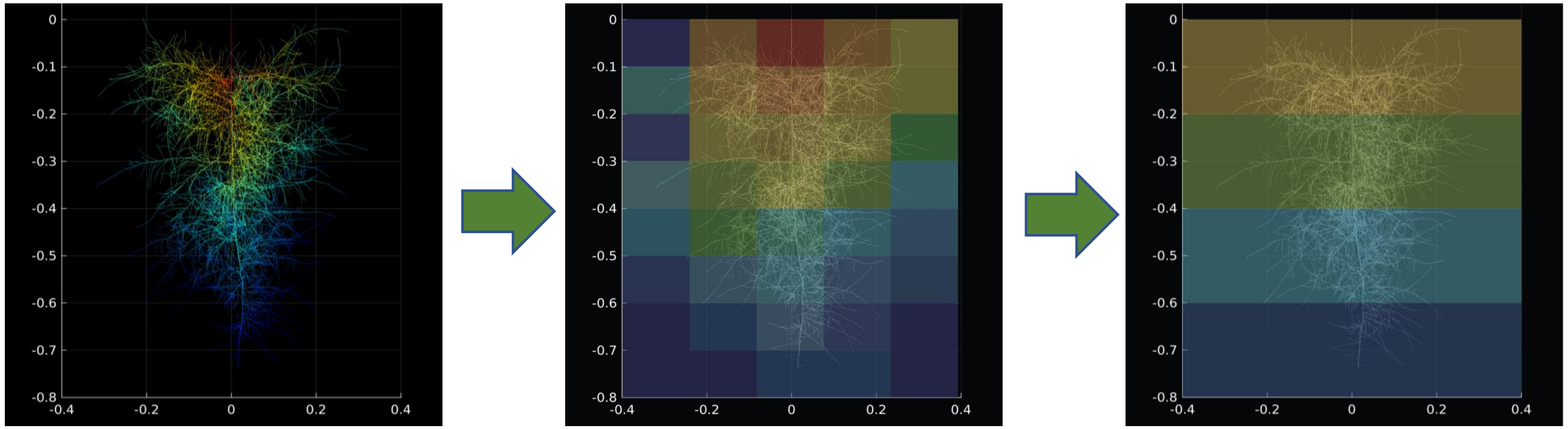
- Plant water uptake
  is faster than
  soil water flow.
- So:
  - Soil dries locally around absorbing roots.
  - Soil dries fastest at depths where plants are taking up

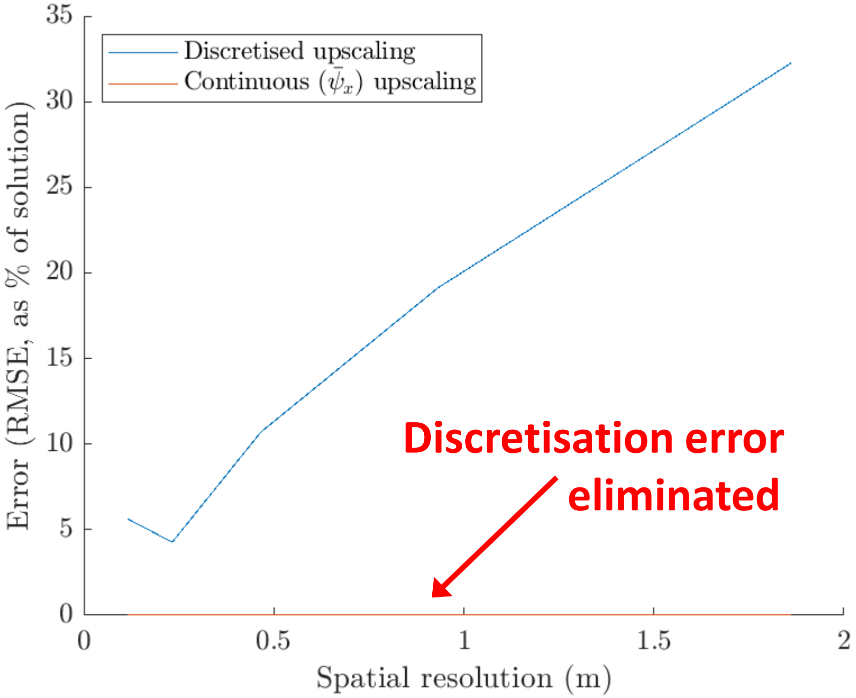
  → vertical heterogeneity & compensating flow
  - Hydraulic conductivity drops nonlinearly in drying soil

  → horizontal heterogeneity & plants cut off

Vertical heterogeneity: Upscaling root-soil hydrodynamics

Full 3D solution | Arbitrary soil blocks | Layers for Earth System Model





Code for general algorithm available at https://github.com/mbouda/genUpscAlg

Given analytical solutions to flow equation:

$$\frac{\partial^2 \psi_x}{\partial s^2} = -\frac{K_r}{K_x}(\psi_x - \psi_s)$$

In terms of mean water potential on root segments:

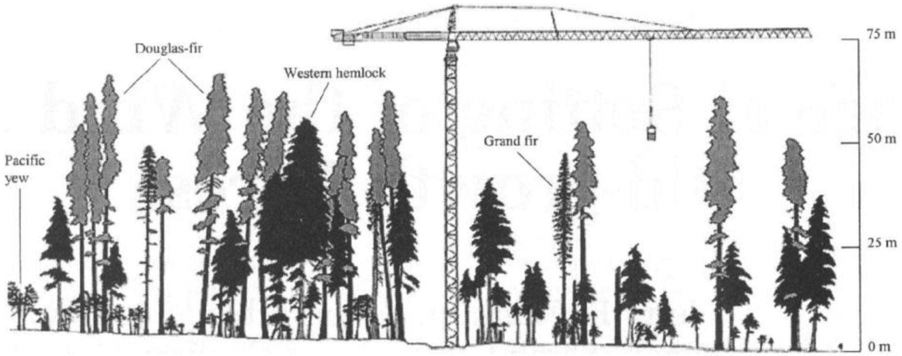
$$\bar{\psi}_x = \frac{\int_0^L \psi_x(s)\, ds}{L}$$

Linear system representing network can be simplified to solve exactly for means in soil regions:

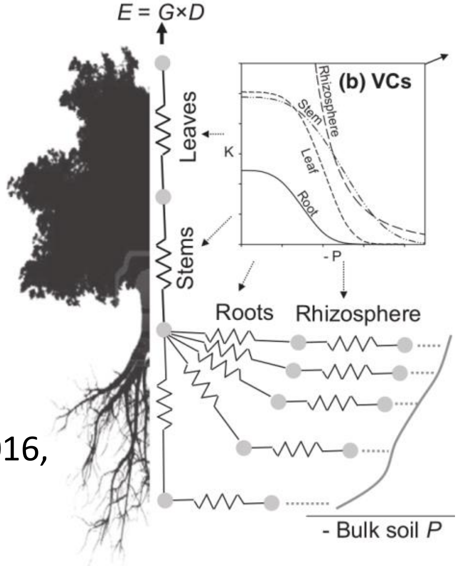
$$\hat{\psi}_x = \frac{\sum_1^n K_r L\, \bar{\psi}_x}{\sum_1^n K_r L}$$

Result: **exact solutions** to continuous flow equations **at any scale**

Proof of concept at site scale (Wind River Crane)



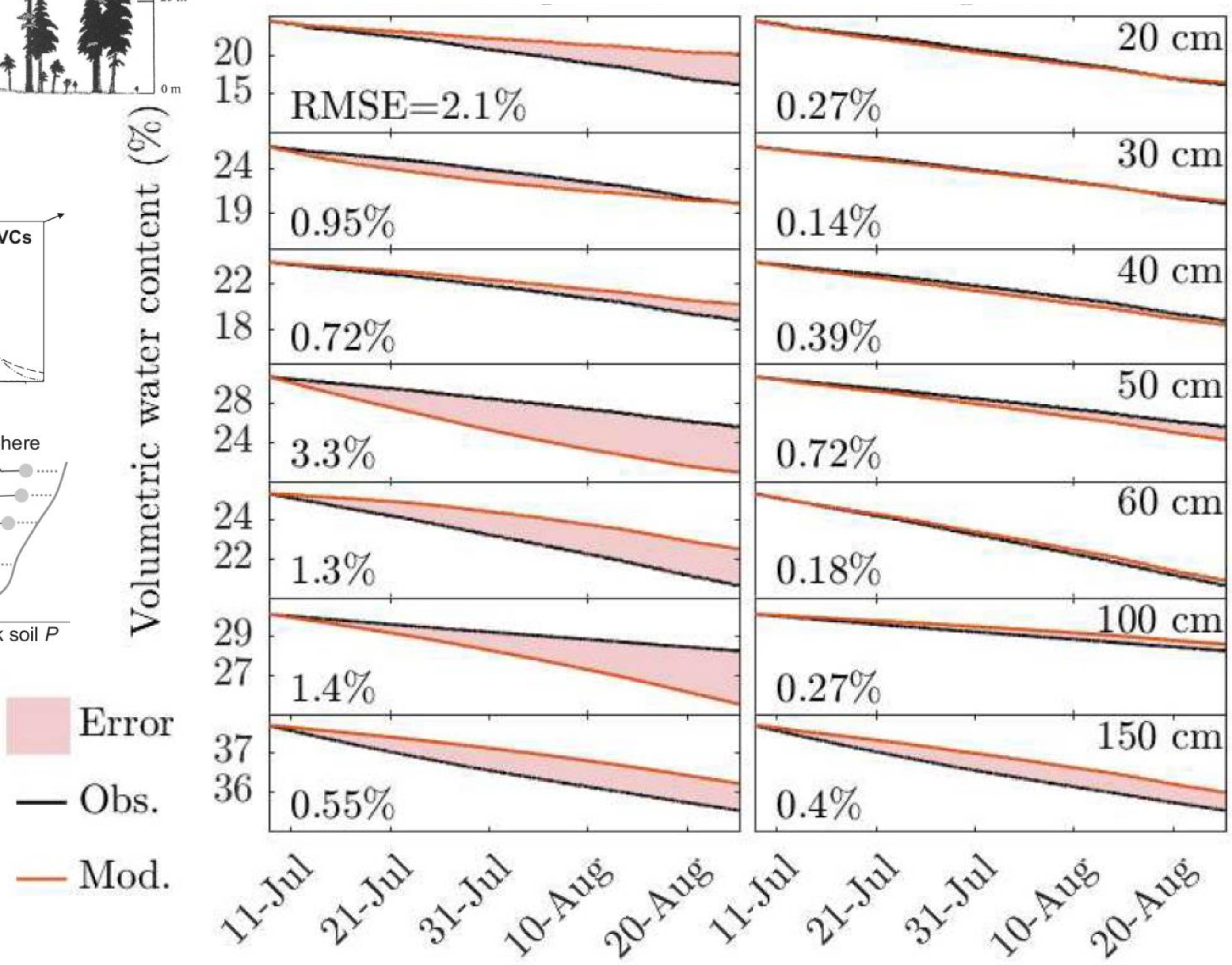
Shaw et al., 2004, Ecosys. 7:427–439.

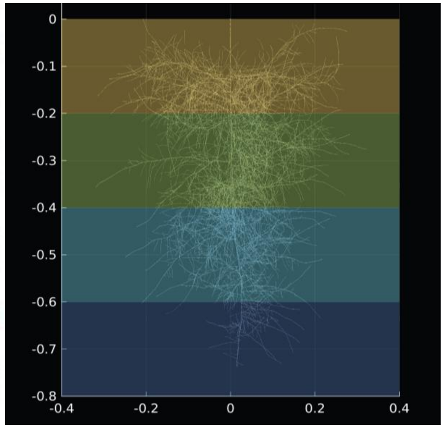


Sperry et al., 2016, New Phytol 212(3):577-589

Discretised parallel

Upscaling Model

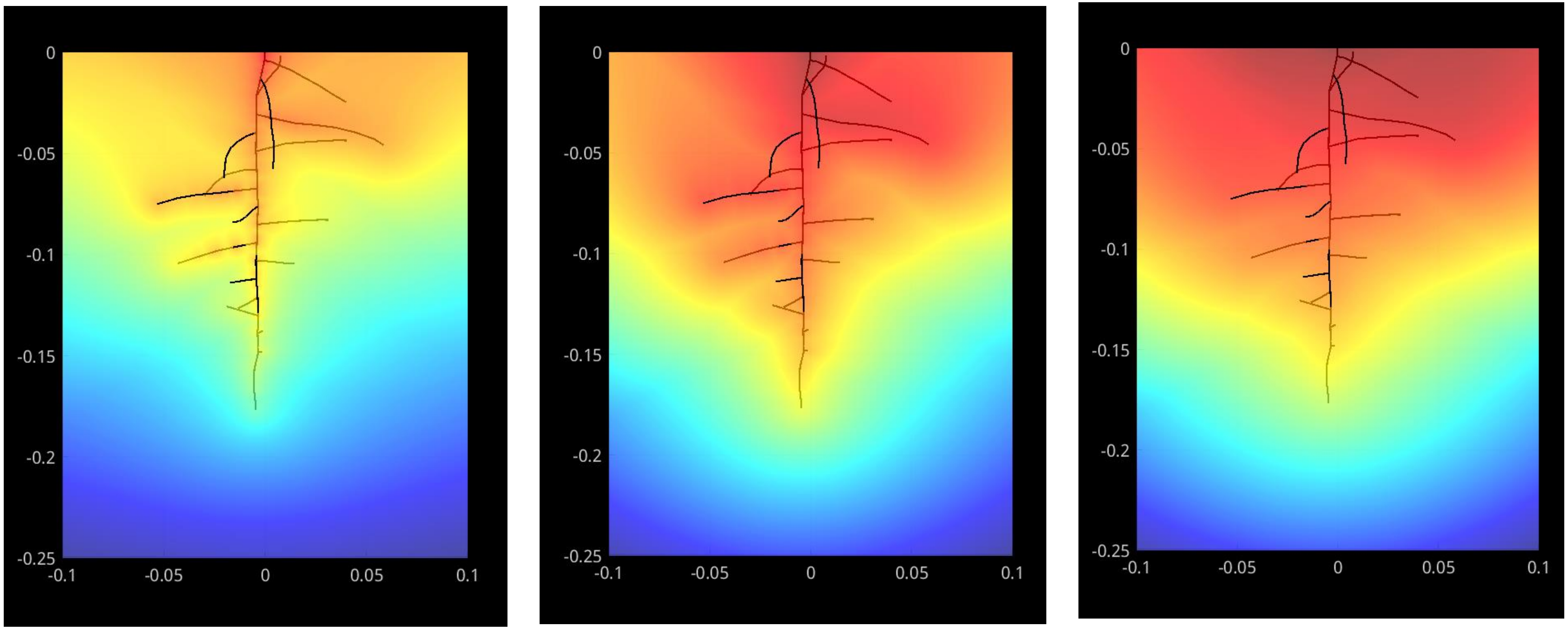




Parameters obtained by inversion

Bouda (2019) J. Adv. Mod. Earth Sys. 11:4597–4613.

Horizontal heterogeneity: requires integration with soil description



Considering soil blocks with non-uniform ψ_s…

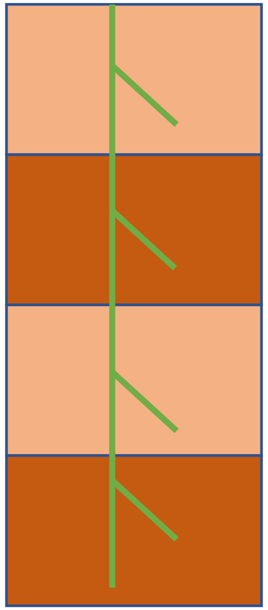
Define a weighted mean soil water potential

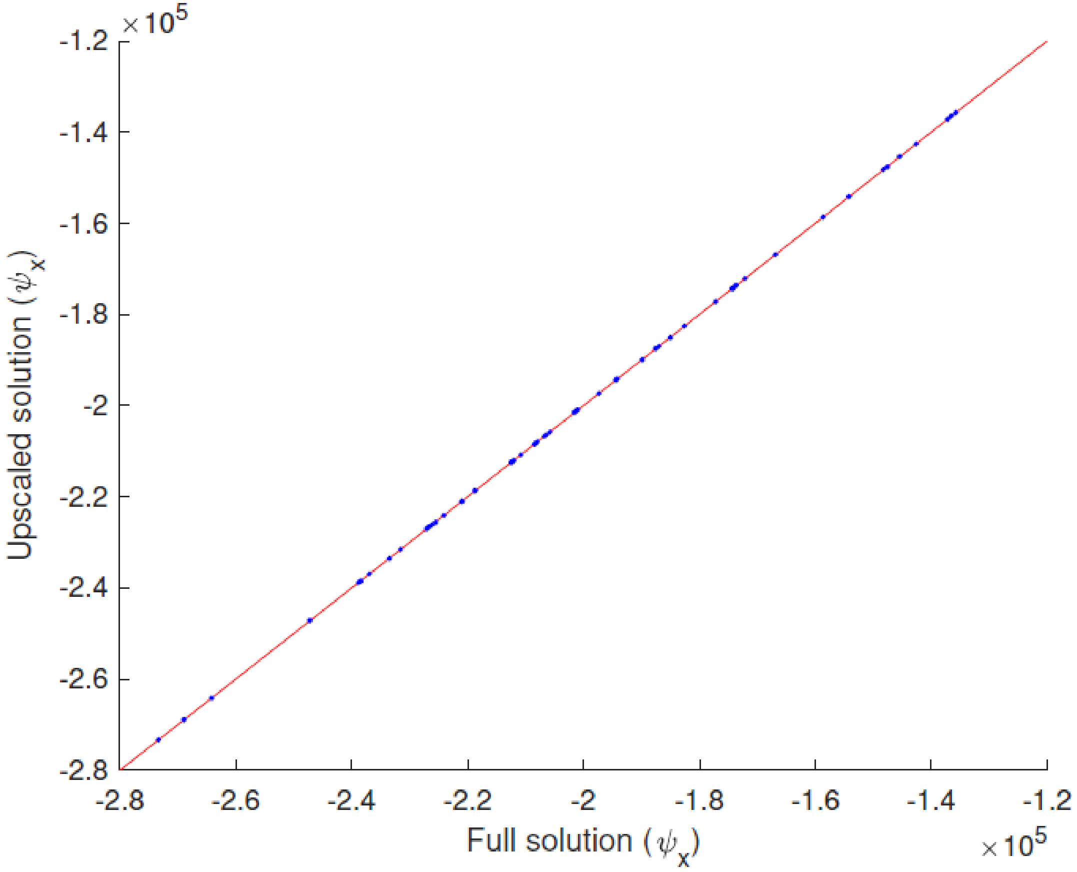
$$\hat{\psi}_s = \frac{\sum_1^n K_r L \psi_s}{\sum_1^n K_r L}$$

Exact upscaled solutions exist for trivial cases.

E.g.: laterals have different ψ_s than main root.

2 distinct values of ψ_s per layer.

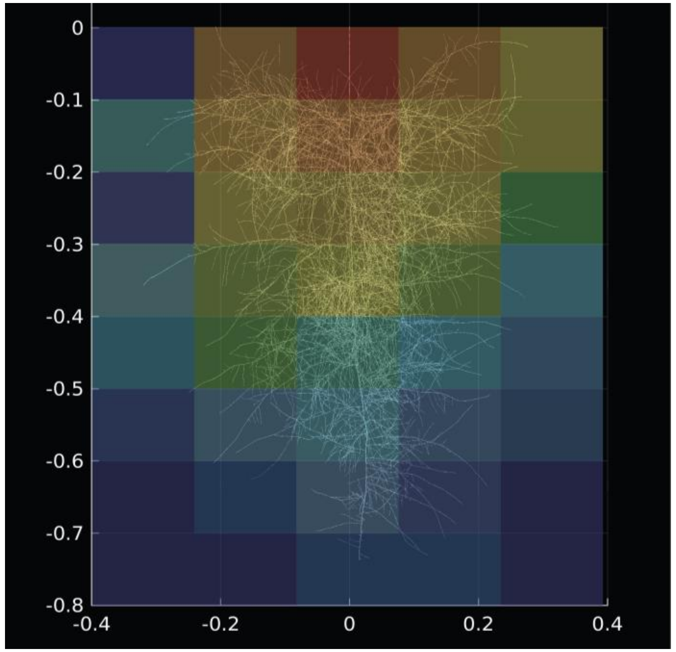




Could use 2-root (dry & wet) model?

Non-uniform ψ_s and non-trivial root system

Using *Pisum sativum* plant, assigning random ψ_s to each root segment.

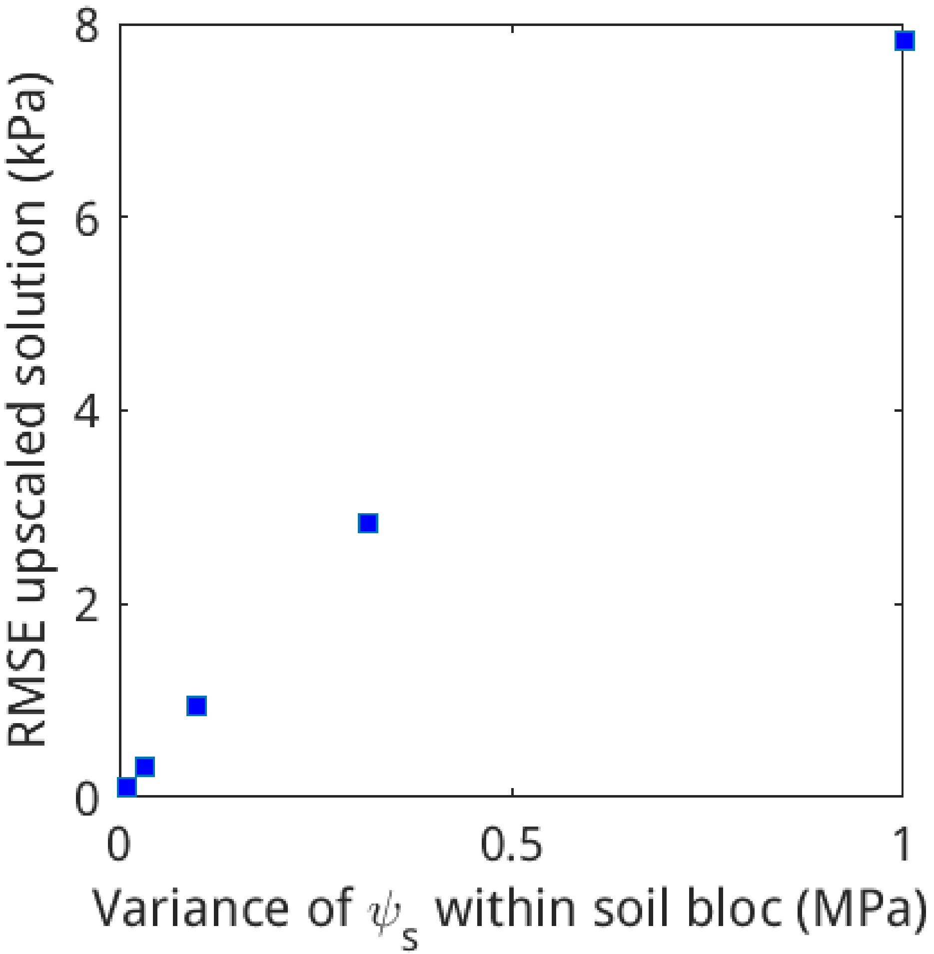


Find solution from weighted mean soil water potential

$$\hat{\psi}_s = \frac{\sum_1^n K_r L \psi_s}{\sum_1^n K_r L}$$

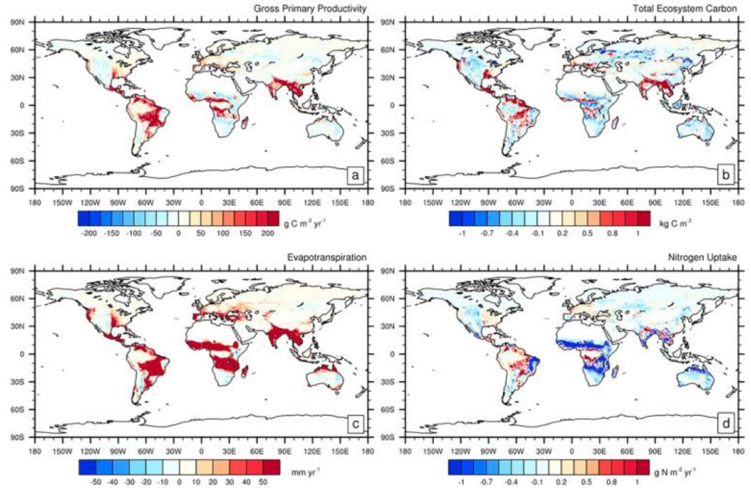
Using $\hat{\psi}_s$ and $\hat{\psi}_x$ solutions to fit upscaled parameters by inversion, prediction error remains ~ kPa when variance of ψ_s is ~ MPa.

Investigate relation $\hat{\psi}_s = f(\psi_s(x, y, z))$ as soil dries…

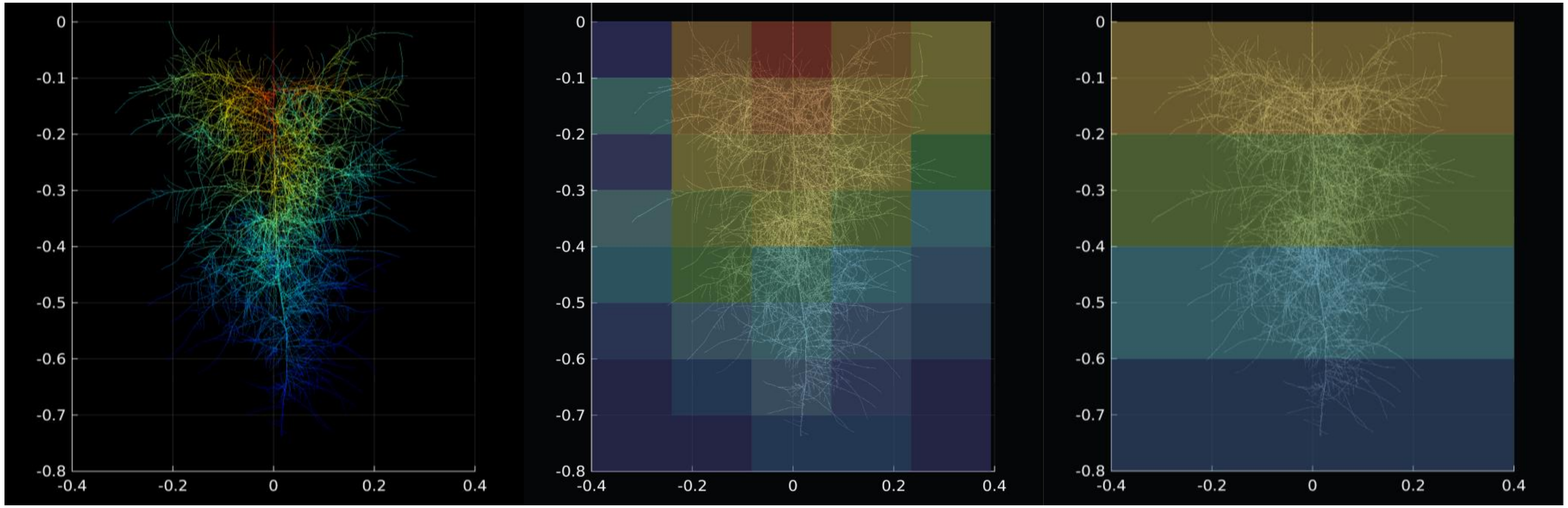


Promise of upscaling approach

- Lowest computational cost (one matrix multiplication per time-step)
- Eliminates known sources of error (structural, discretisation…)
    - Good ‘target’ for coupling to soil-side formulations.
    - Robust predictions under no-analogue scenarios require process-based formulation, not heuristic or approximation
- We need models adequate to the questions we’re asking
    - e.g., effect of root plasticity on water & carbon cycles:



Drewniak (2019)
J. Adv. Mod. Earth Sys.
11 (1), 338-359.



Thank you!

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