Implementing plant hydraulics in the NCAR Community Land Model (CLM)

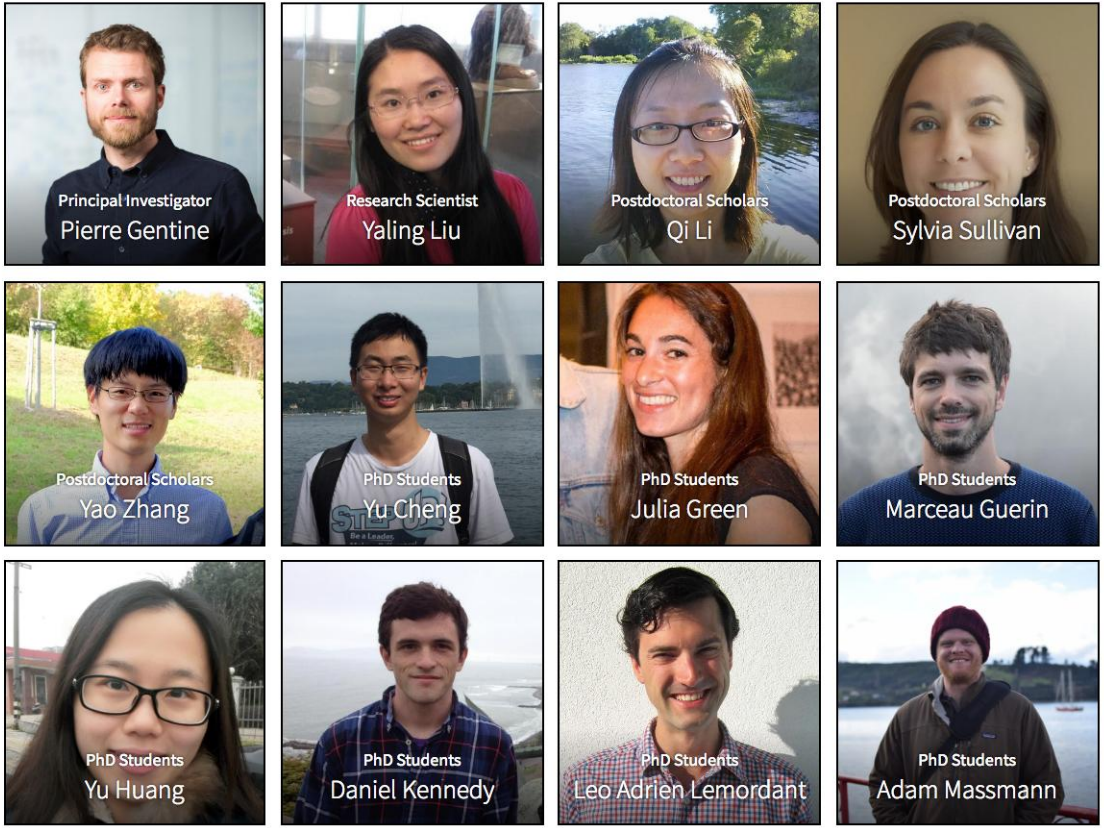
and the implications for vegetation water stress

Daniel Kennedy, Pierre Gentine
Columbia University

COLUMBIA | ENGINEERING

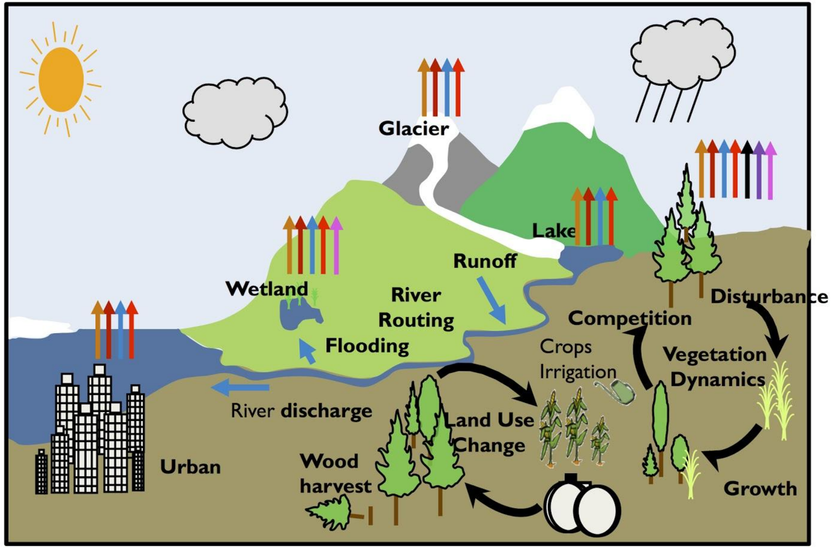
Gentine Lab

"Investigating the terrestrial carbon and water cycles using multiscale modeling and observations"



Community Land Model (CLM)

Motivation:
Land is the critical interface through which humanity affects, adapts to, and mitigates global environmental change



Comprehensive representations of land biogeophysics, hydrology, plant physiology, biogeochemistry, anthropogenic land use, and ecosystem dynamics

slide courtesy: Dave Lawrence

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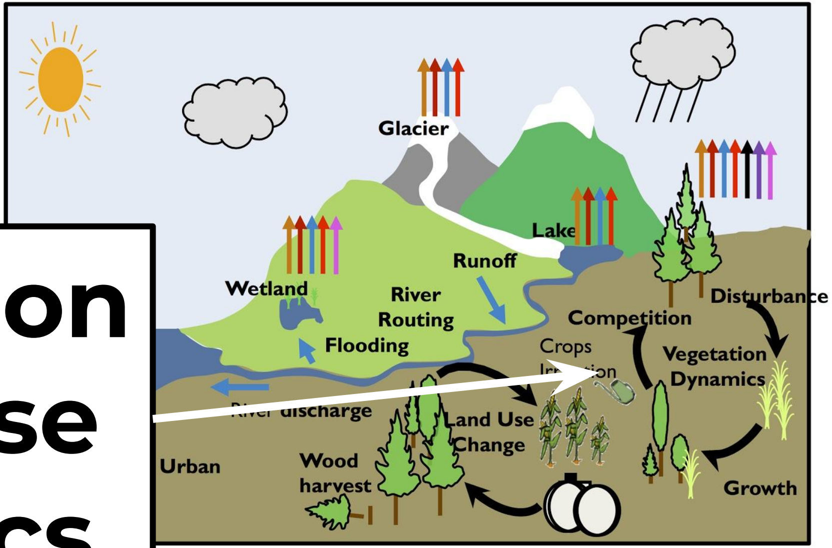
Vegetation water use dynamics



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Vegetation adjust to evolving environmental conditions

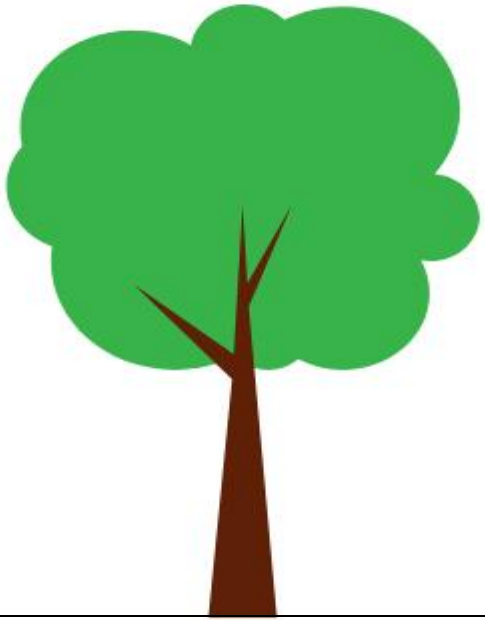
- leaf area and orientation
- biochemistry
- stomatal conductance
- … among others

How does this affect the terrestrial carbon/water cycles?

Dry leaves avoiding the sun
ZF2 Flux Tower: Manaus, Brazil
Photo Credit: Dr. Charlie Koven

Cover of New Phytologist, 219:3
Special Issue on
Drought Impacts on Tropical Forests

Plant
Hydraulic
Stress



tree from vecteezy.com

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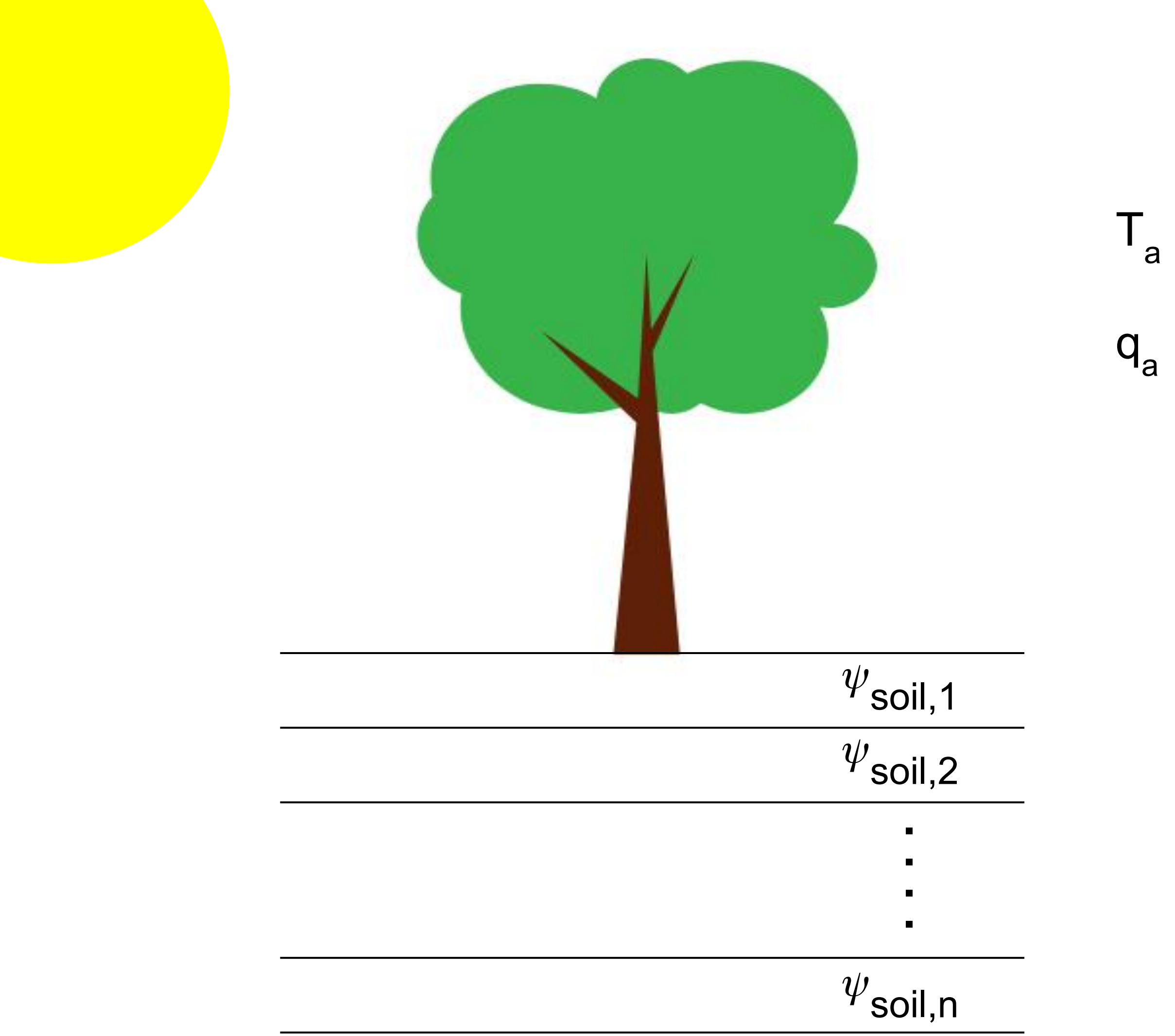

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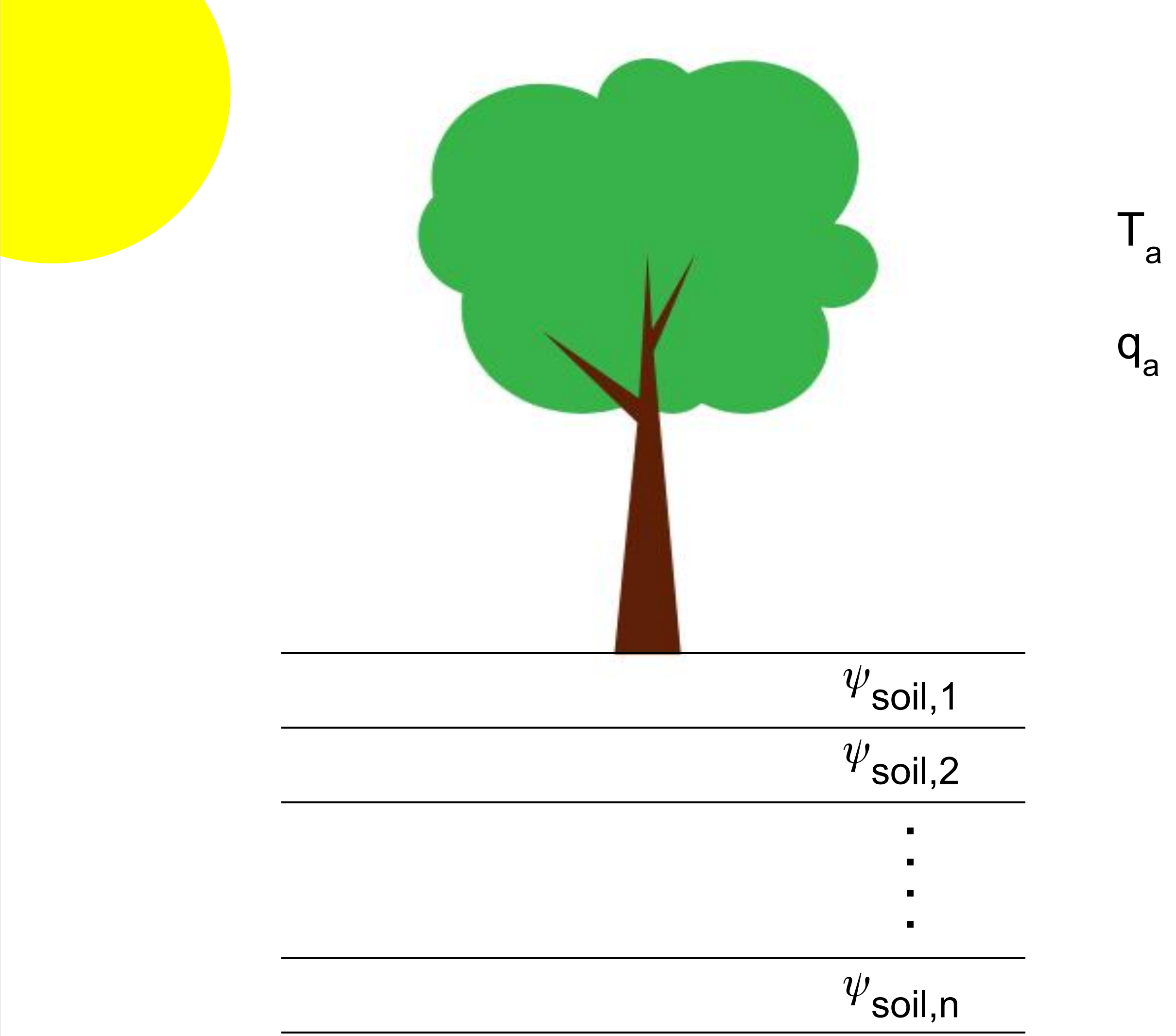

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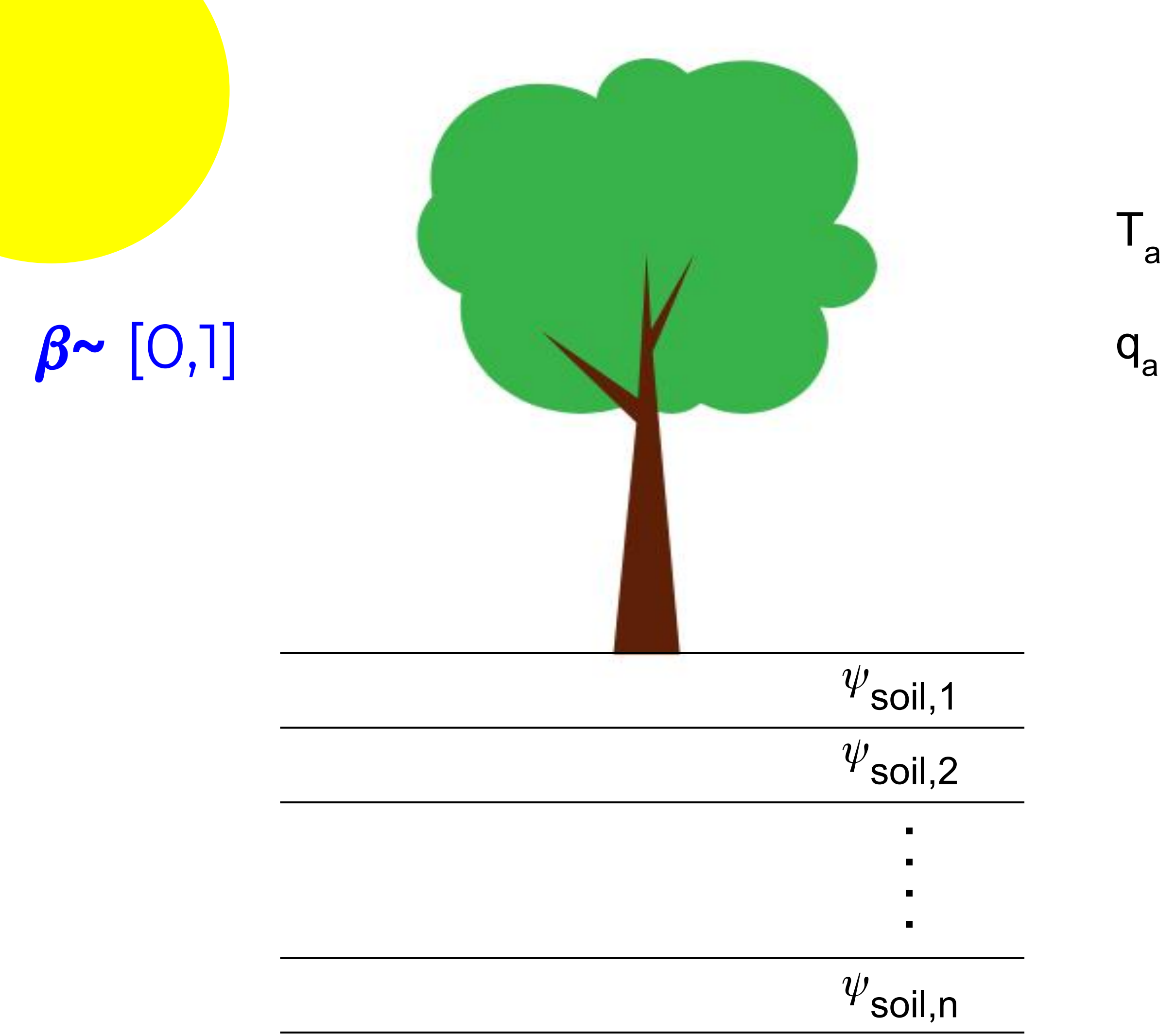

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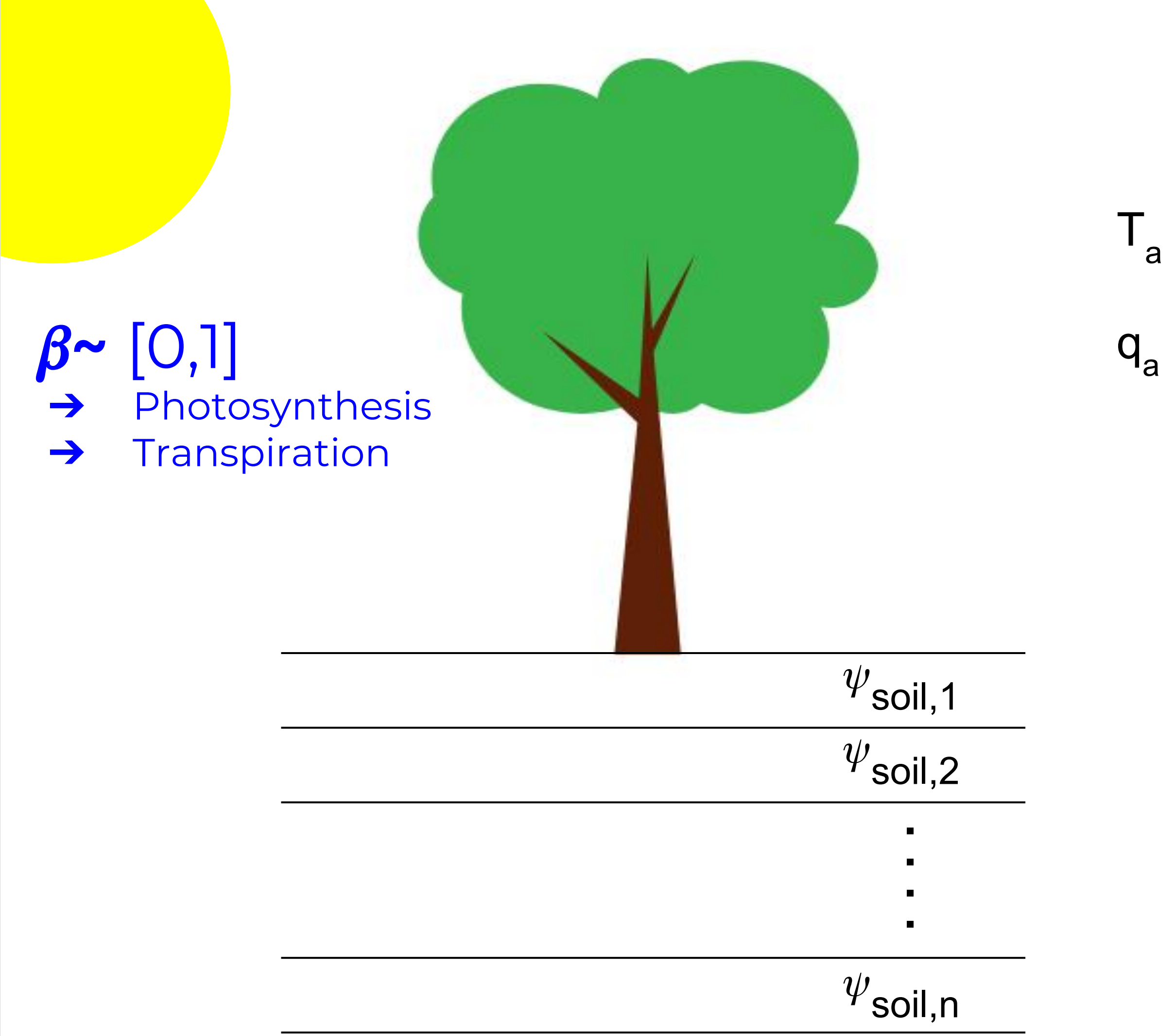

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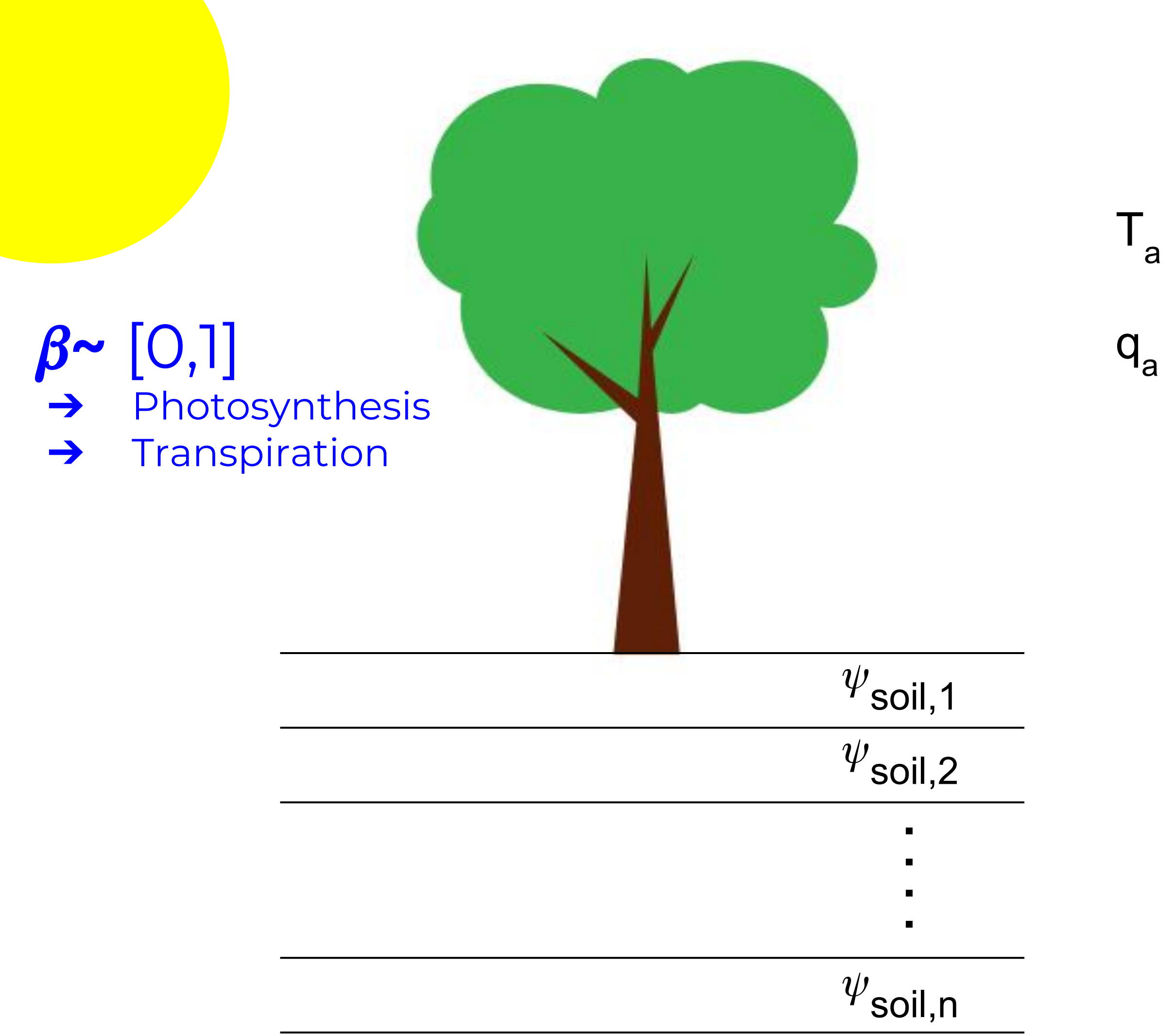

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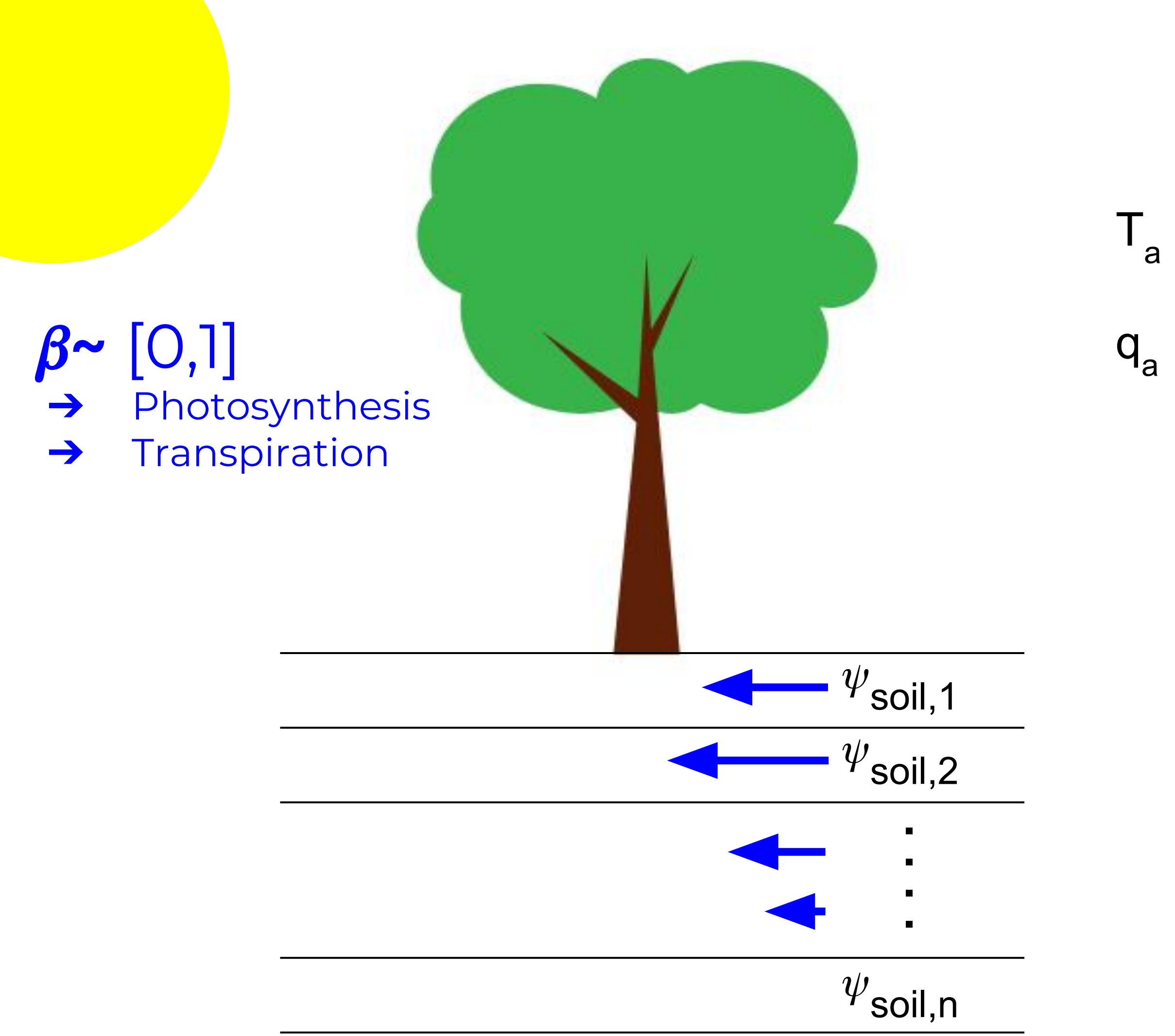

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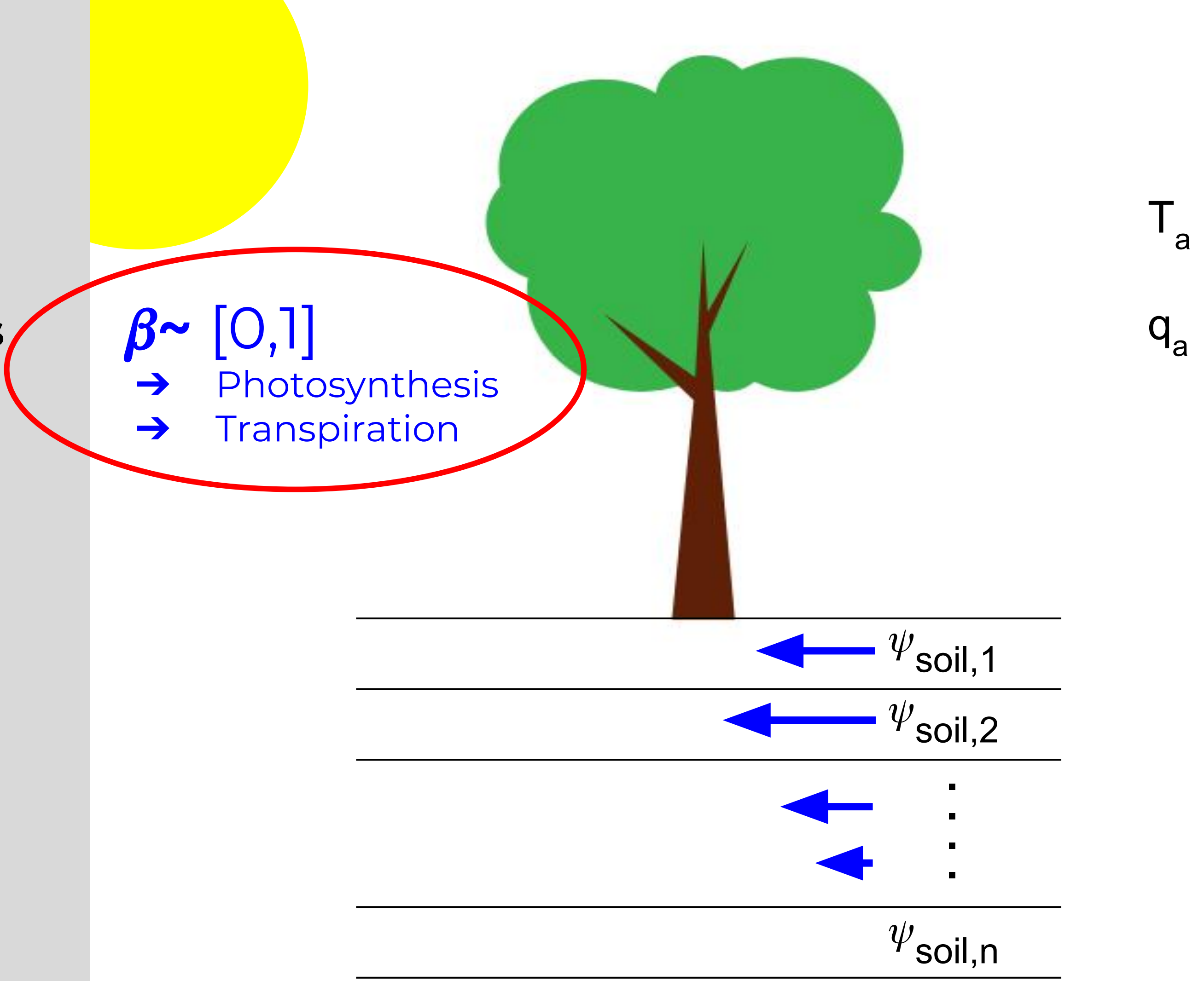

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CLM5 uses the Medlyn stomatal conductance model*

g_s: stomatal conductance
g_0: Medlyn intercept parameter
g_1: Medlyn slope parameter
D: Vapor pressure deficit
A: Photosynthesis
C_a: CO_2 concentration

$$g_s^* \approx g_0 + \left(1 + \frac{g_1}{\sqrt{D}}\right) \frac{A}{C_a}$$

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Medlyn et al. 2011 (GCB)
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What's missing?

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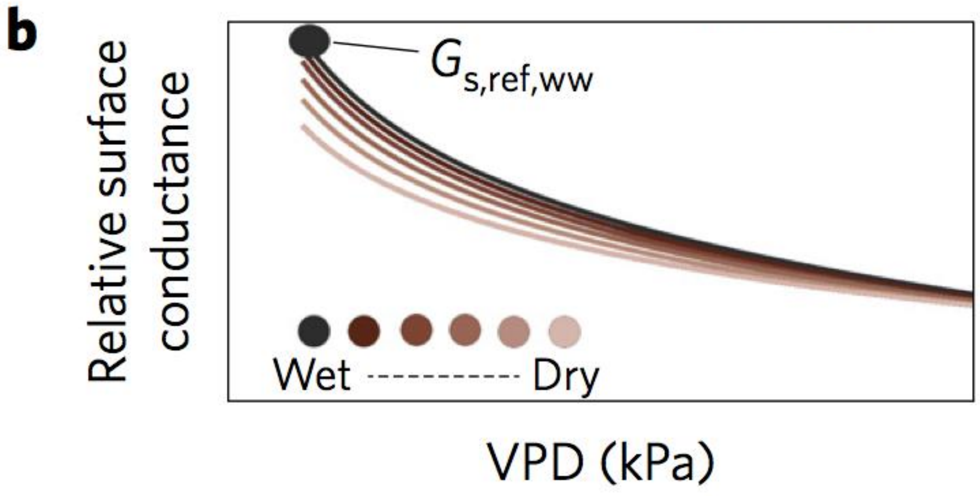
Stomatal conductance models often need: a water stress factor (β) to account for soil moisture



Novick et al. 2016: Nature Climate Change

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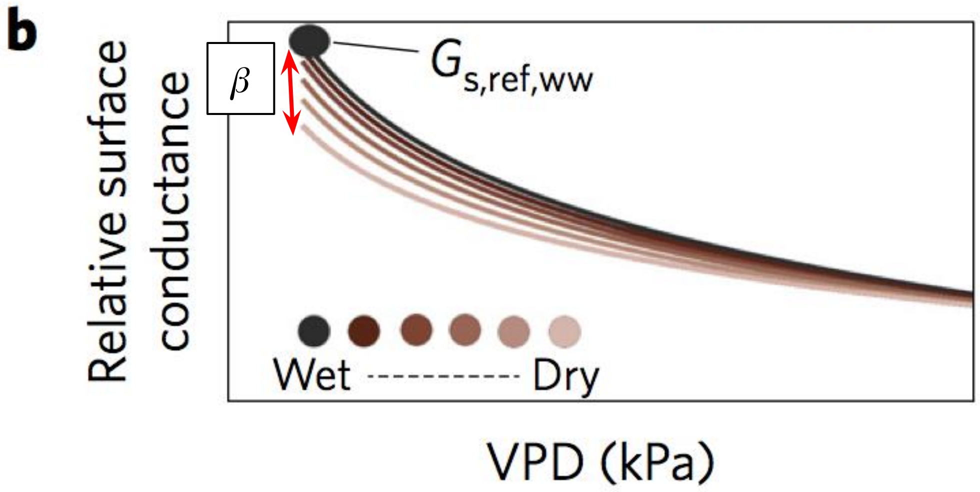

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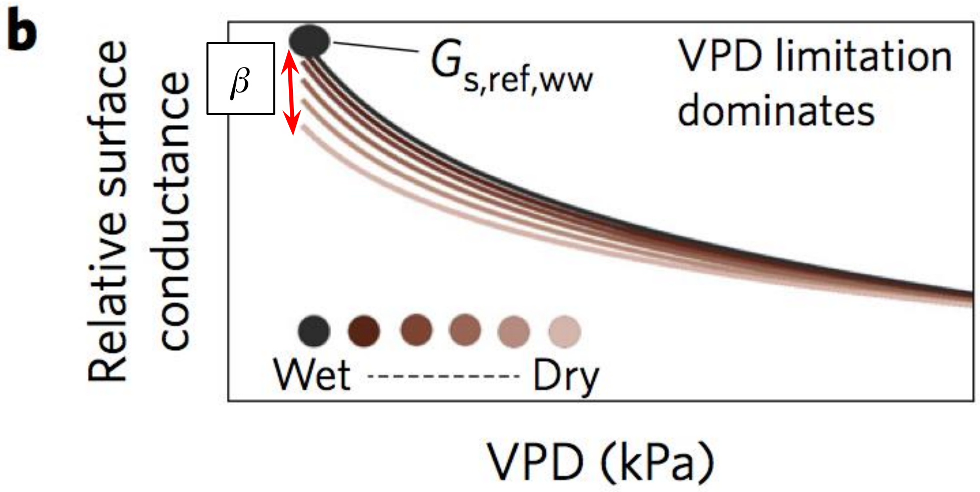

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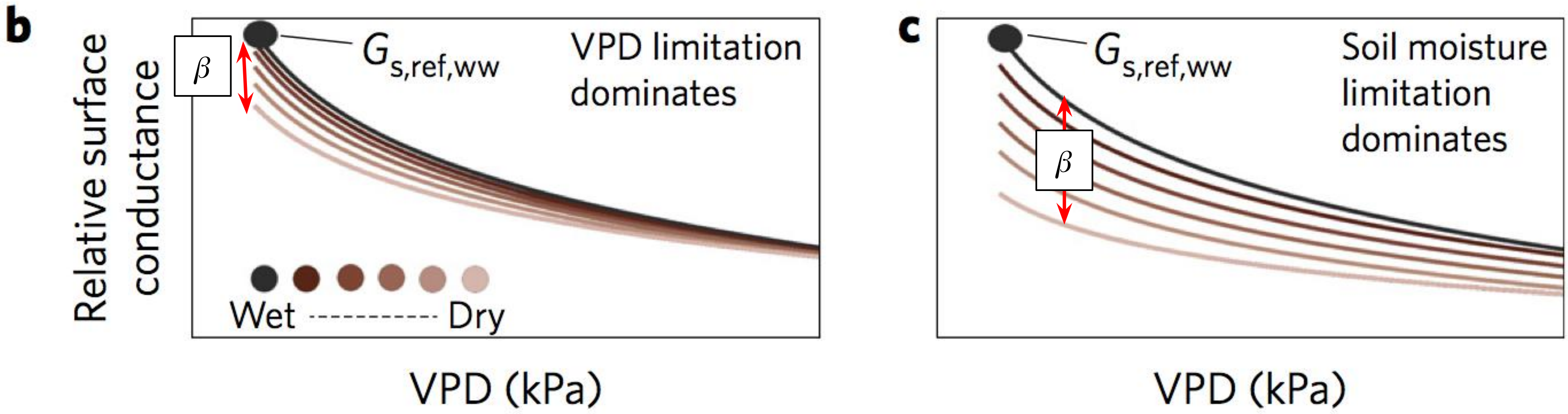

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CLM Method for calculating β (before CLM5)

$\psi_{soil,i}$: water potential in soil layer *i*

r_i: root fraction in soil layer *i*

p_c:
soil water potential when stomates are fully closed (parameter)

p_o:
soil water potential when stomates are fully closed (parameter)

$$\beta = \sum_{i=1}^{nlevsoi} r_i \cdot \frac{\Psi_{\text{soil},i} - p_c}{p_o - p_c}$$

CLM Method for calculating β (before CLM5)

Shortcomings:

- ψ_{soil} measurements not readily available to constrain empirical relationship
- Does not comport with plant hydraulic theory
- Cannot represent the spectrum of water use strategies

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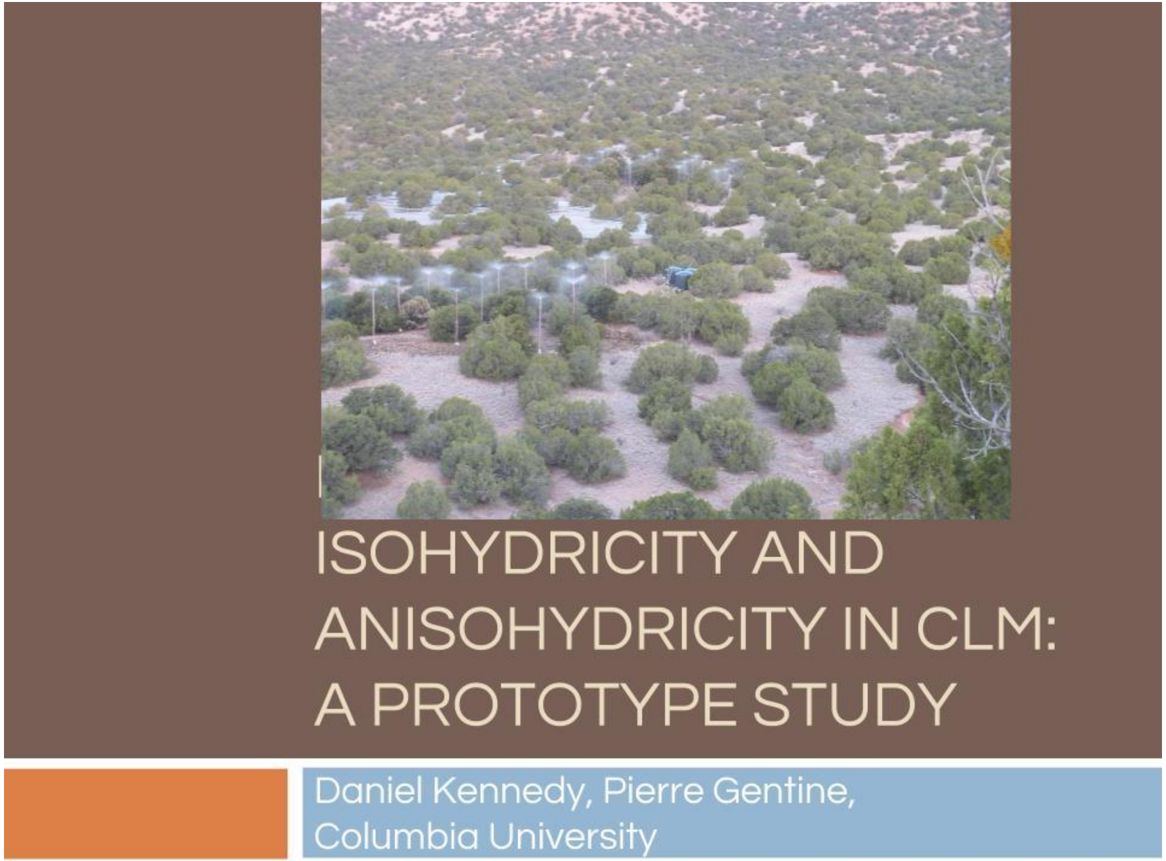
How I got started with CLM

- March, 2015
- LMWG Winter Meeting (happening again next week)
- Not yet using CLM in any capacity
- Toy model results on what it might look like to implement a β function that is more in line with plant hydraulic theory



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1. Prognose leaf water potential (ψ_{leaf})
2. Use ψ_{leaf} to calculate β

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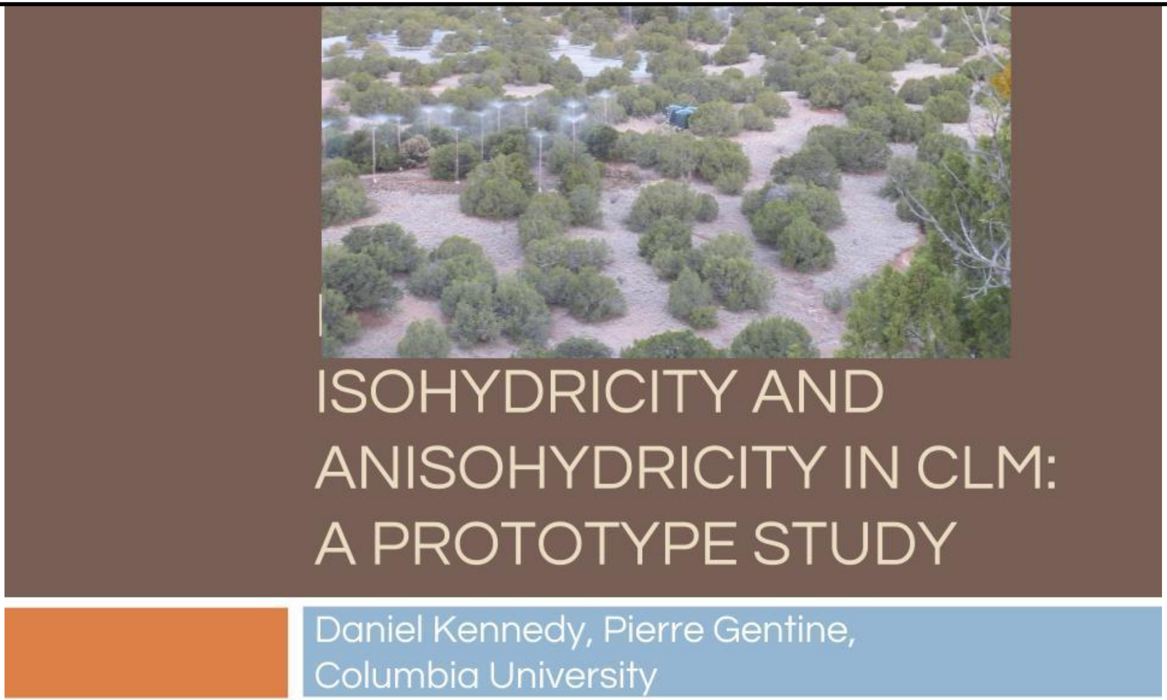

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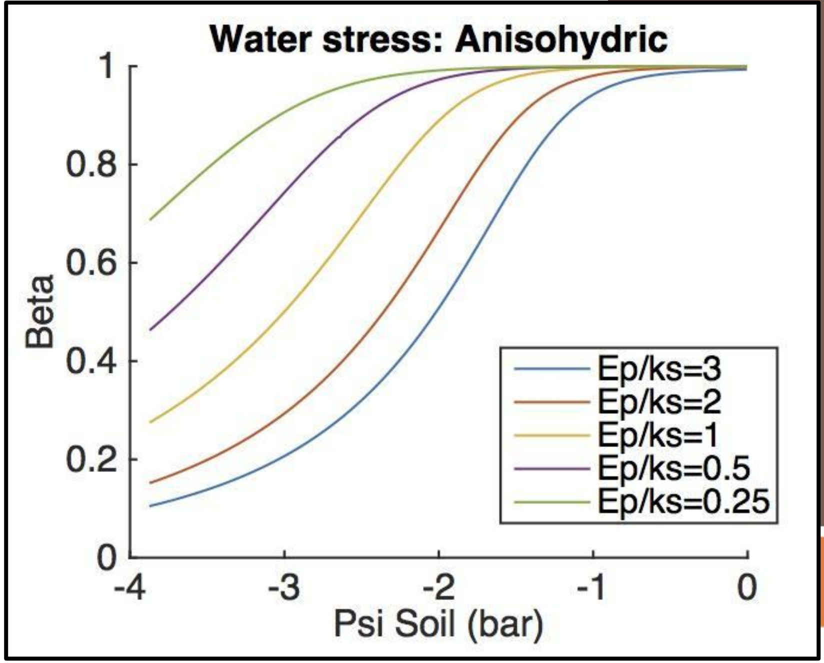

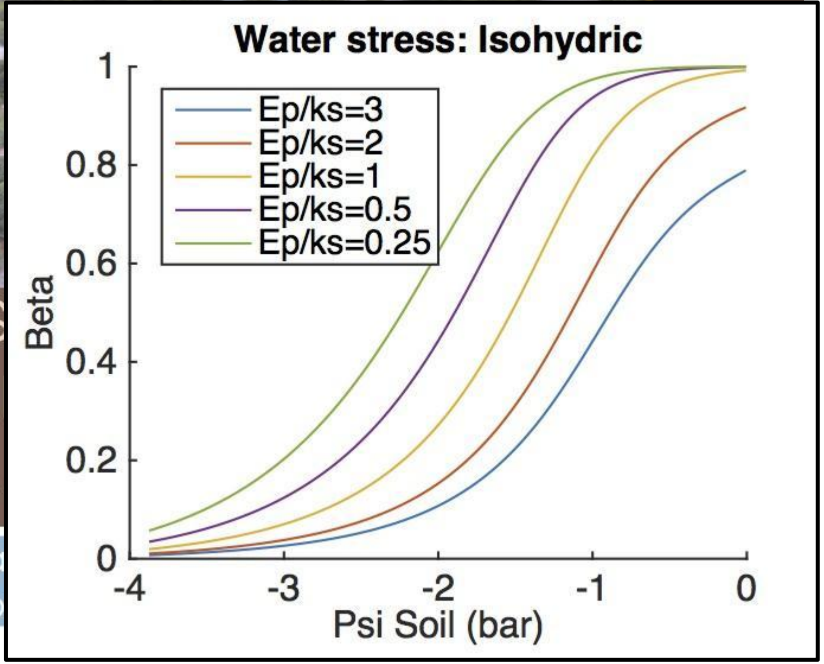

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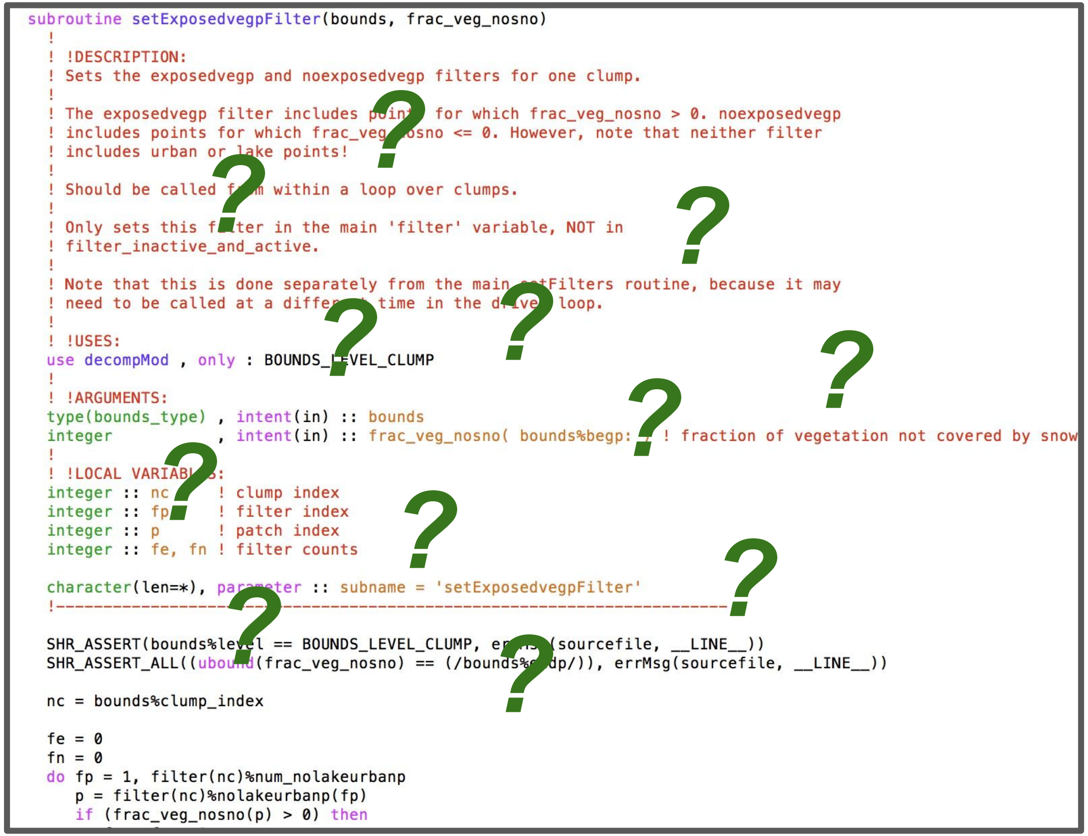

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  ! Should be called from within a loop over clumps.
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  ! Only sets this filter in the main 'filter' variable, NOT in
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  ! Note that this is done separately from the main setFilters routine, because it may
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  !
  ! !ARGUMENTS:
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Success!

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July 2016 - PHS is accepted for CLM5 as the default vegetation water use scheme

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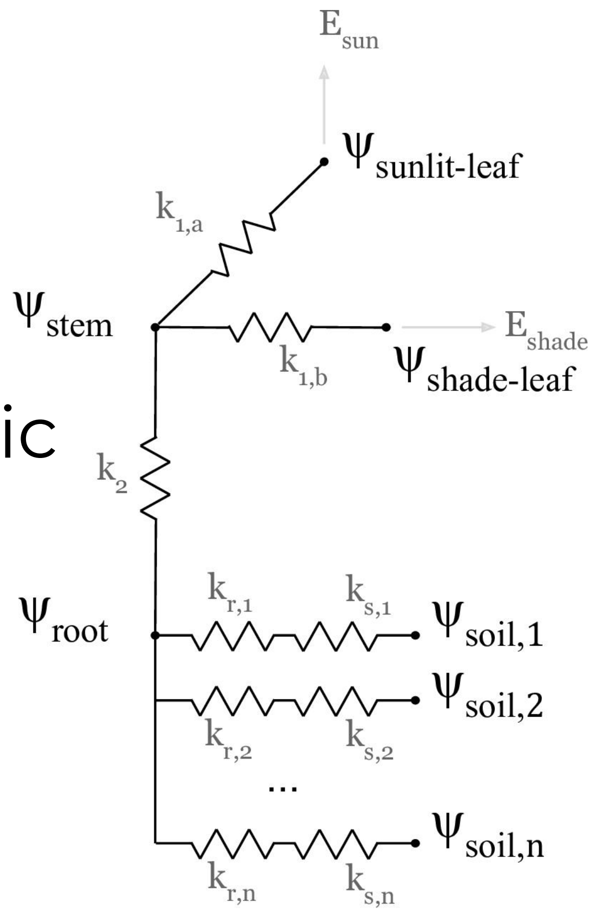
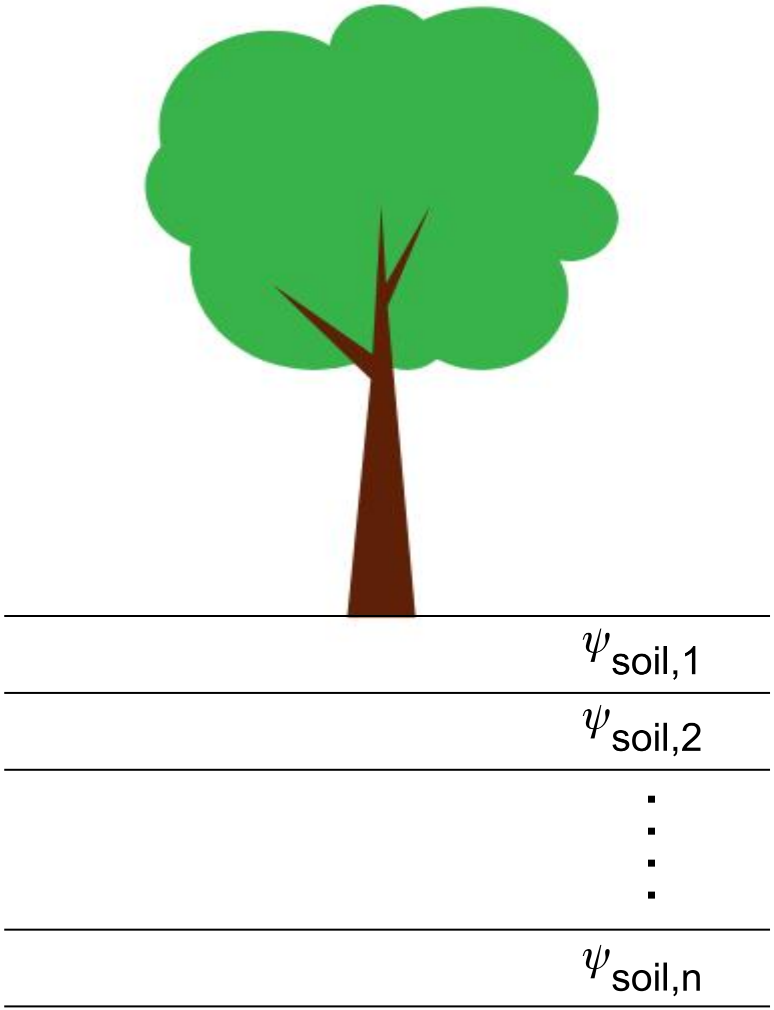


Plant **H**ydraulic **S**tress

model vegetation water potential

- CLM already models soil water potential over a discretized soil column

tree from vecteezy.com



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- We add four new water potential nodes through the vegetation

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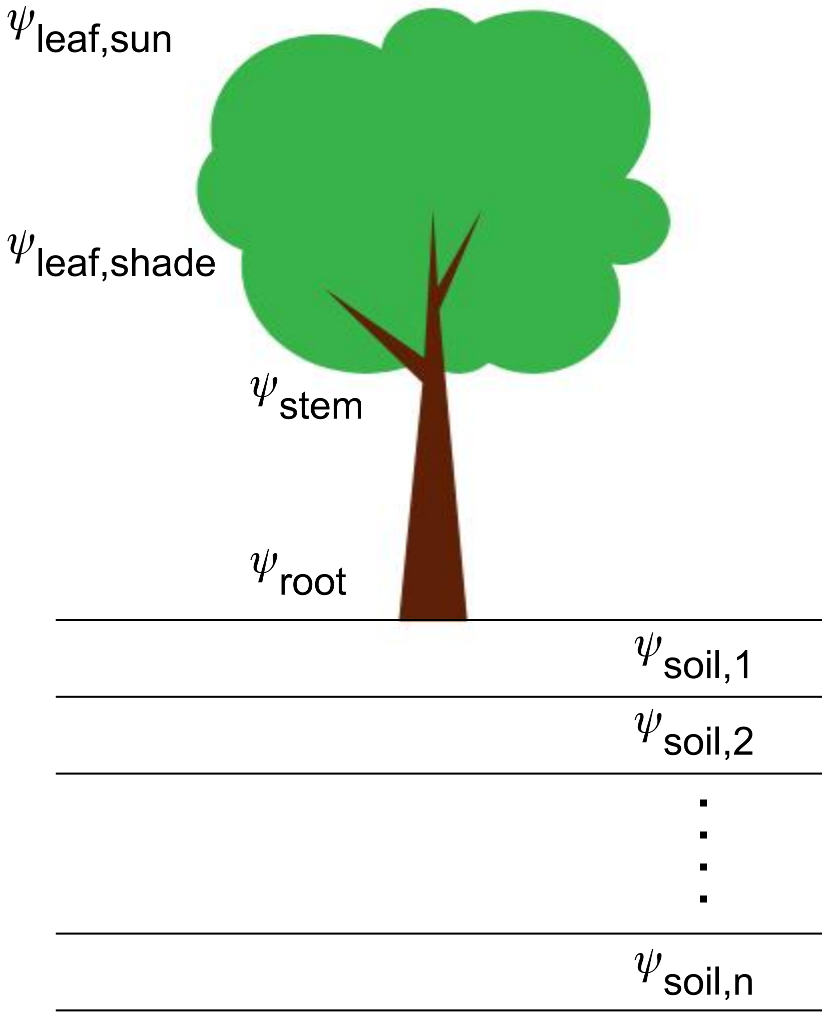

Plant **H**ydraulic **S**tress

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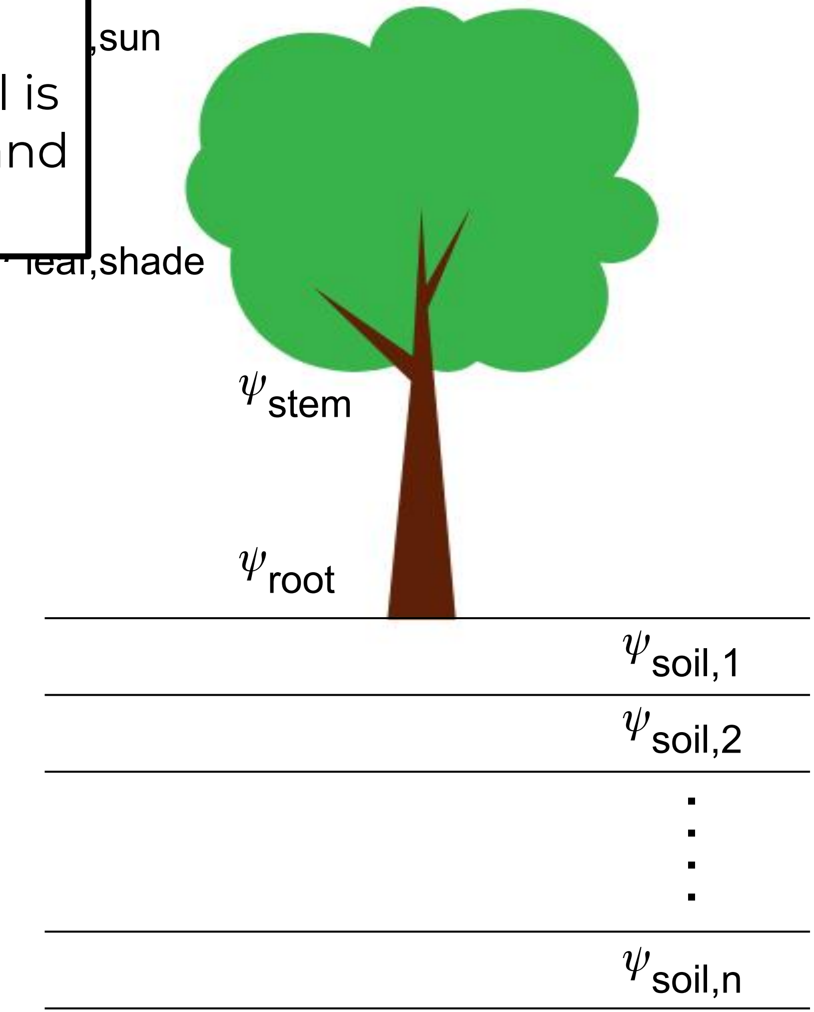

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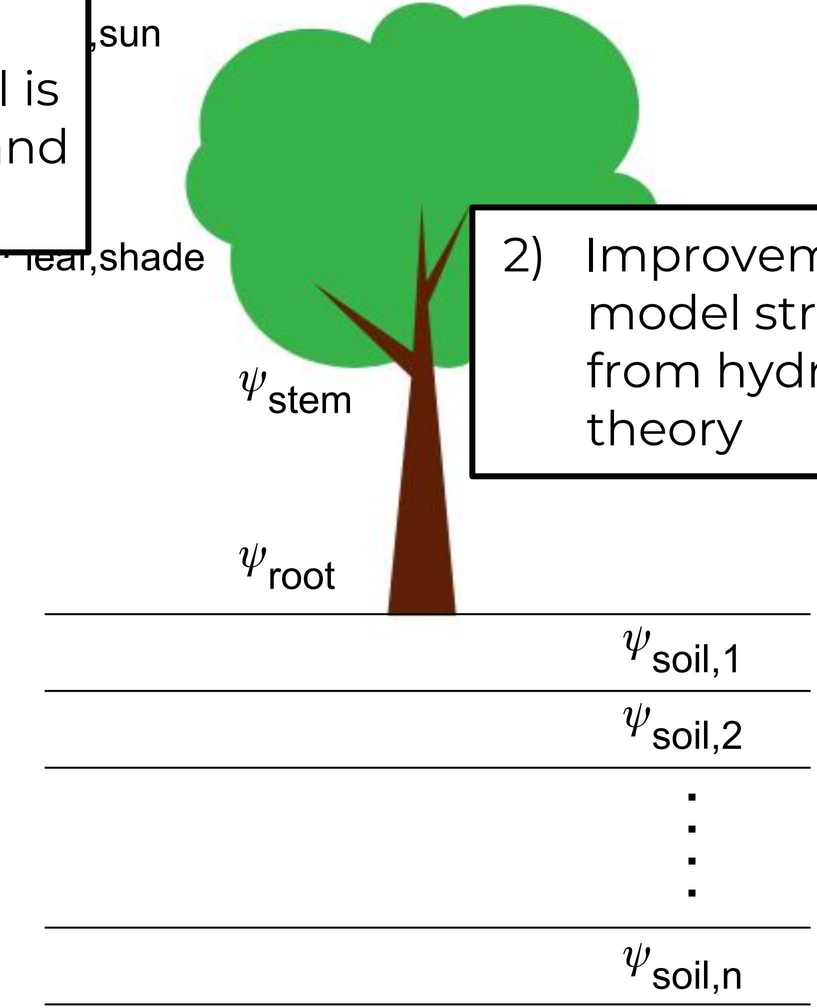

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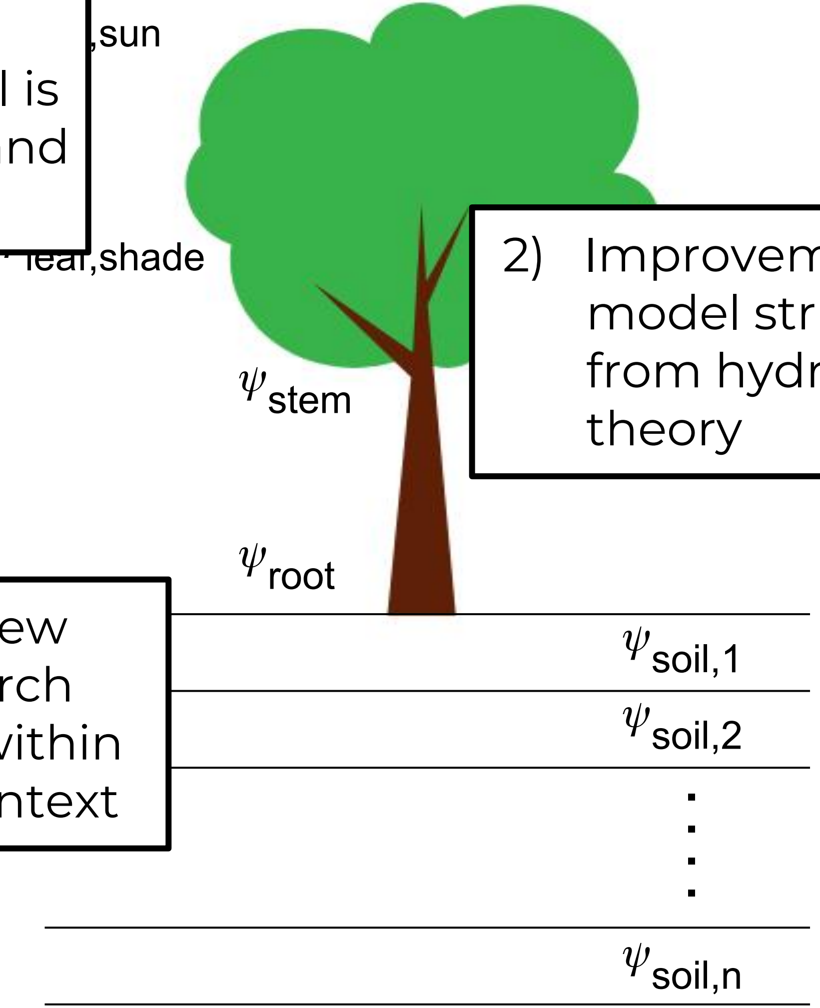


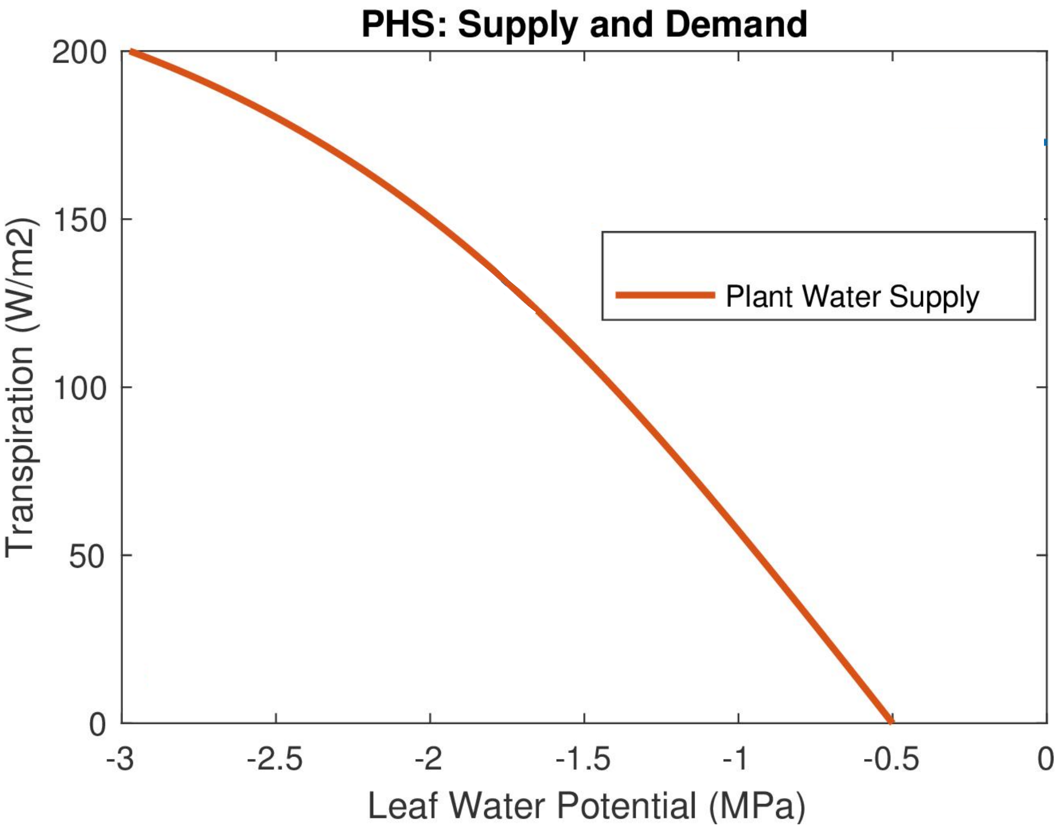
2) Improvement in model structure from hydraulic theory

3) Enables a new set of research questions within the ESM context

tree from vecteezy.com

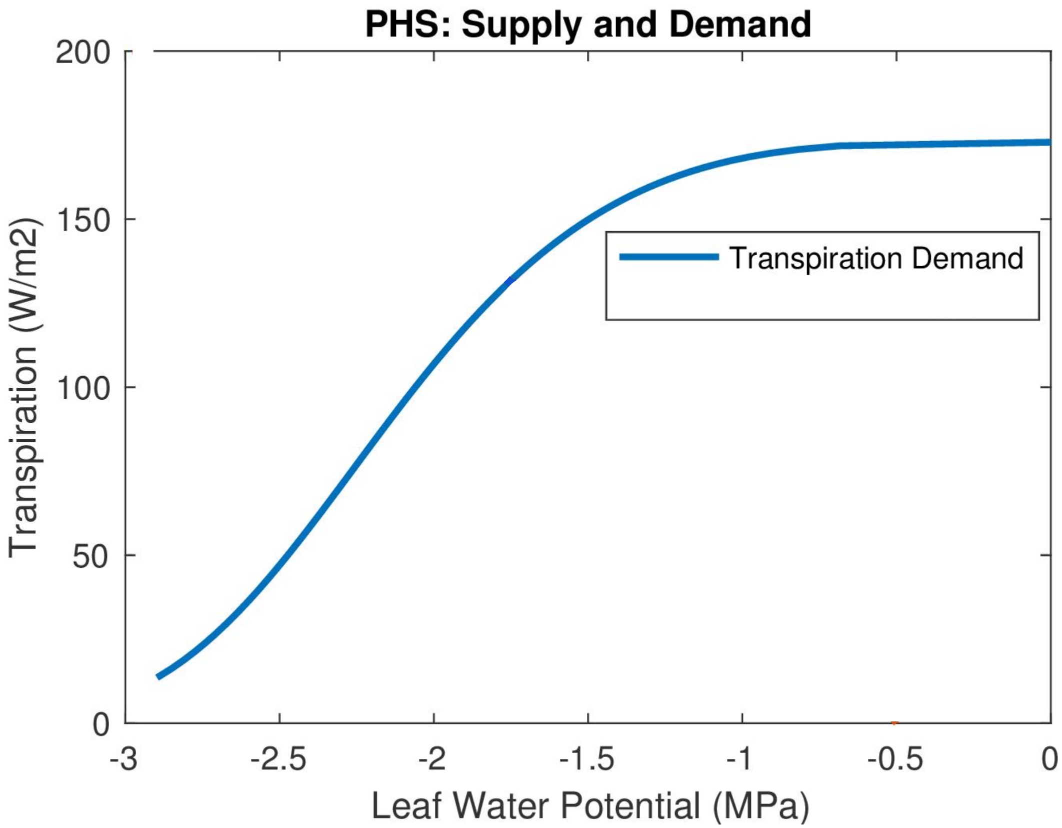
PHS transpiration solution

- Supply increases when you lower leaf water potential



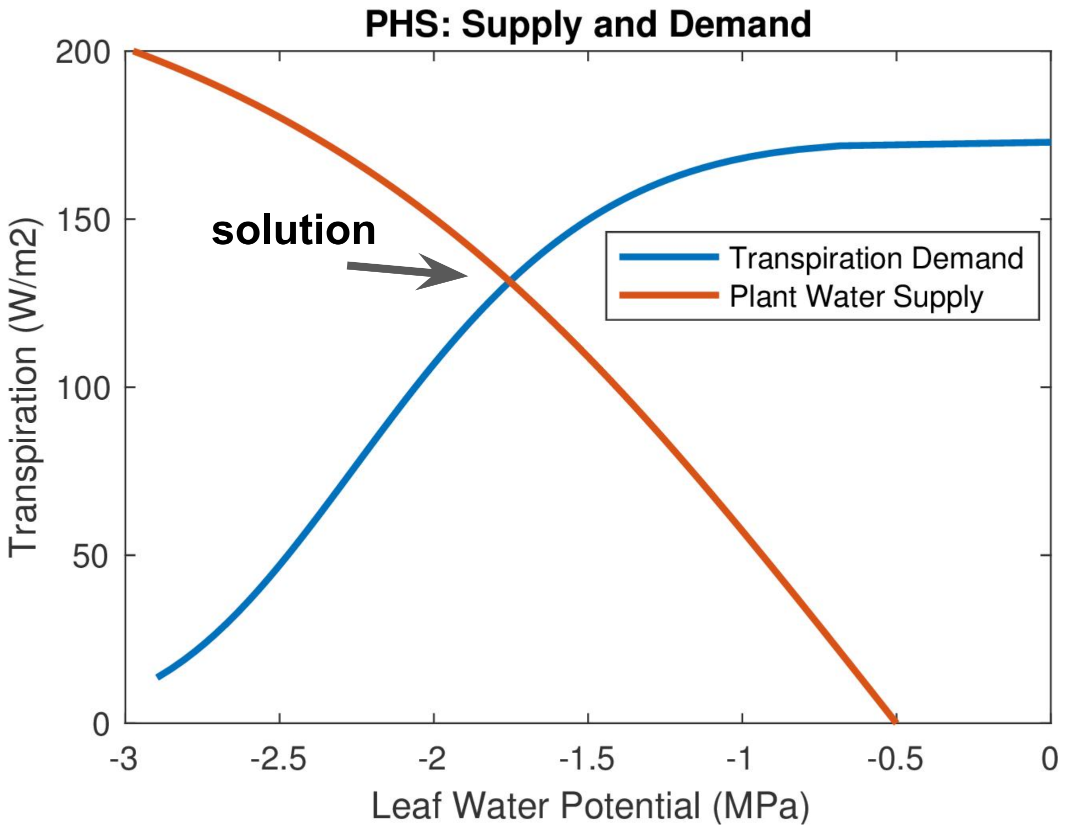
PHS transpiration solution

- Supply increases when you lower leaf water potential
- But water stress also increases
- Which leads to lower transpiration demand



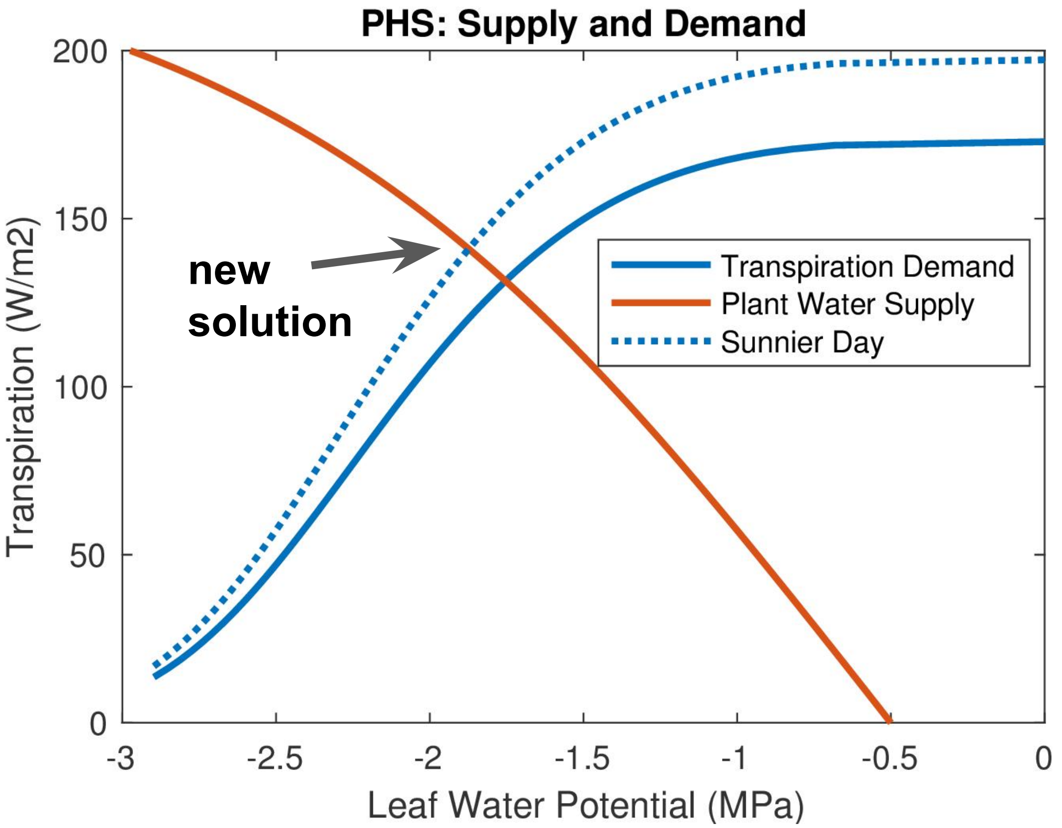
PHS transpiration solution

- Supply increases when you lower leaf water potential
- But water stress also increases
- Which leads to lower transpiration demand
- Transpiration solution matches supply with demand



What about a sunnier day?

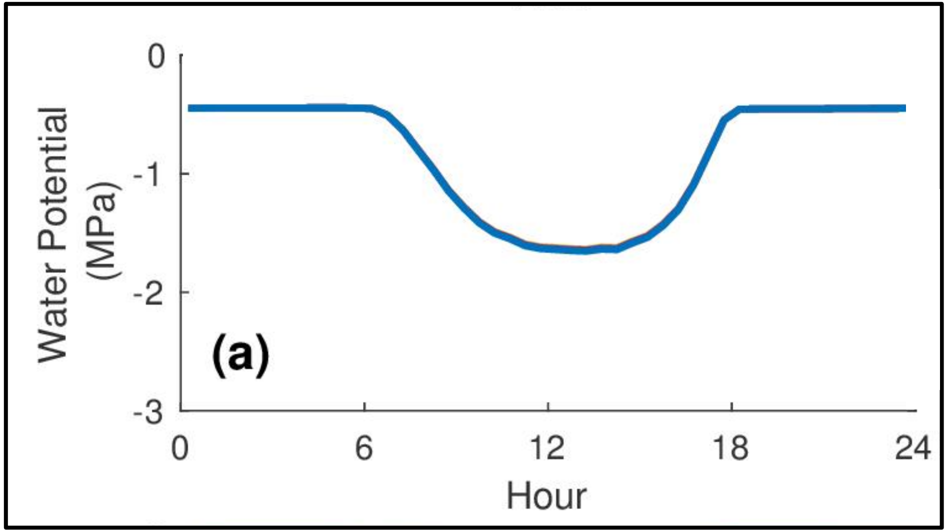
- Still matches supply with demand
- More light leads to increase in unstressed GPP/Transpiration
- New solution
- More transpiration
- Lower leaf water potential
- (associated with lower β)



CLM5 models veg. water potential

Reflecting the expected:

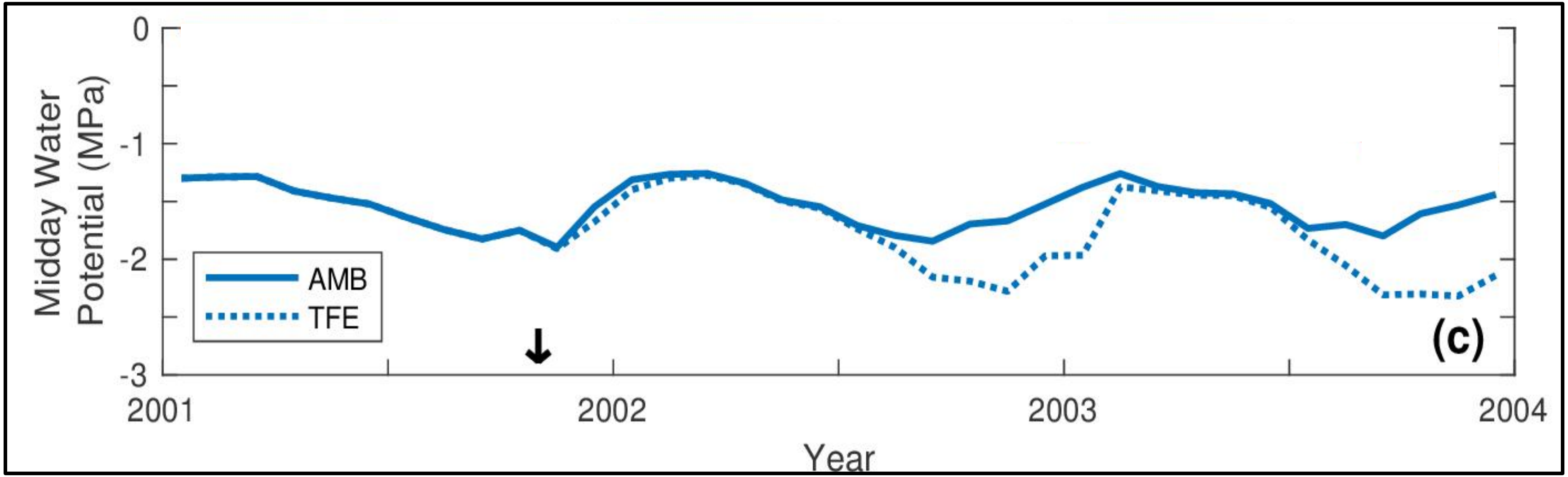
diurnal cycle



CLM5 models veg. water potential

Reflecting the expected:

seasonal cycle



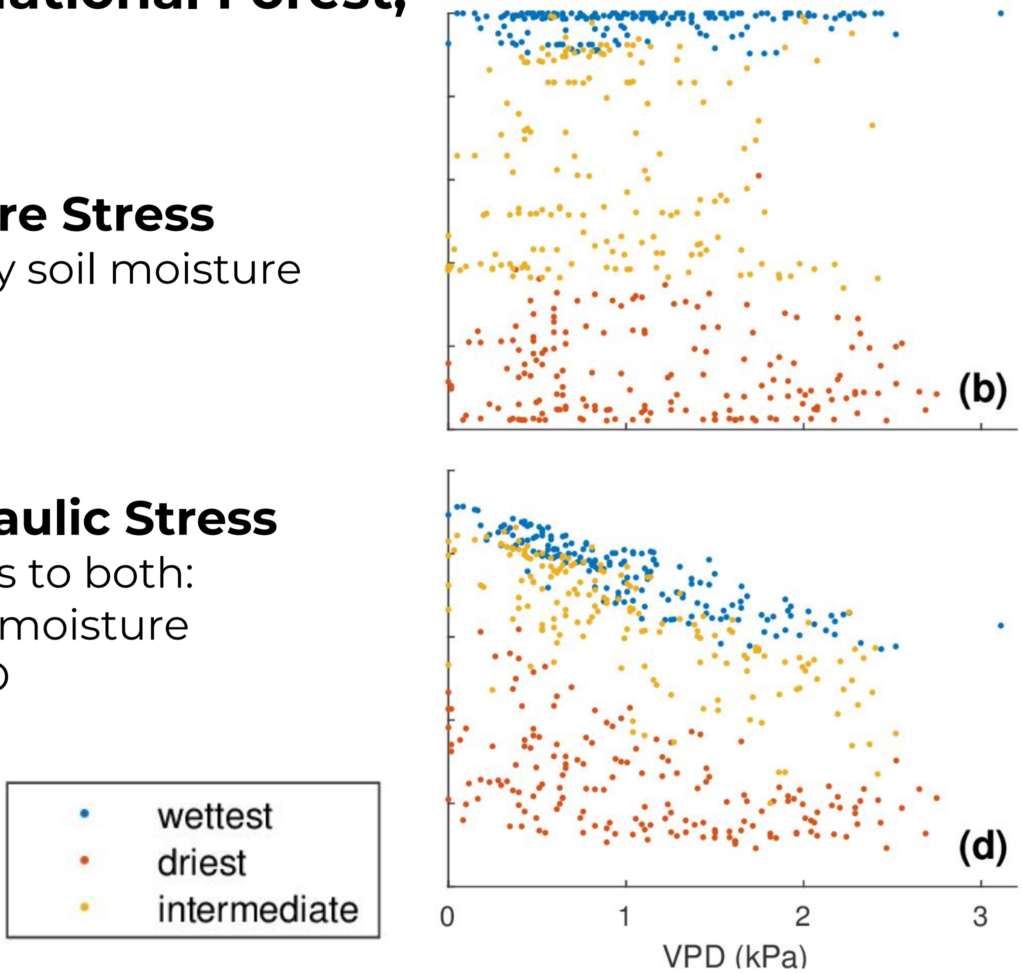
Caxiuana National Forest, Brazil

Soil Moisture Stress

- driven by soil moisture
- (CLM4.5)

Plant Hydraulic Stress

- responds to both:
    - soil moisture
    - VPD
- CLM5



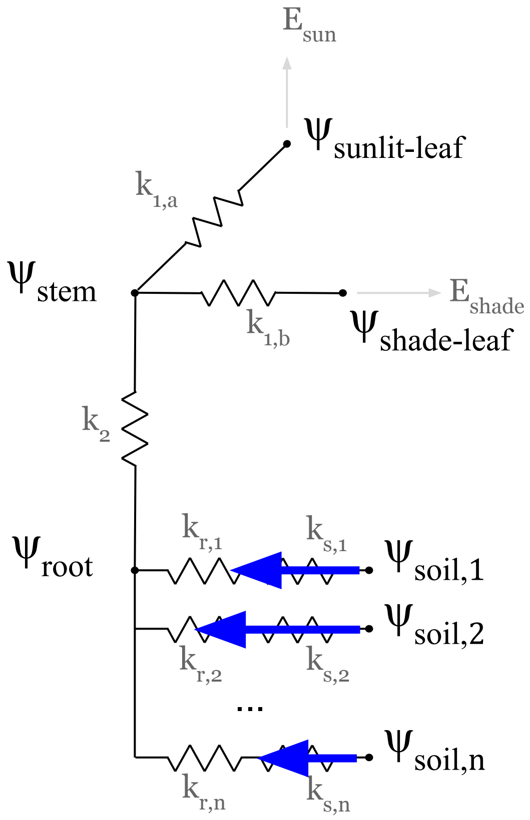
Stress vs. VPD

(and soil moisture)

The stress function now depends on atmospheric dryness (vapor pressure deficit)

Data subdivided by root-zone soil moisture

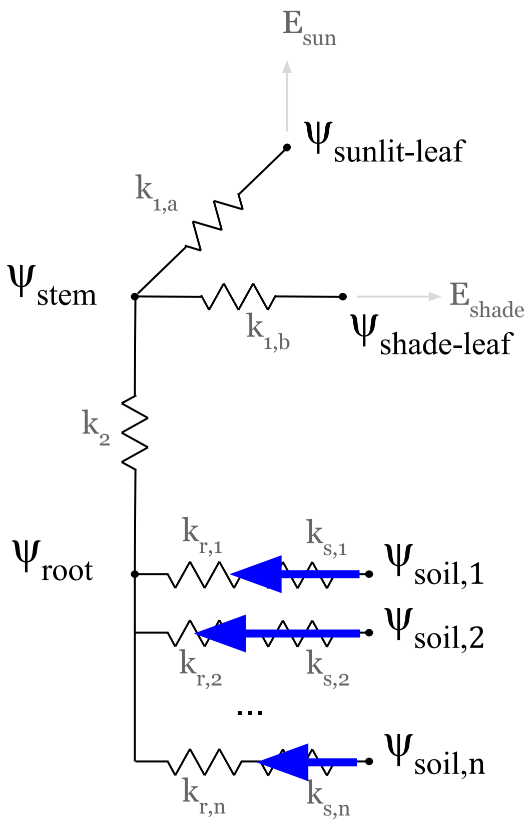
Root Water Uptake



Root Water Uptake

Governed by Darcy's Law

- $q = -k \Delta\psi$
- $q_i = -k_i \, (\psi_{root} - \psi_{soil,i})$

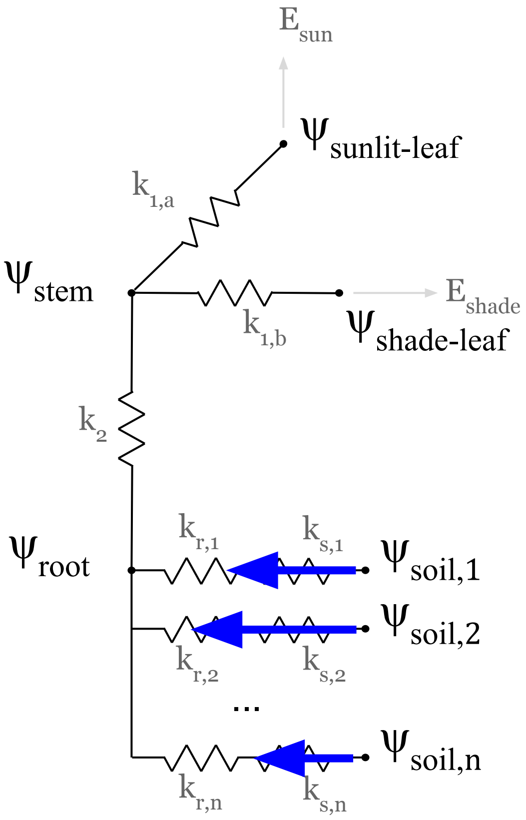


Root Water Uptake

Doable with PHS

Governed by Darcy's Law

- $q = -k \, \Delta\psi$
- $q_i = -k_i \, (\psi_{root} - \psi_{soil,i})$

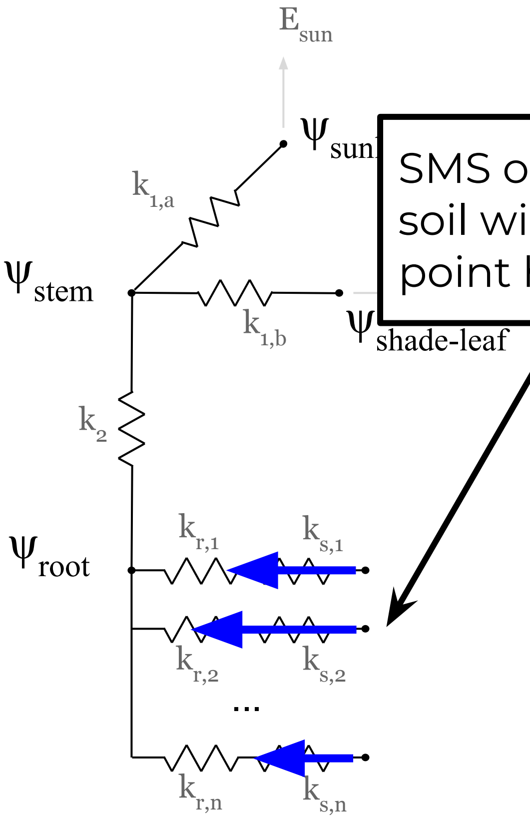


Root Water Uptake

Doable with PHS

Governed by Darcy's Law

- $q = -k \; \Delta\psi$
- $q_i = -k_i \; (\psi_{root} - \psi_{soil,i})$



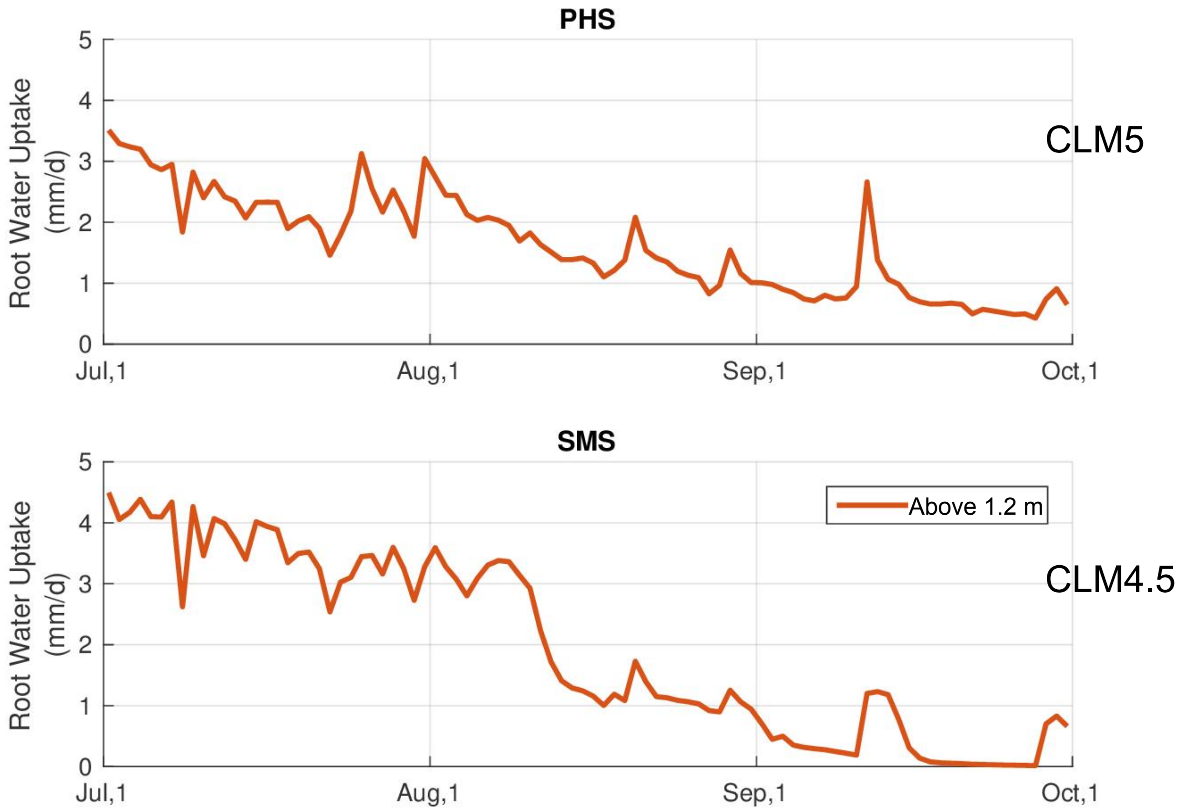
SMS opts for soil wilting point heuristic

PHS implements mechanistic Root Water Uptake (RWU)

Same soil parameters
Same root distribution

Higher layers dry out and water contribution falls off

Caxiuana, 2002



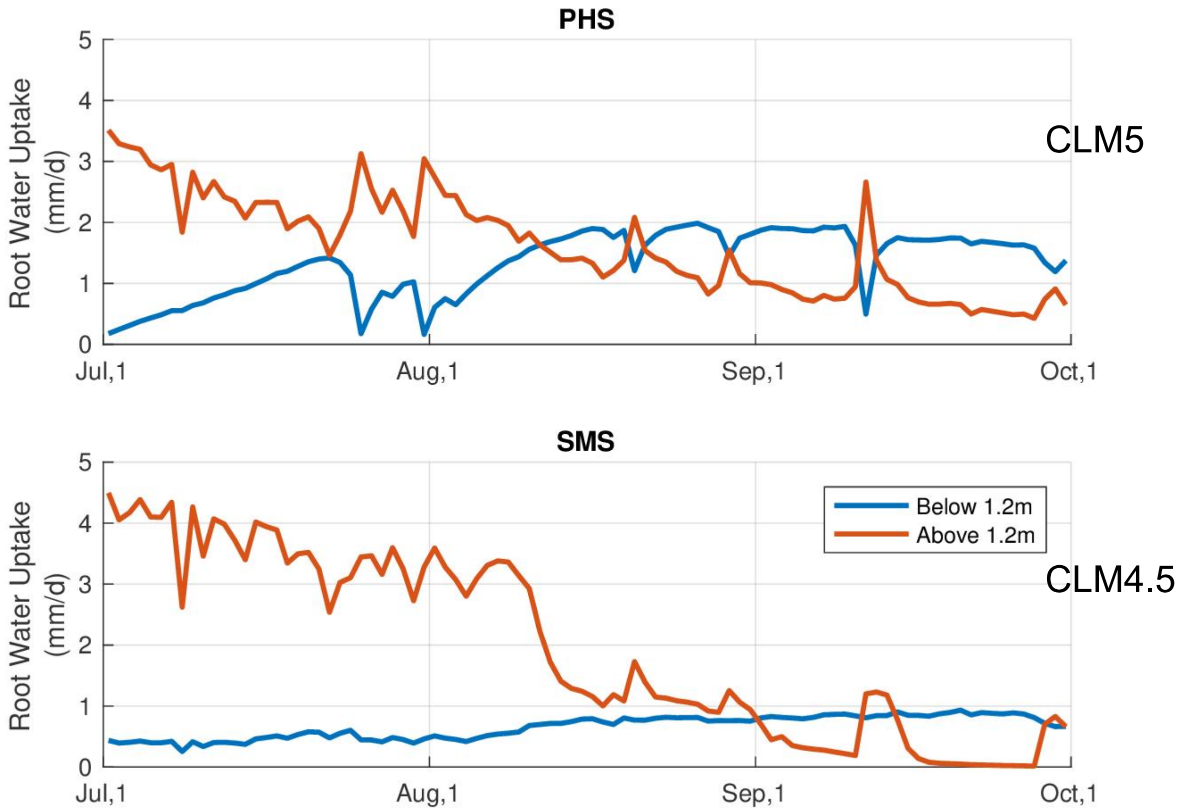
PHS implements mechanistic Root Water Uptake (RWU)

Same soil parameters
Same root distribution

Higher layers dry out and water contribution falls off

PHS partially compensates with water from deep soil

Caxiuana, 2002



PHS implements mechanistic Root Water Uptake (RWU)

Same soil parameters
Same root distribution

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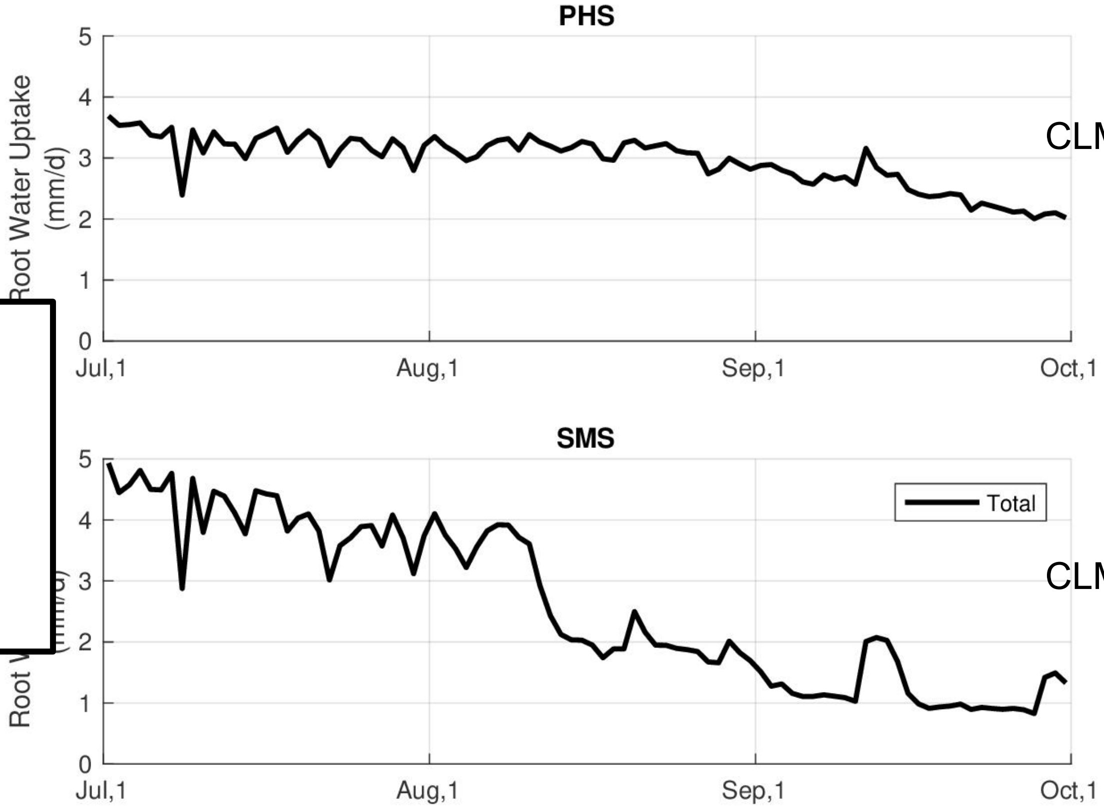
water from deep soil

SMS missing flexibility to access reserves of soil water at depth

Caxiuana, 2002



CLM5

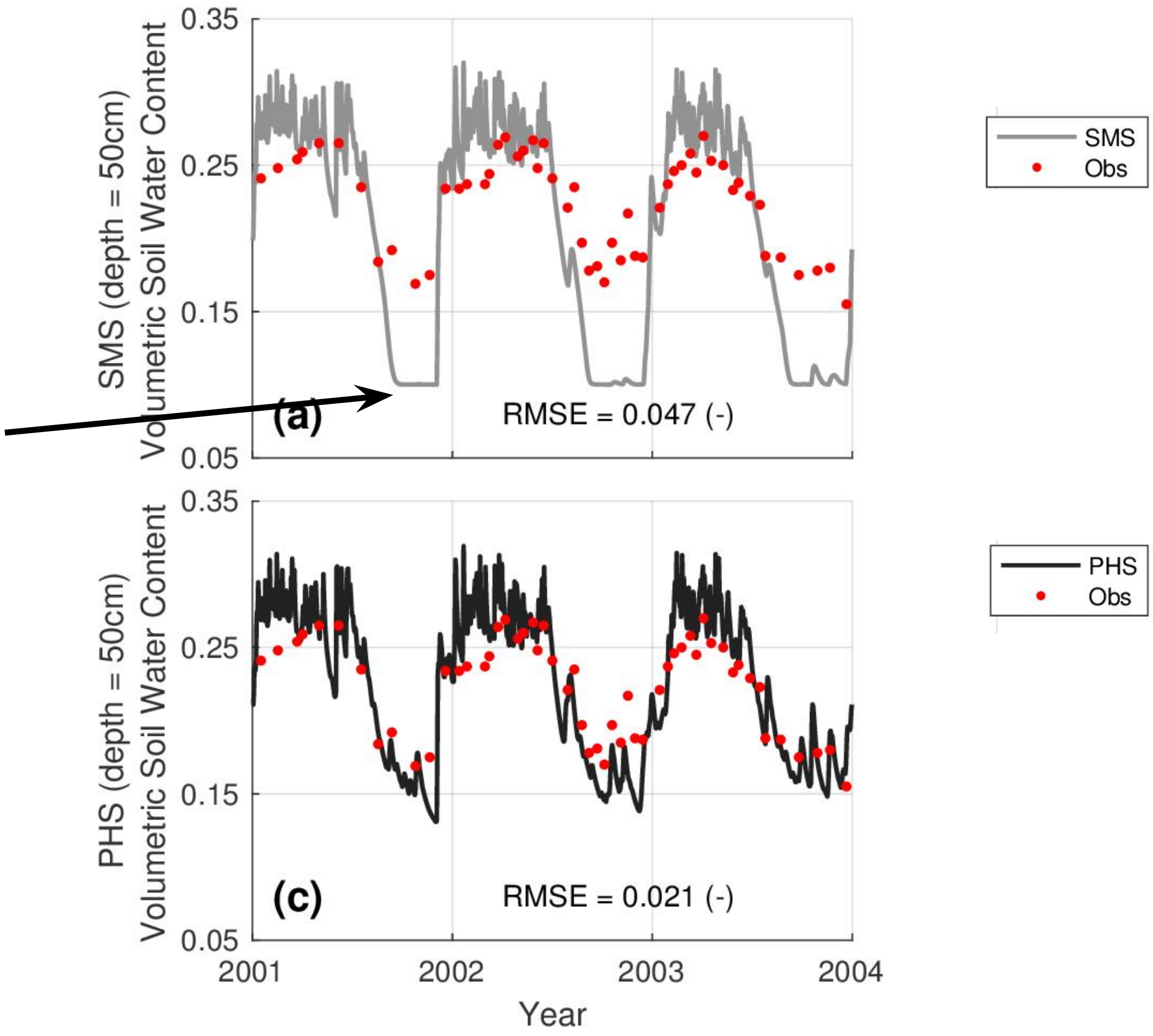
CLM4.5

PHS yields improved soil moisture dynamics

SMS root zone is too dry during dry episodes

SMS

PHS



PHS implements mechanistic Root Water Uptake (RWU)

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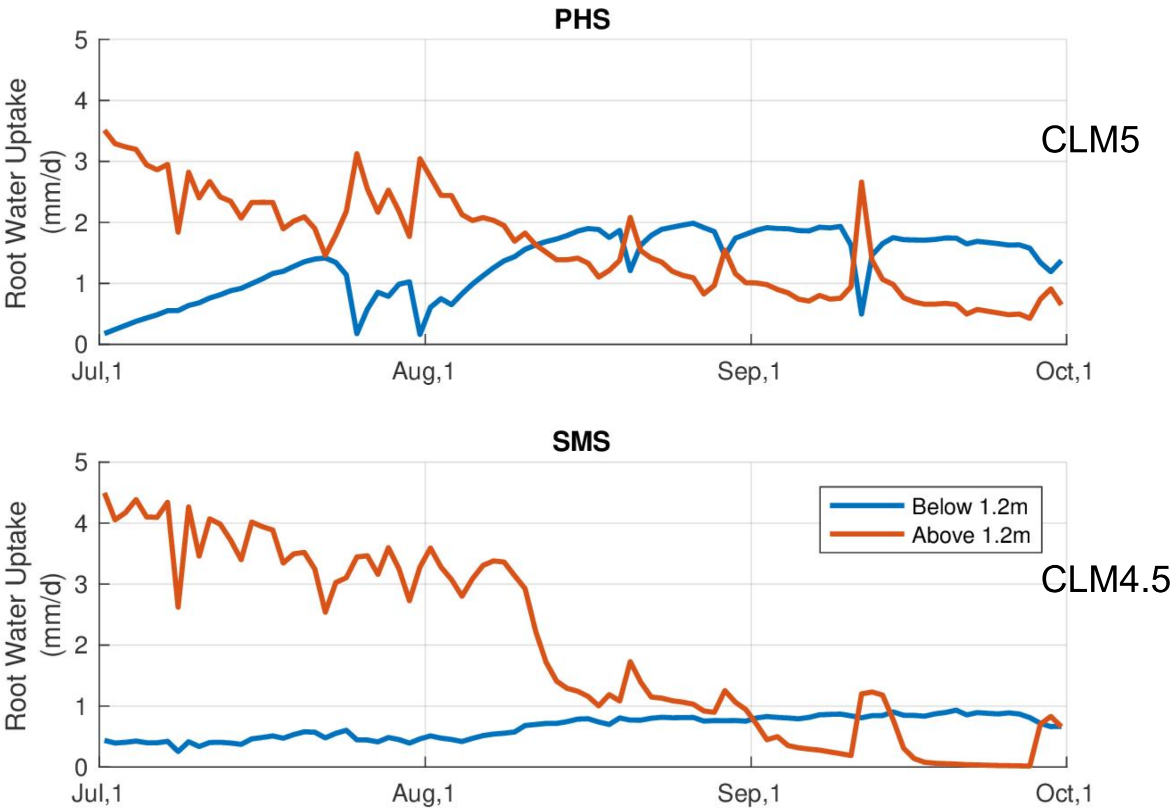
Caxiuana, 2002



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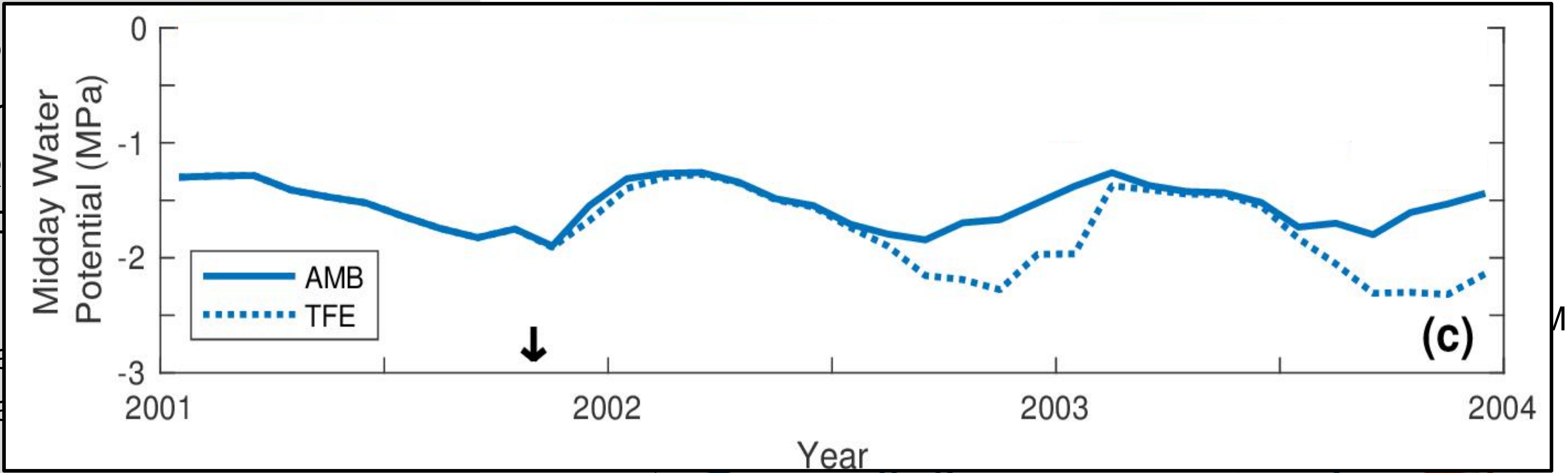
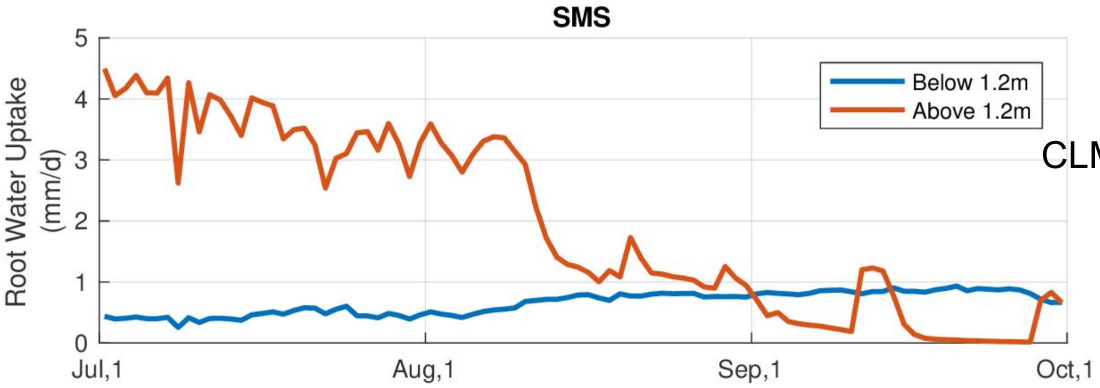


M5

Higher layers dry out and water contribution falls off

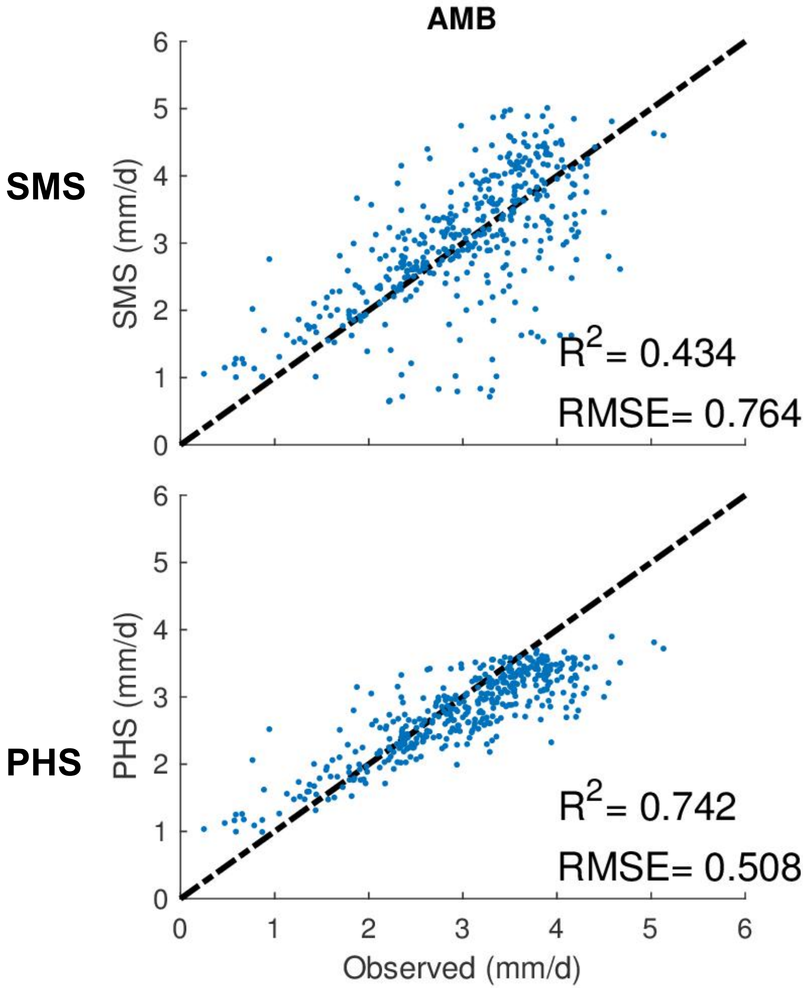
PHS partially compensates with water from deep soil



CLM4.5

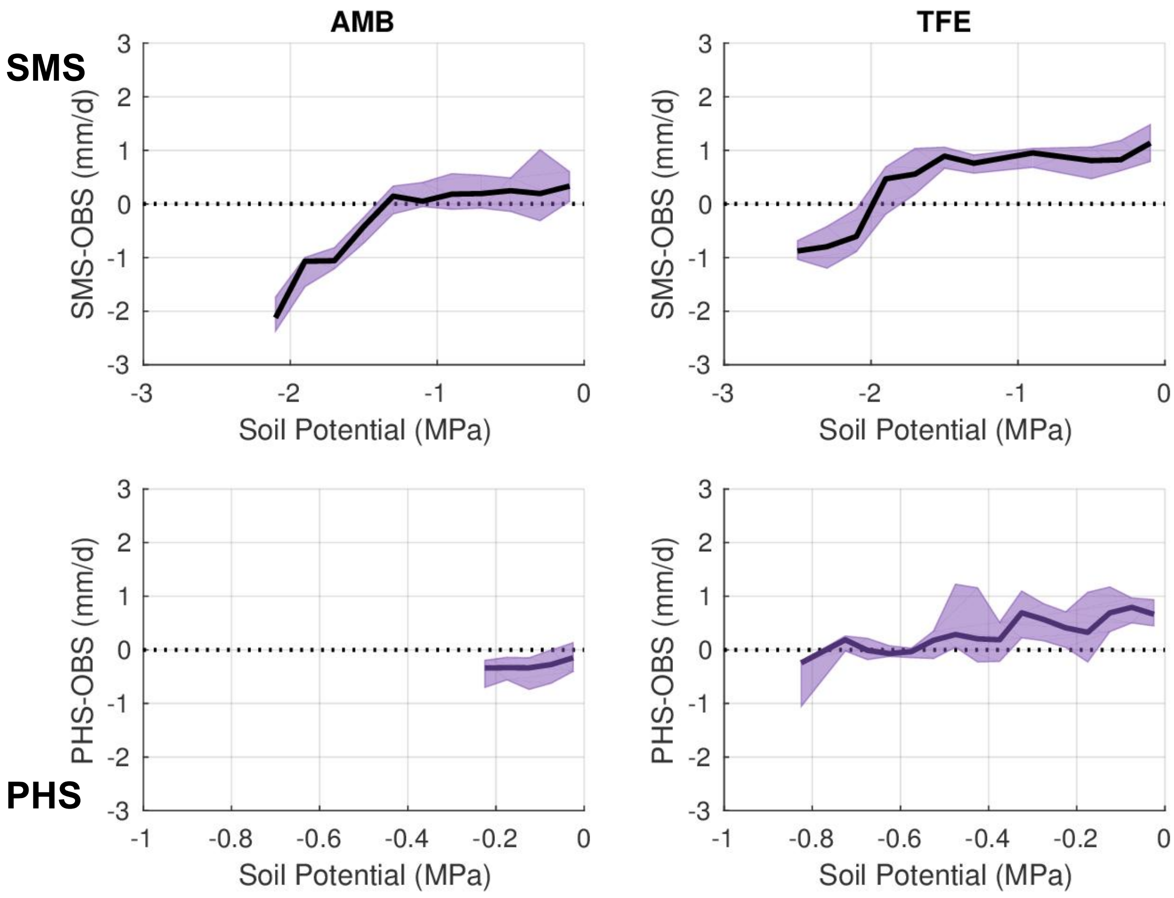
Transpiration: comparison with observations

- Improvement with PHS in RMSE and R^2
- (Single site)
    - Caxiuana, Brazil



Transpiration: comparison with observations

- Plotting transpiration: model - observations
- Line represents median
- Shading spans interquartile range
- Bin widths are
  - PHS, 0.05 MPa
  - SMS, 0.2 MPa
  - n>= 10 days
- PHS improvements derive from relationship between transpiration and soil potential



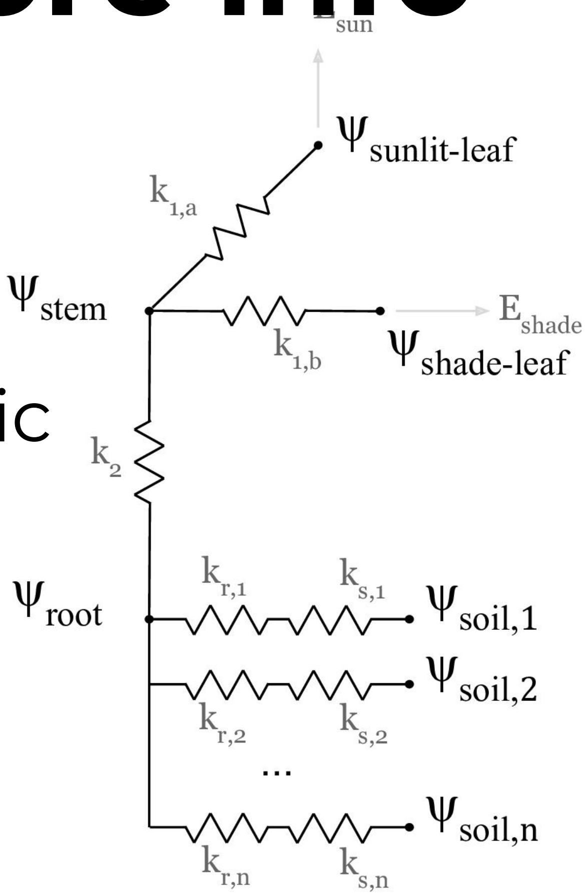
where to find more info

CLM Technical note
- Section 2.11
- cesm.ucar.edu/models/cesm2/land/

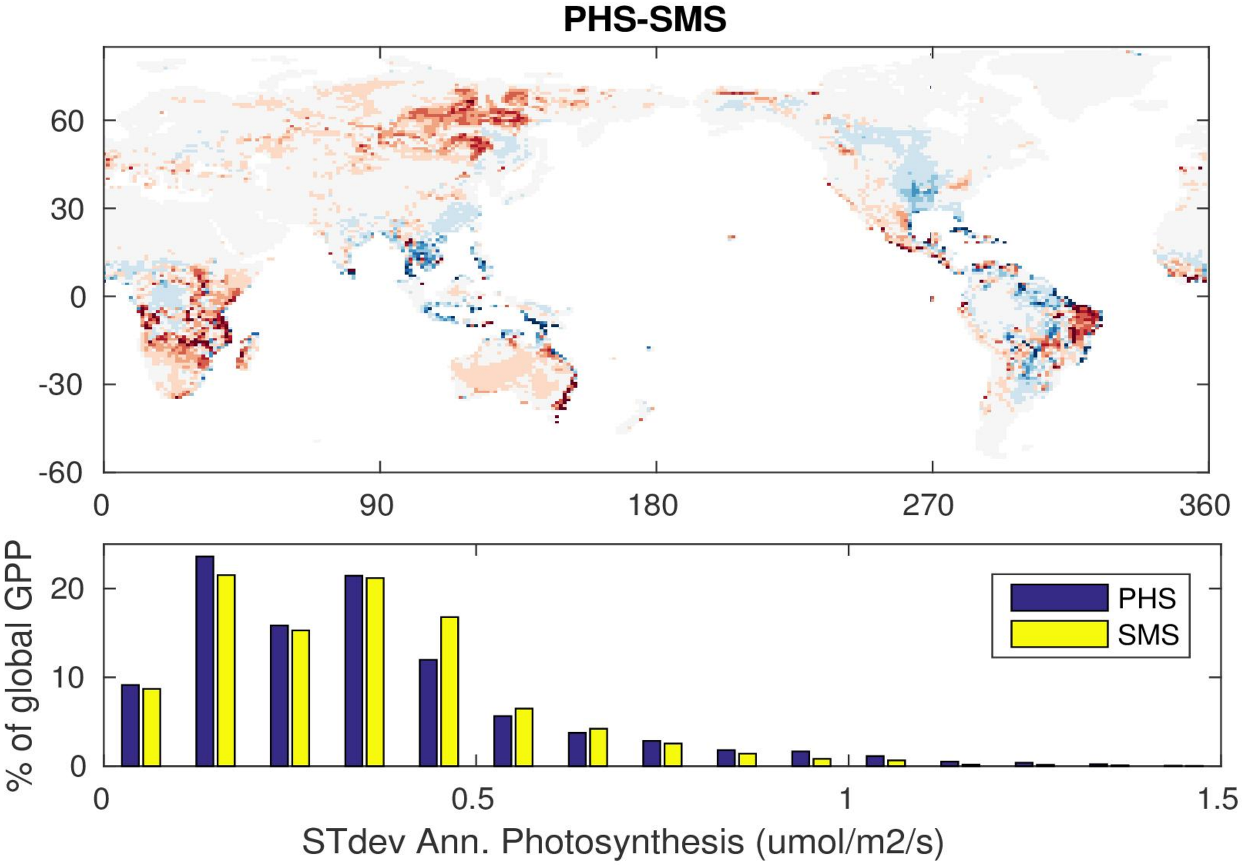
The code
- https://github.com/ESCOMP/ctsm/tree/master/src/biogeophys
- PhotosynthesisMod.F90
- SoilWaterPlantSinkMod.F90

The paper
- Implementing plant hydraulics in the Community Land Model, version 5
- Kennedy et al. 2019, *JAMES*

Plant
Hydraulic
Stress



next week...



StDev GPP

thank you!

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- Co-authors and the NCAR LMWG
- Columbia Water Center
- NCAR CISL
- Data providers

slides online:
goo.gl/GYTKYC