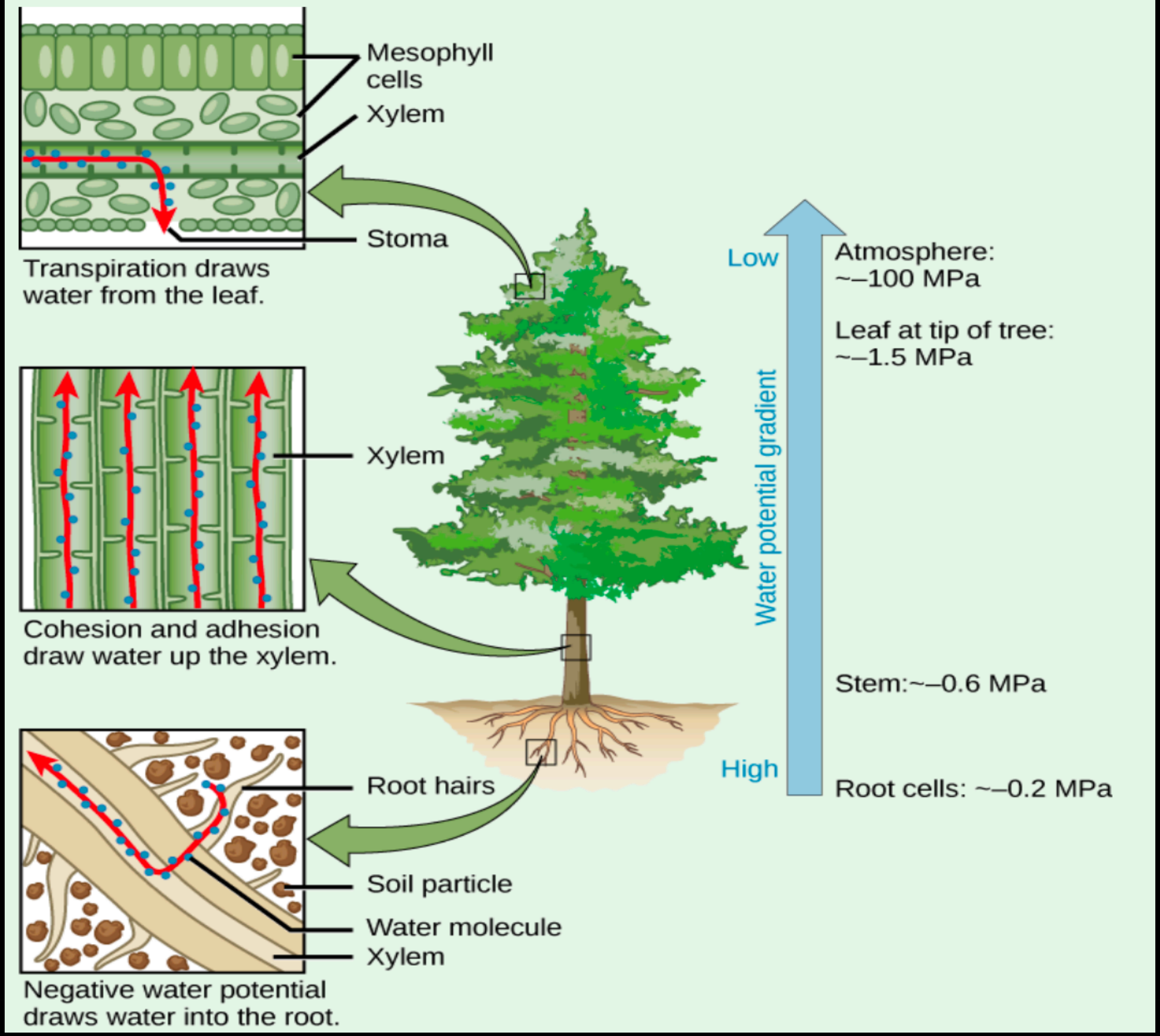
Soil-plant-atmosphere-continuum physics
From the soil to the leaves and back down

Pierre Gentine – Columbia University

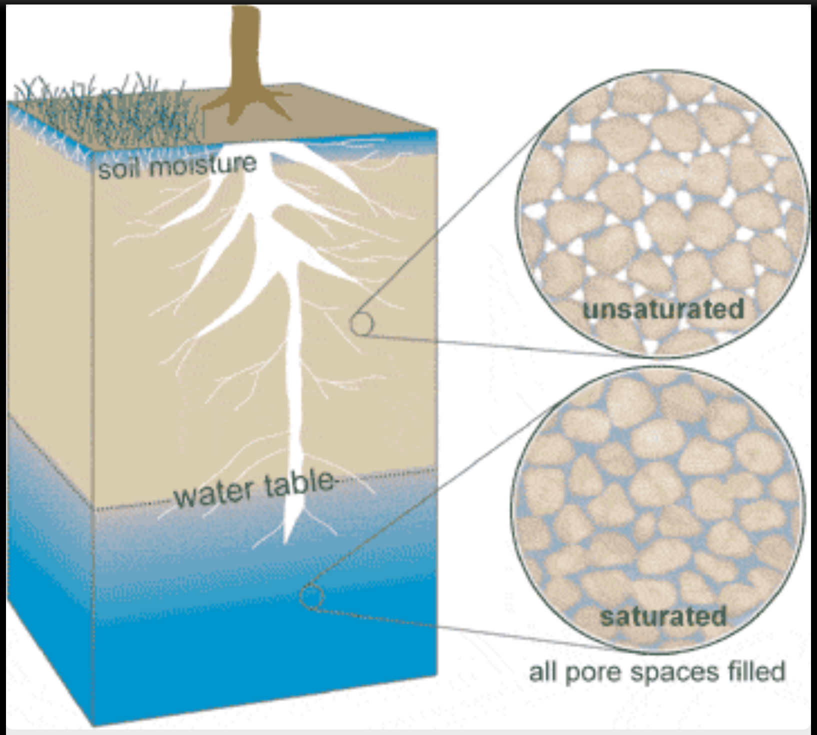


KISS workshop 2019

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

Story line

1. Soil physics – Darcy’s law and moisture balance
2. Xylem transport
3. Leaf-gas exchange – role of water
4. Phloem – flowing back down
5. Scales (time+space)



Surface hydrology 101

What drives the flow?

Total energy: hydraulic head

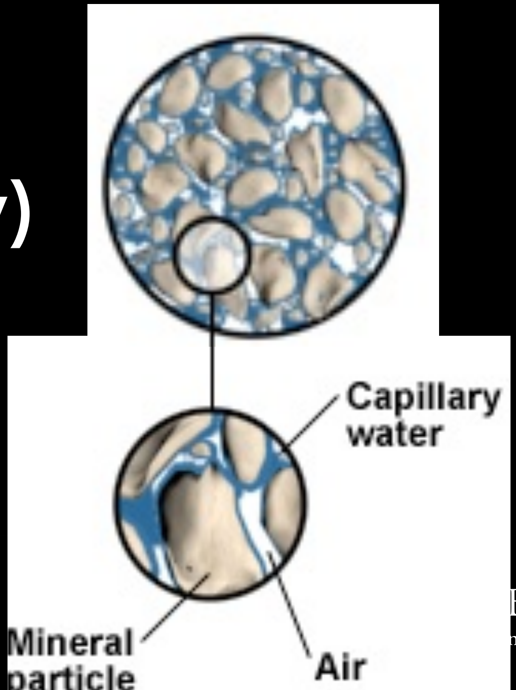
$$h = \rho g z + \psi + KE$$

0

- Potential energy $\rho g z$
- Internal pressure: matrix potential ψ

ψ <0

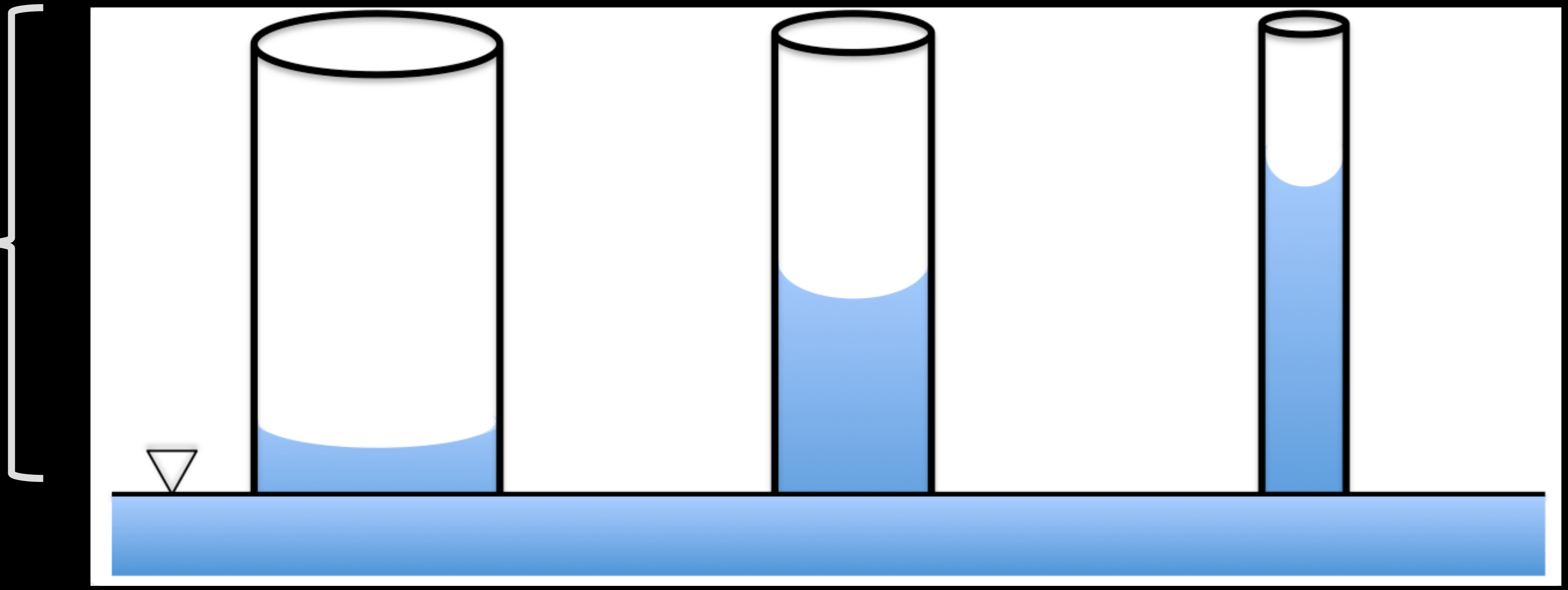
Capillary effect (hold water against gravity)



1. Soil physics

Relationship between soil moisture θ and potential ψ
Meniscus analogy

θ



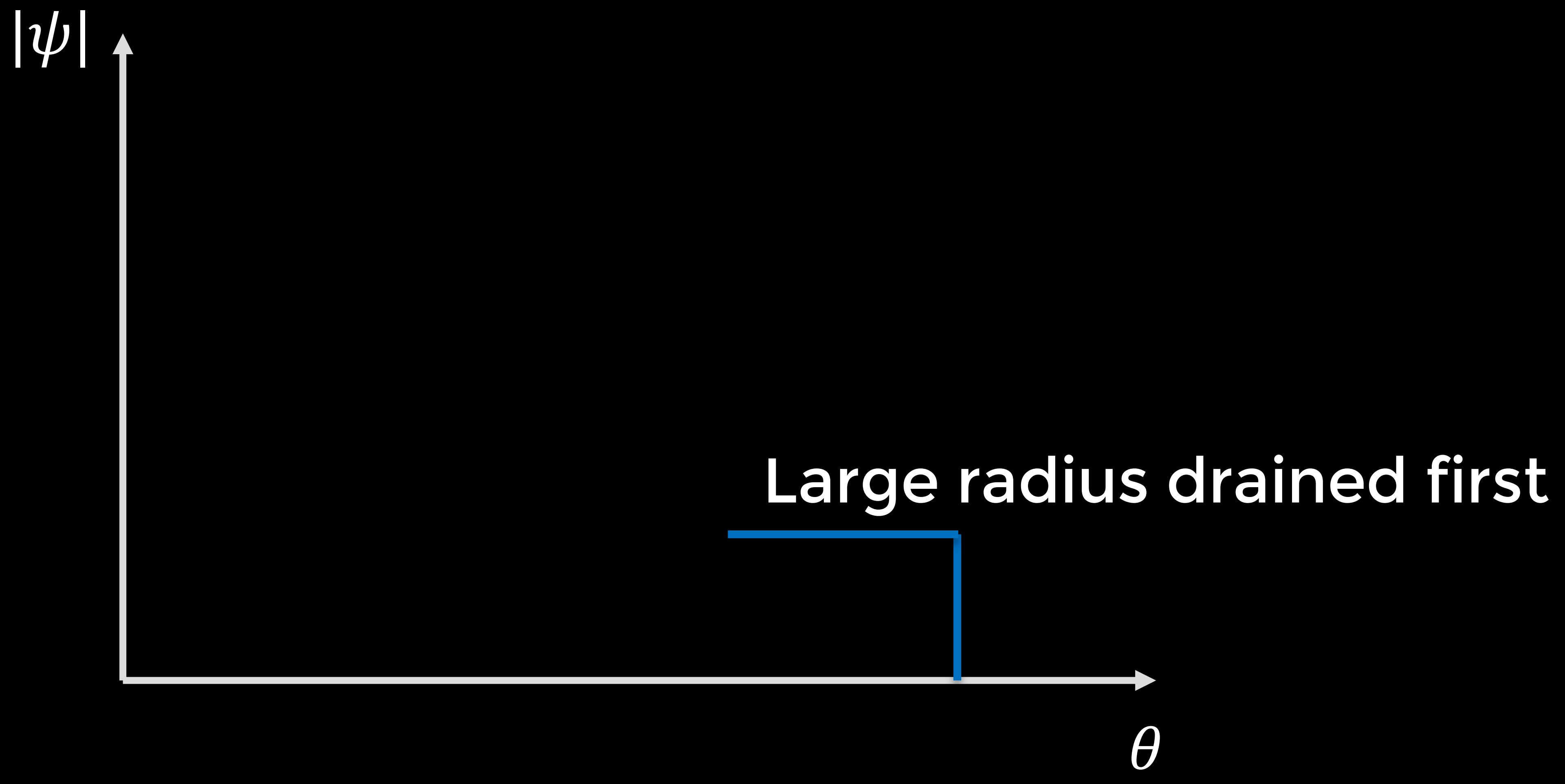
$\Delta P \sim 1/r$

Relationship between soil moisture θ and potential ψ

Meniscus analogy: pull and record θ and ψ

1. Soil physics

Relationship between soil moisture θ and potential ψ
Meniscus analogy: pull and record θ and ψ



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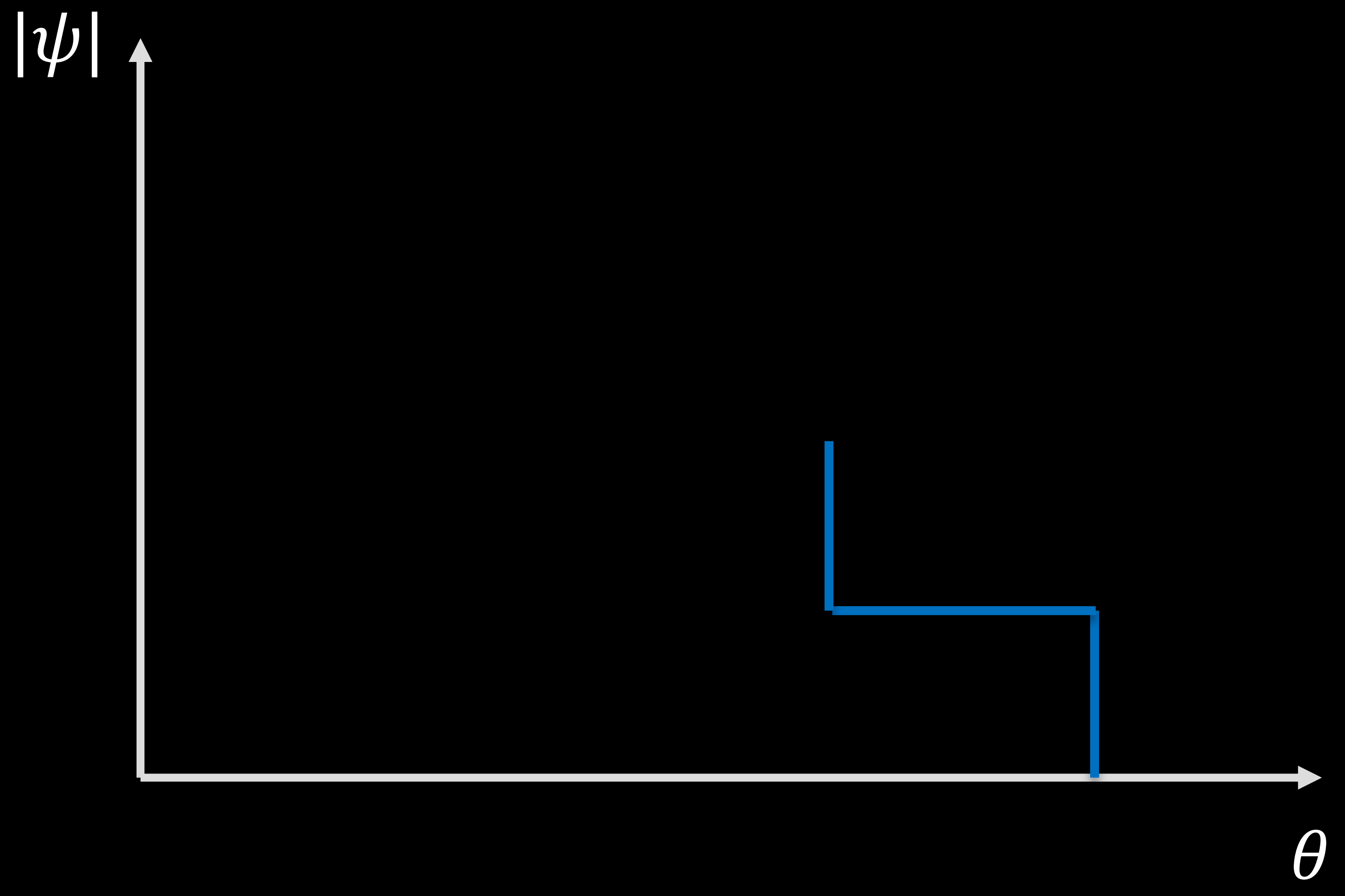

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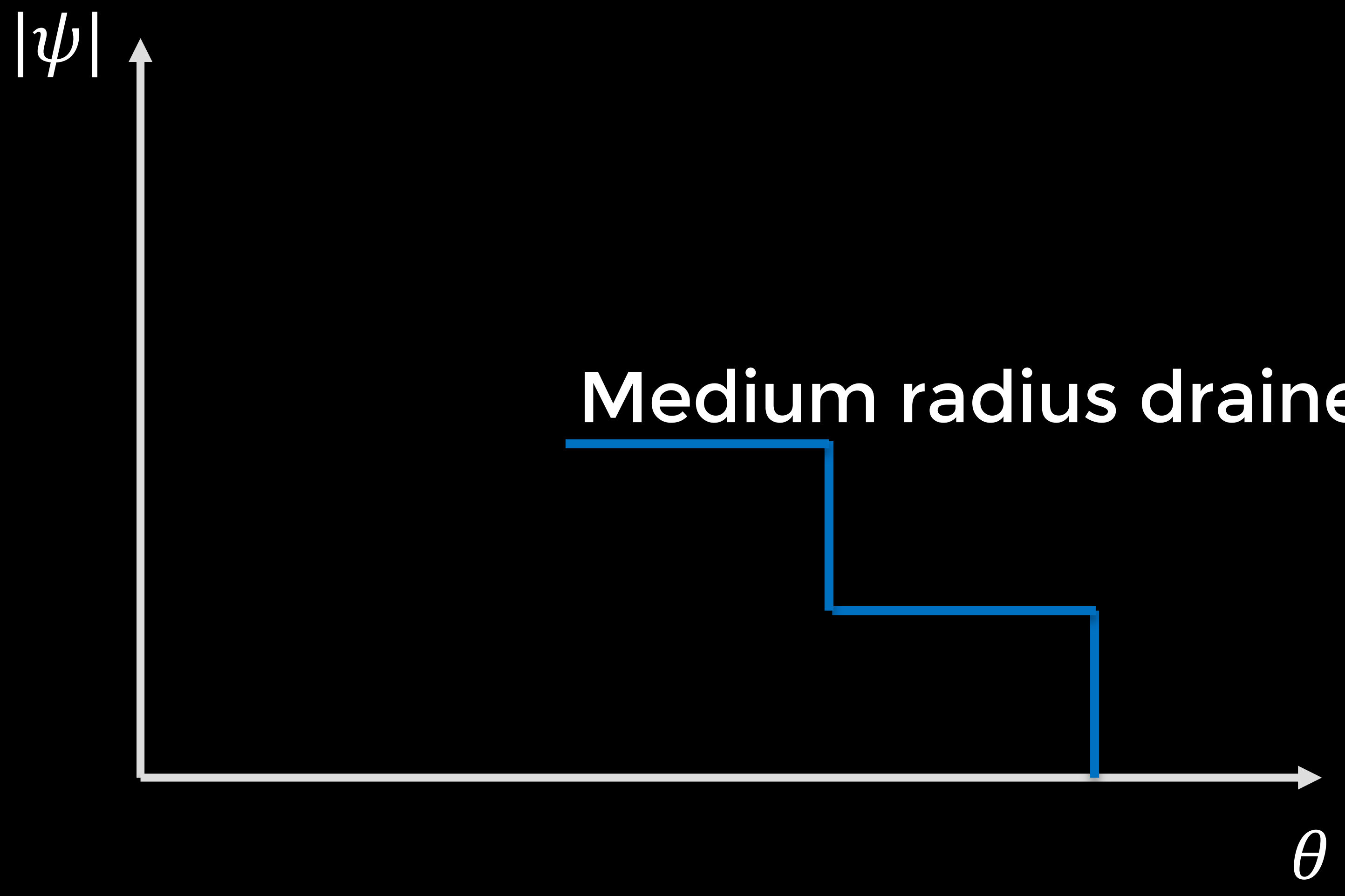

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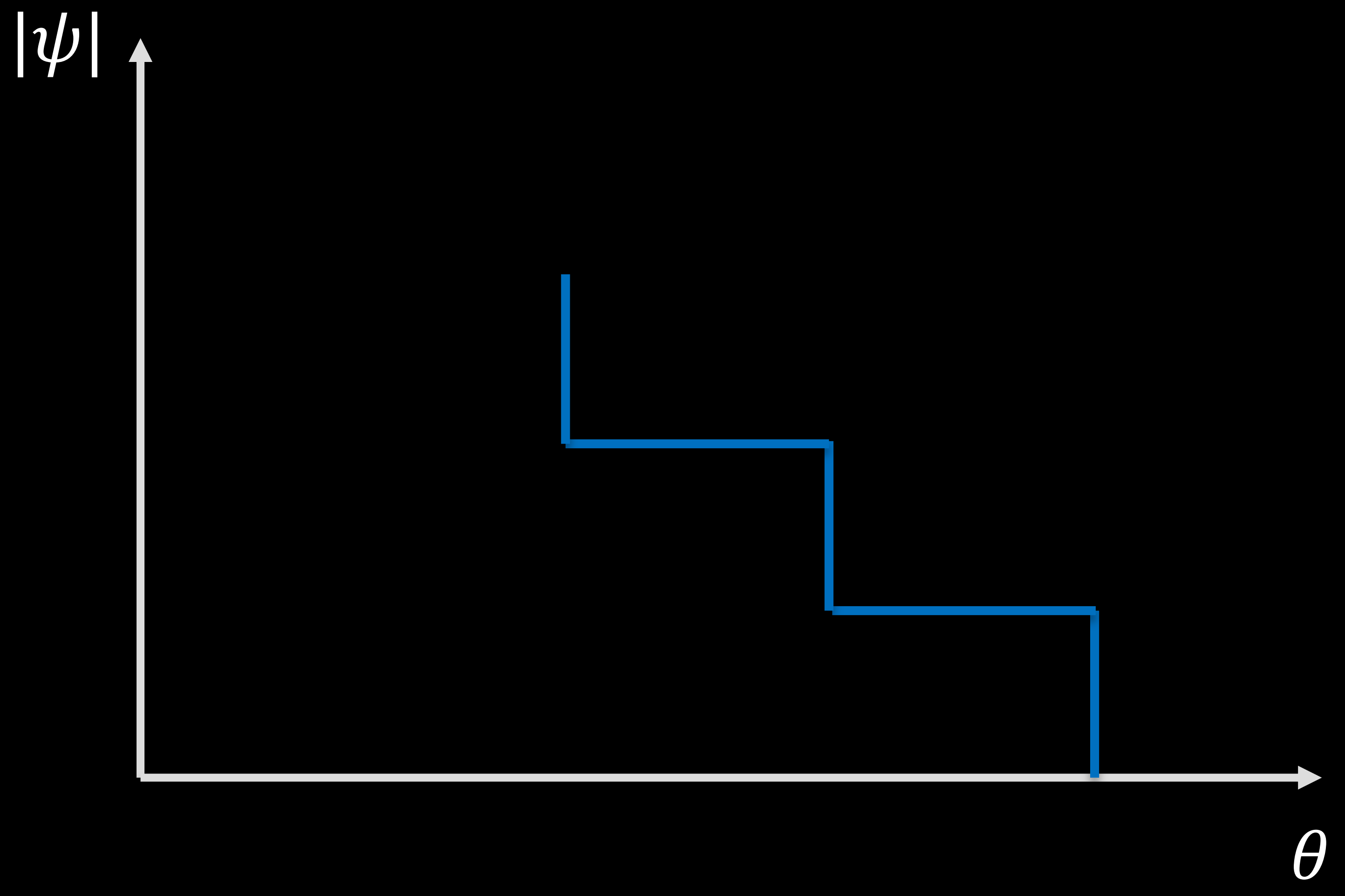

1. Soil physics

Relationship between soil moisture θ and potential ψ
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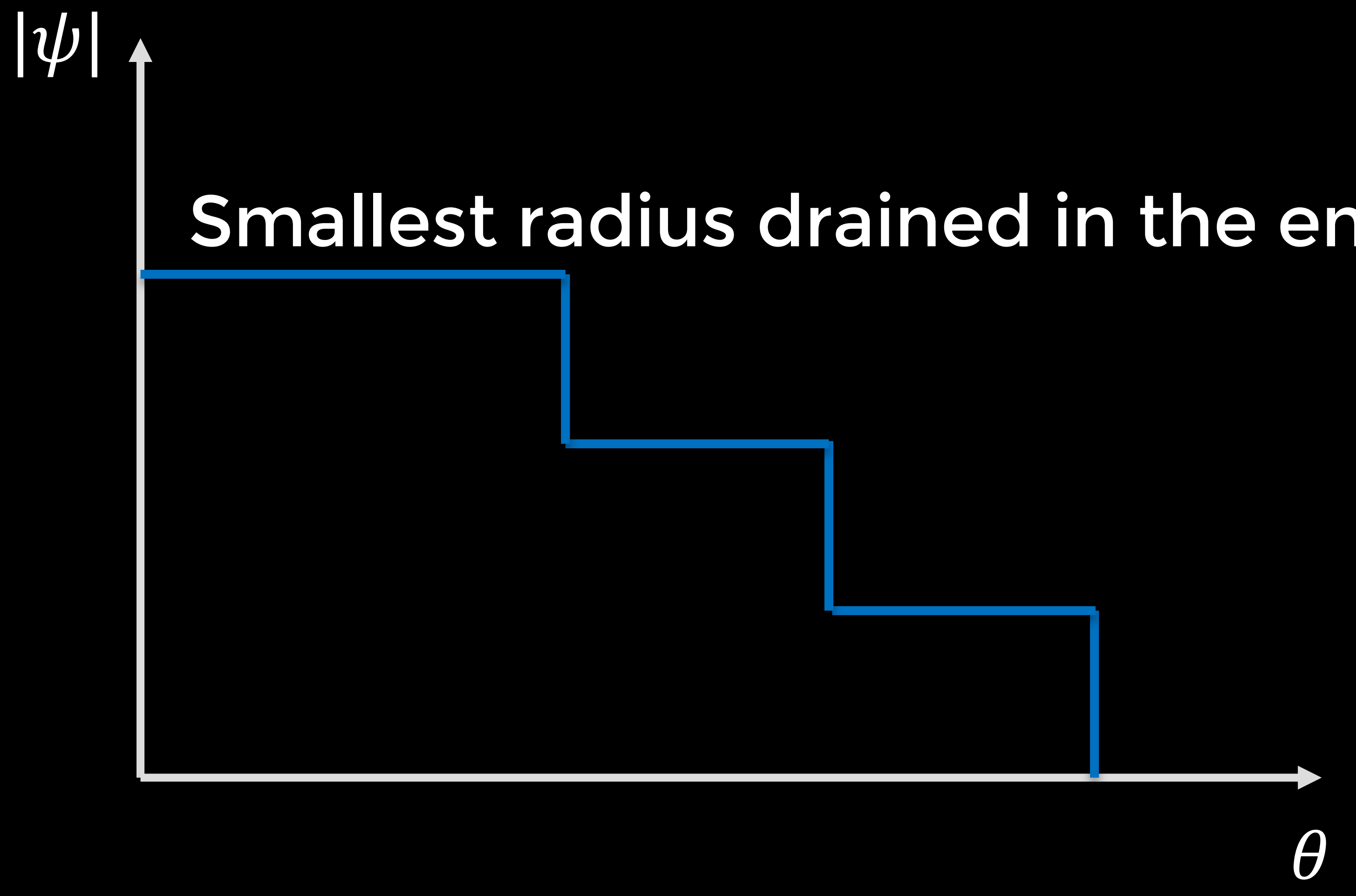
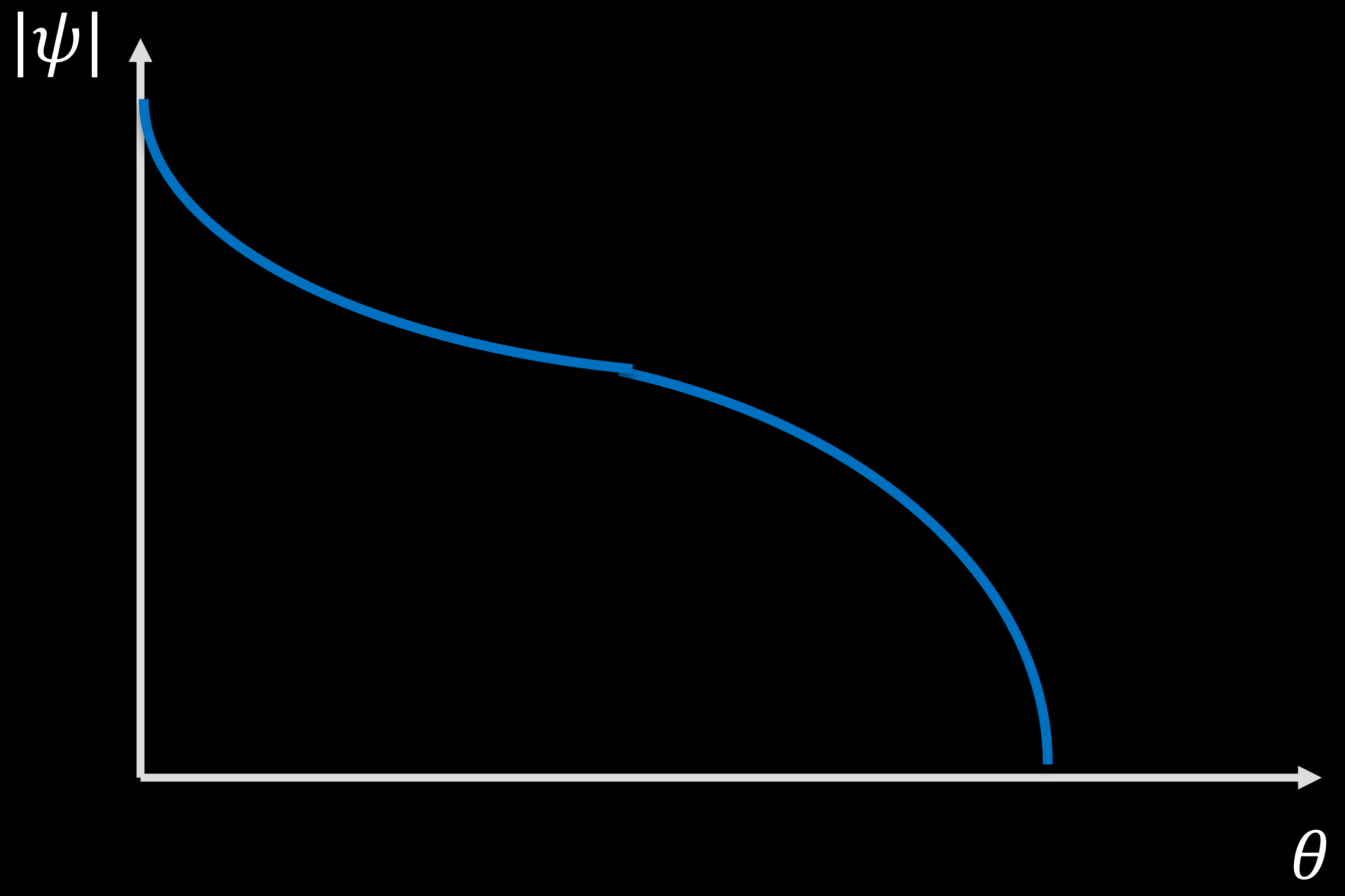


1. Soil physics

Relationship between soil moisture θ and potential ψ
Reality continuous pore size distribution

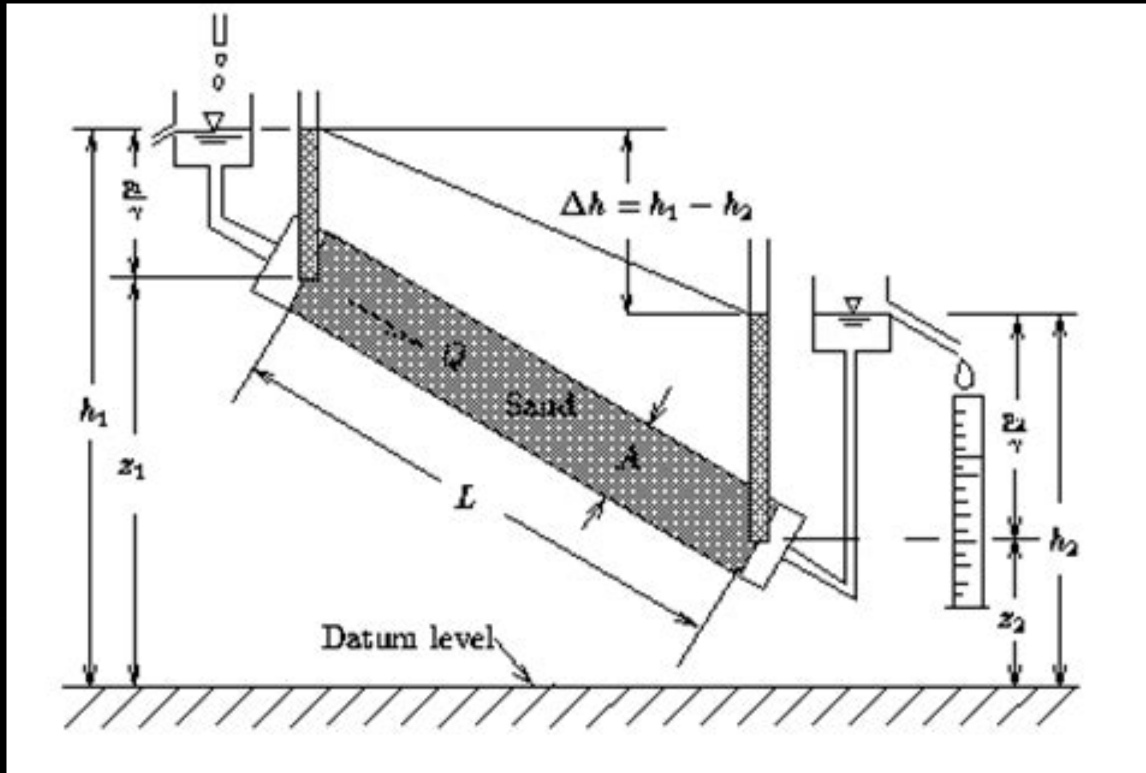


So $\theta(\psi)$ or $\psi(\theta)$

Darcy's law

$$\mathbf{q} = \frac{\mathbf{Q}}{A} = -K \nabla h$$

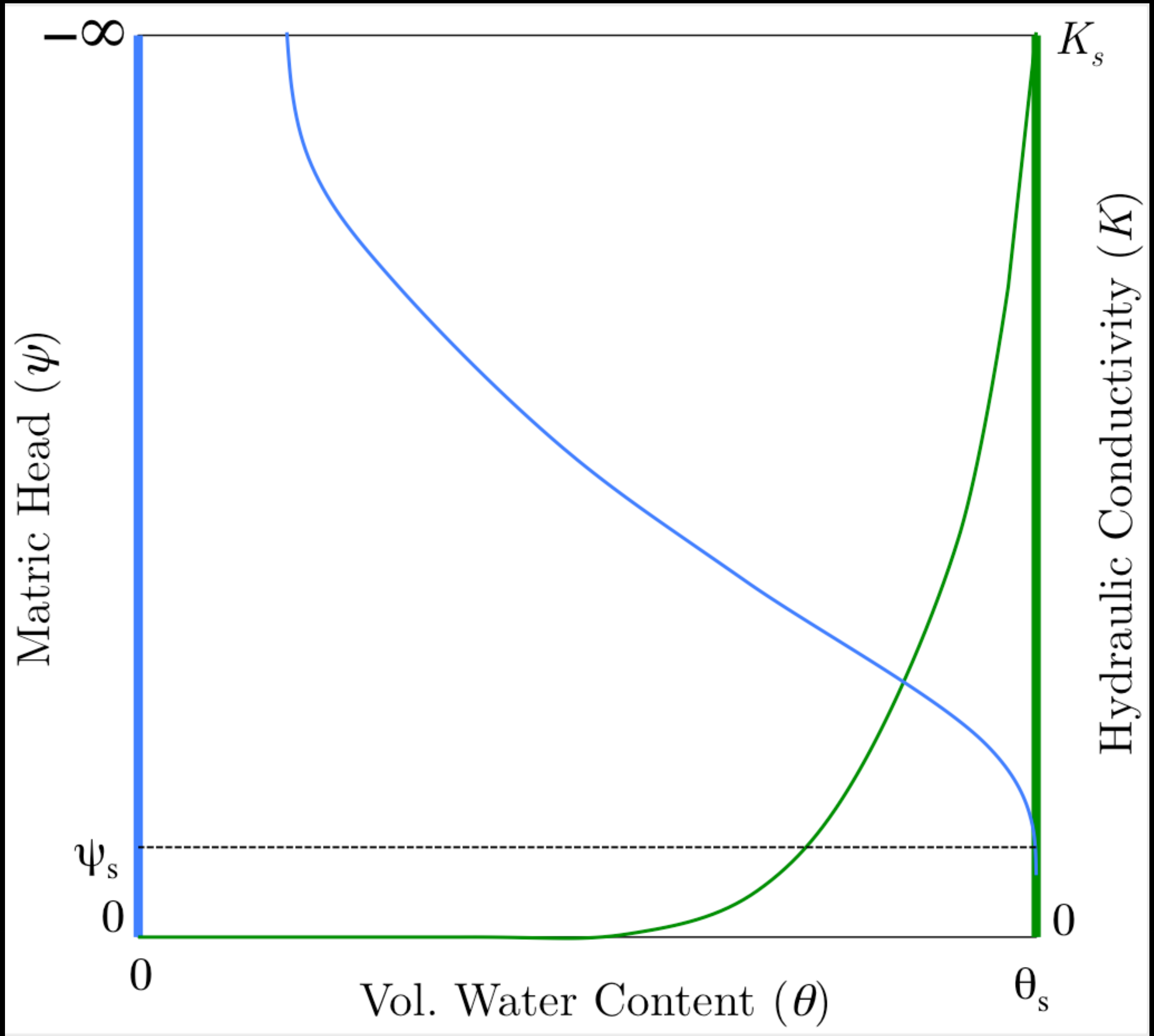
Q: discharge (L^3/T)
A: area (L^2)
q: Darcy's flux (L/T)
K: hydraulic conductivity



1. Soil physics

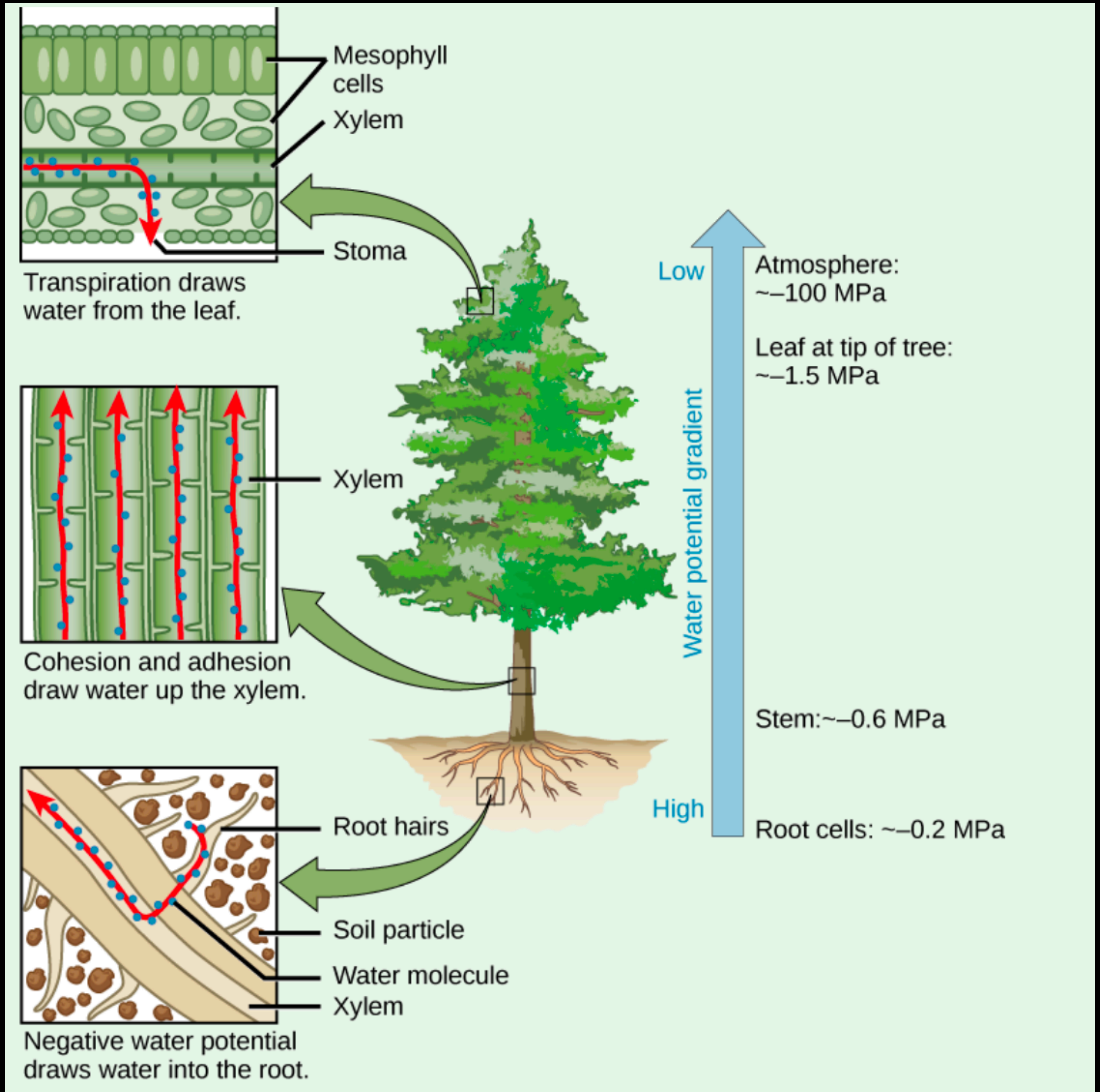
$$K = K(\theta)$$

More conductive at high water content

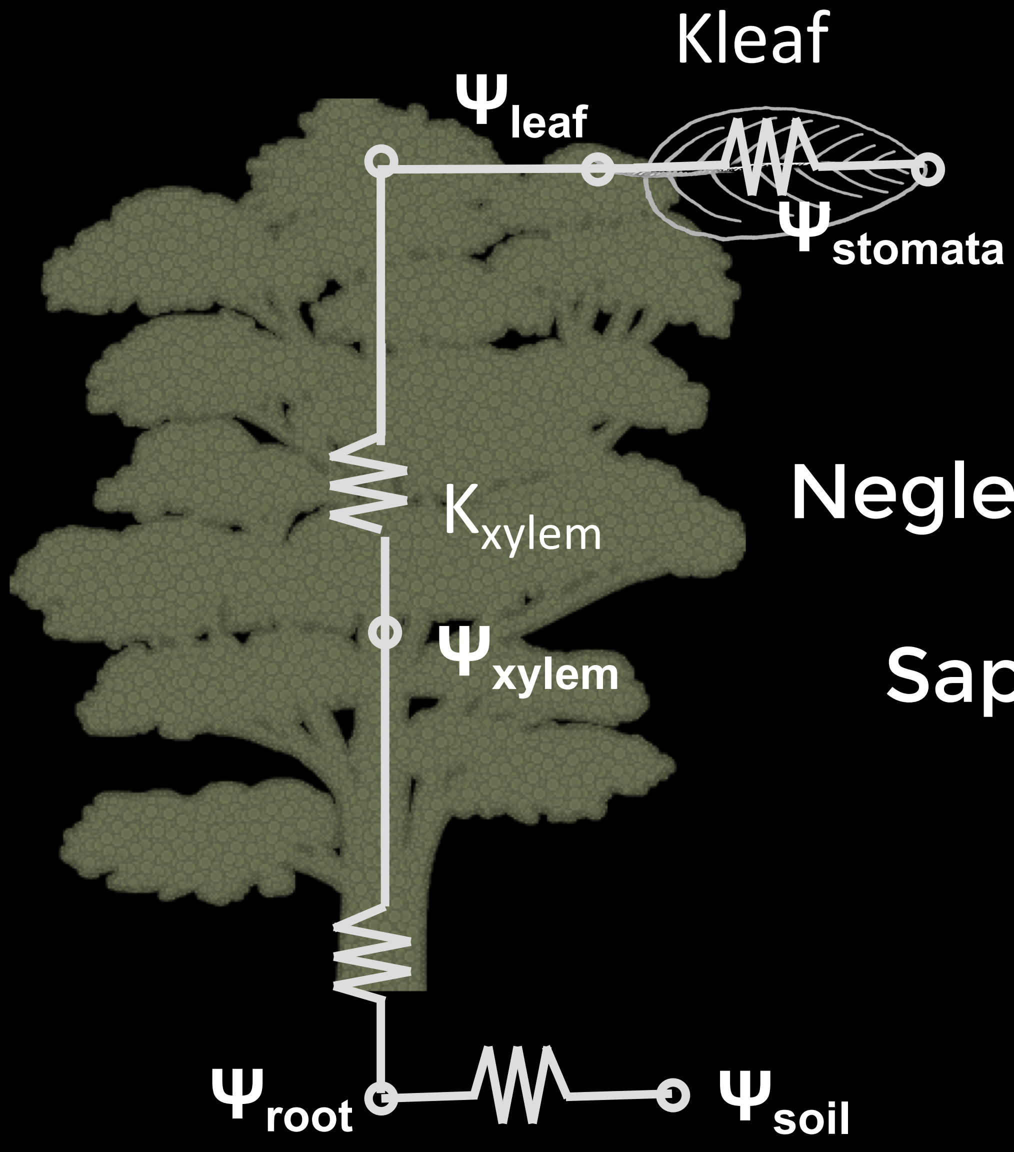


2. Xylem

Ascent of water to the leaves: **sap** through the xylem (cohesion-tension theory). Driven by **transpiration**



2. Xylem



Also obey Darcy's law
Menisci better analogy ☺

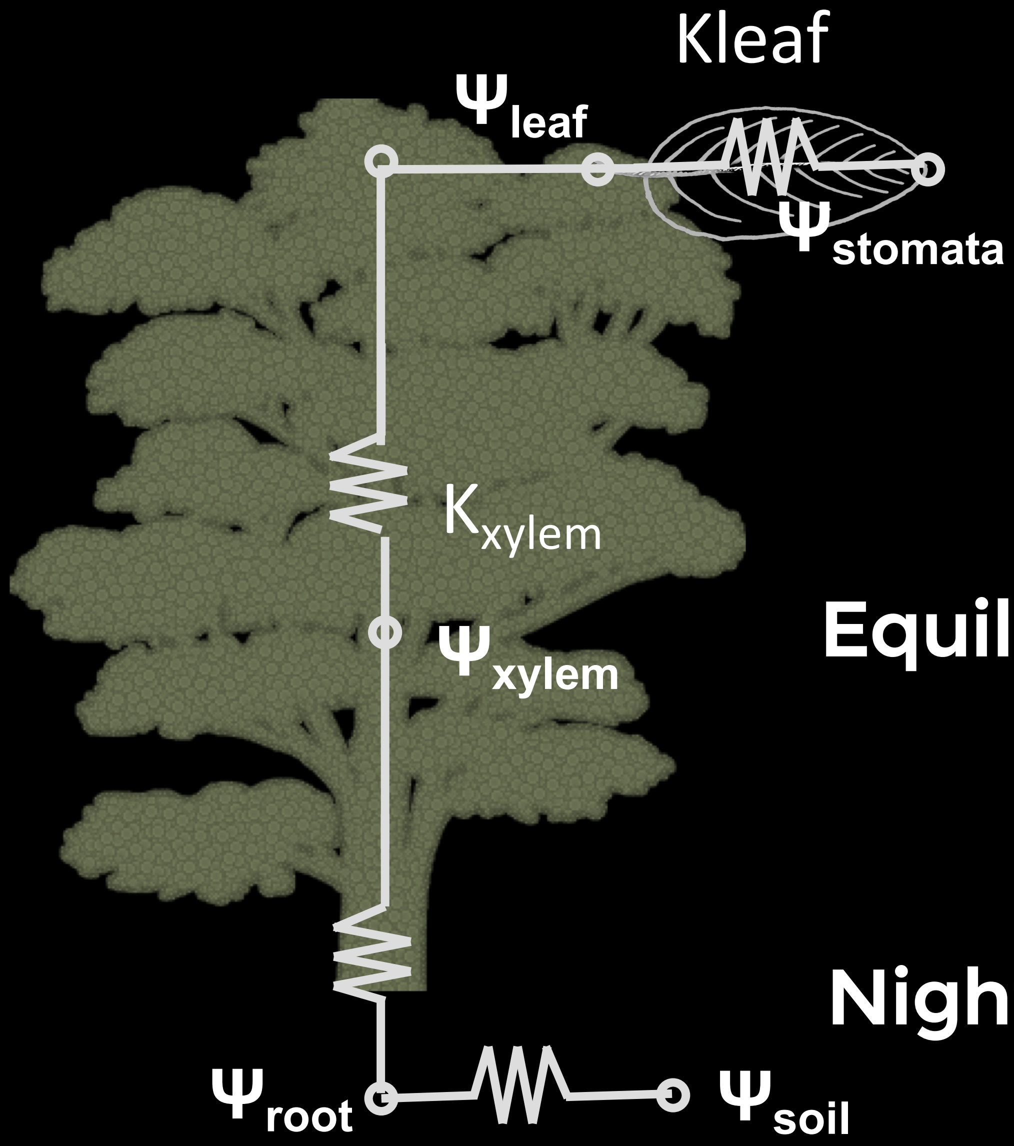
$$\text{Sap density} = -K_{xylem}(\psi)\,\frac{\partial h}{\partial z}$$

Neglect storage for now and integrate

$$\text{Sap} = K_{xylem}(\psi_{xylem})\,(\psi_{root}-\psi_{leaf}-\rho g z)$$

=Transpiration

2. Xylem



Key trick

At night:
No transpiration

So (if negligible storage)
No sap

Equilibrium of potential in the SPAC!

$$\psi_{\text{leaf}} = \psi_{\text{root}} + \rho g z = \psi_{\text{soil}} + \rho g z$$

Nighttime leaf potential = soil value!
(Root zone)

2. Xylem

Embolism

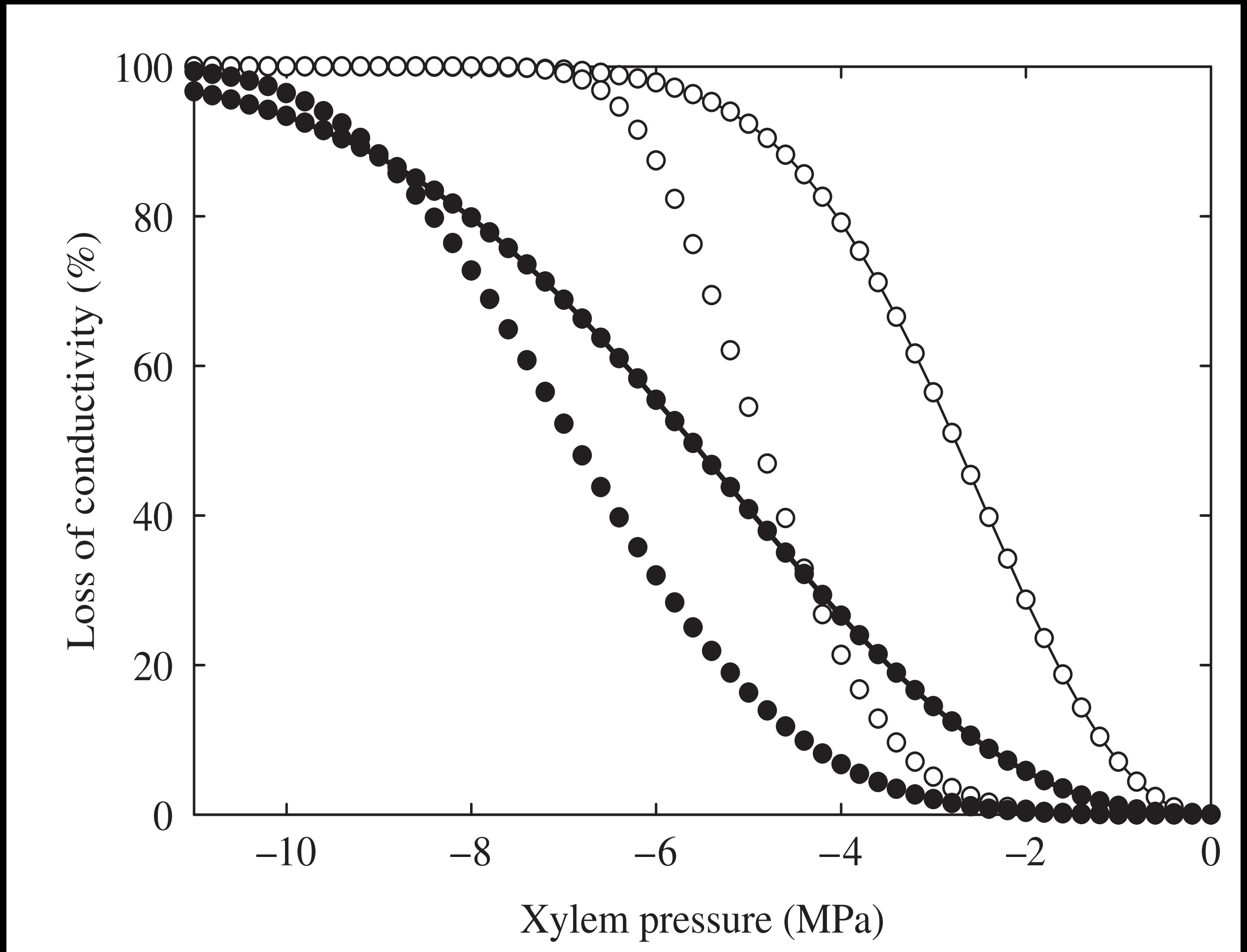
$K_{xylem}=f(\psi)$ like in soil

Why?

Water in xylem is metastable (under tension)

Bubble of air form as xylem is under more and more negative tension

(Can be ice too - drought and freezing tolerance are a bit alike)



Weibull type function

2. Xylem

Embolism

A few important questions

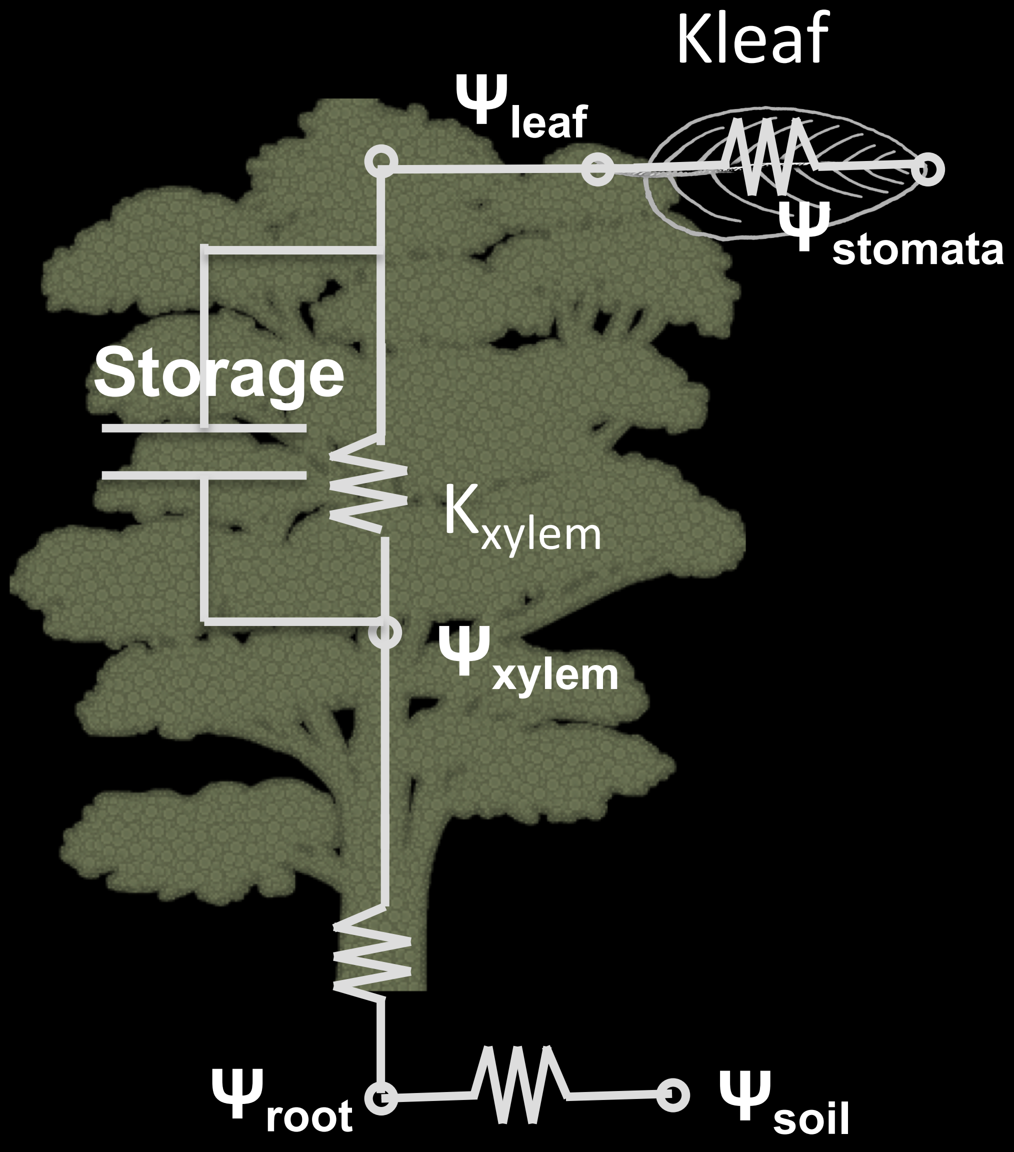
- Is refilling instantaneous?

- Memory of embolized vessels – permanent damage
  Cell implosion?

Red: intact
Uncolored: embolized

Mayr et al. Plant Phys 2014

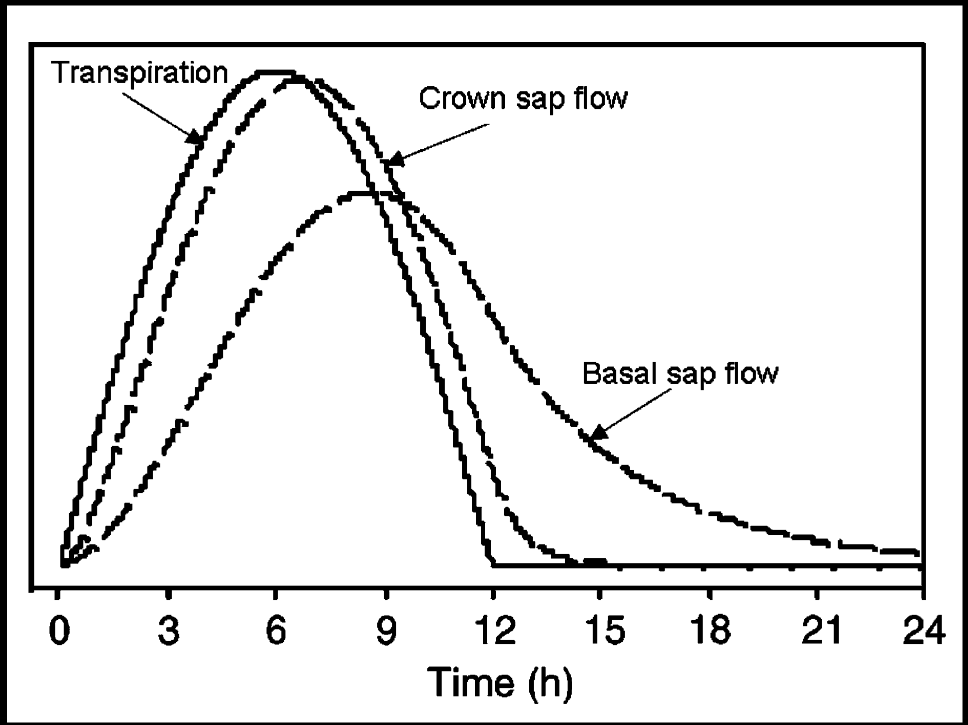
Storage

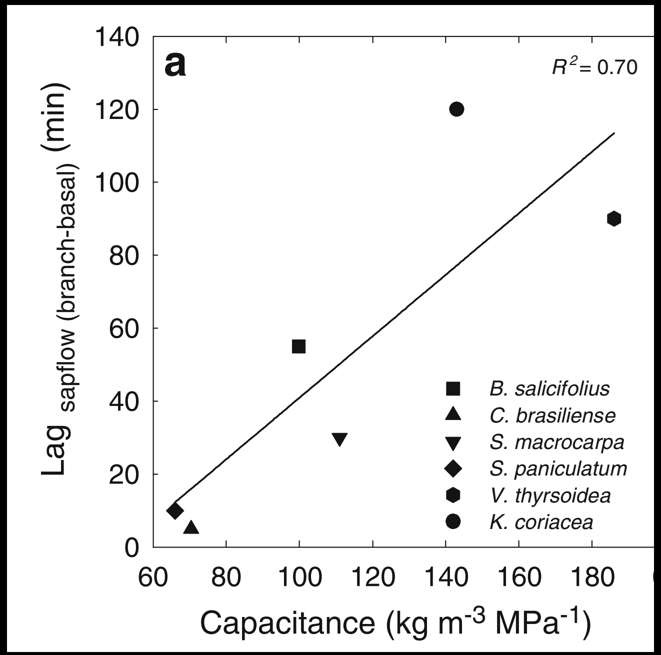


In reality plant store water

Imbalance between sap and transpiration

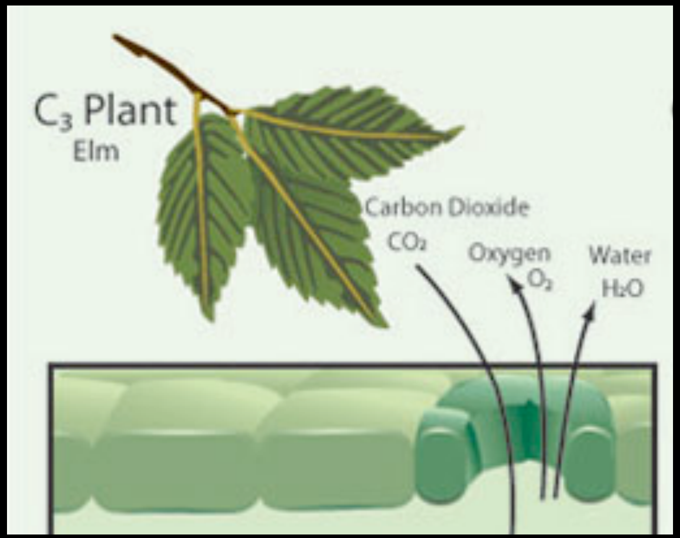
dStorage/dt = Sap - Transpiration





Phillips et al *Plant Soil* 2009

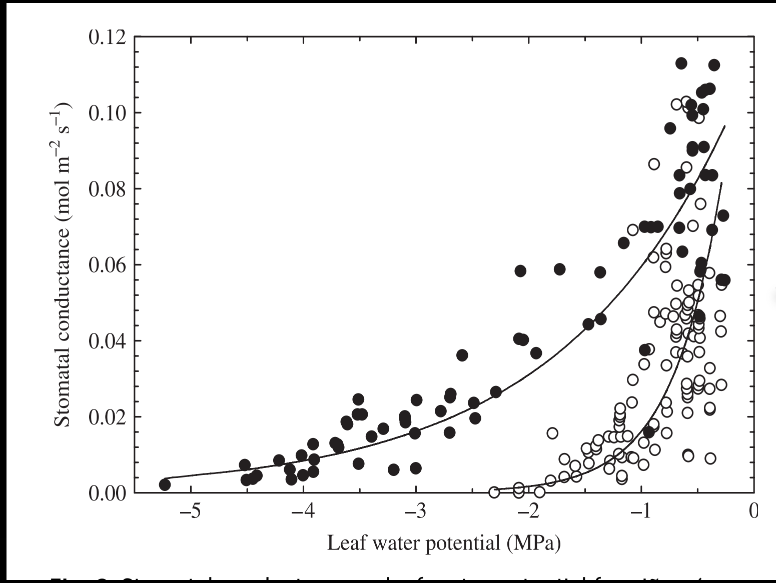
2. Leaf



Leaf gas exchange

Water and carbon cycles are coupled through stomata

Stomata close and open in response to water stress



Klein et al. 2014

2. Leaf

Transpiration $T = g_{stomata}\ VPD_{leaf}$

$$GPP = 1.6\ g_{stomata}\ (C_a - C_i)$$

$$g_{stomata} = f(VPD, \psi_{leaf})$$

In the absence of stress in the xylem

$$g_{stomata} \sim GPP/\ VPD_{leaf}^{0.5}\ \text{(Medlyn model)}$$

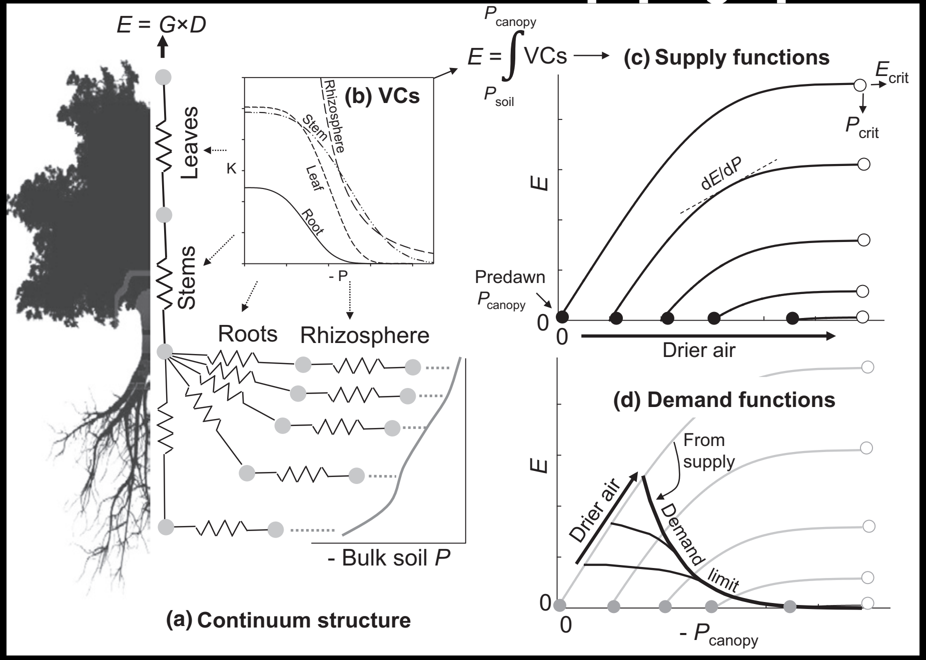
or

$$g_{stomata} \sim GPP\ .\ RH\ \text{(Ball-Berry model)}$$

Cowan and Farquahr 1977, Ball and Berry 1986, Farquhar and Sharkey 1982, Katul *et al* 2009, Medlyn *et al* 2011

Impact of ψ_{leaf} on leaf gas exchange?
Still relatively ad-hoc
Either modifies g_{max} or V_{cmax}

- Sperry introduced a concept of supply-demand: canopy water demand is regulated in proportion to threat to supply posed by xylem cavitation

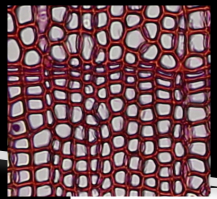


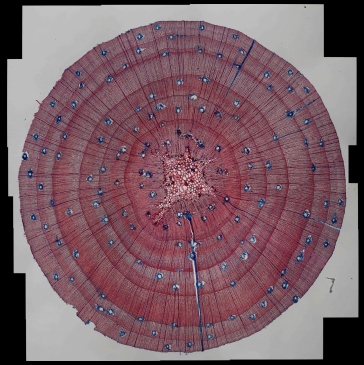
- Wolf & Anderegg: Carbon maximization theory based on constraints (e.g. supply and demand)

Sperry New Phyt 2016, Wolf et al. PNAS 2016, Anderegg Ecol Letters 2018

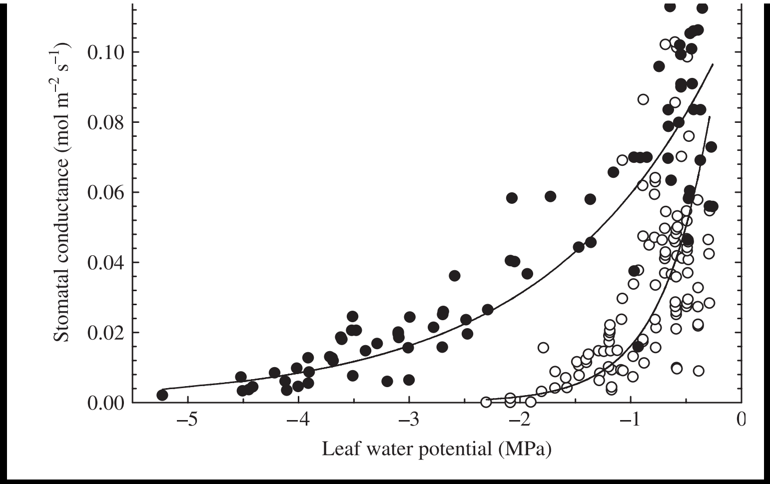
Xylem vs. leaf stress

Interplay between xylem and leaf gas exchange

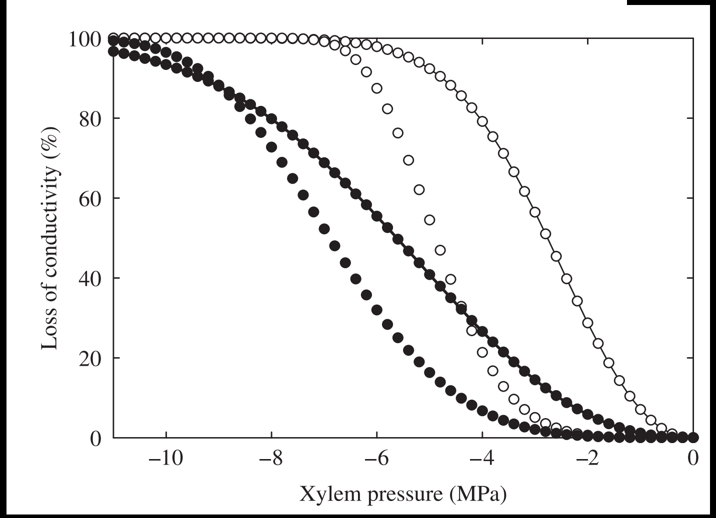




Stomatal response to leaf water stress



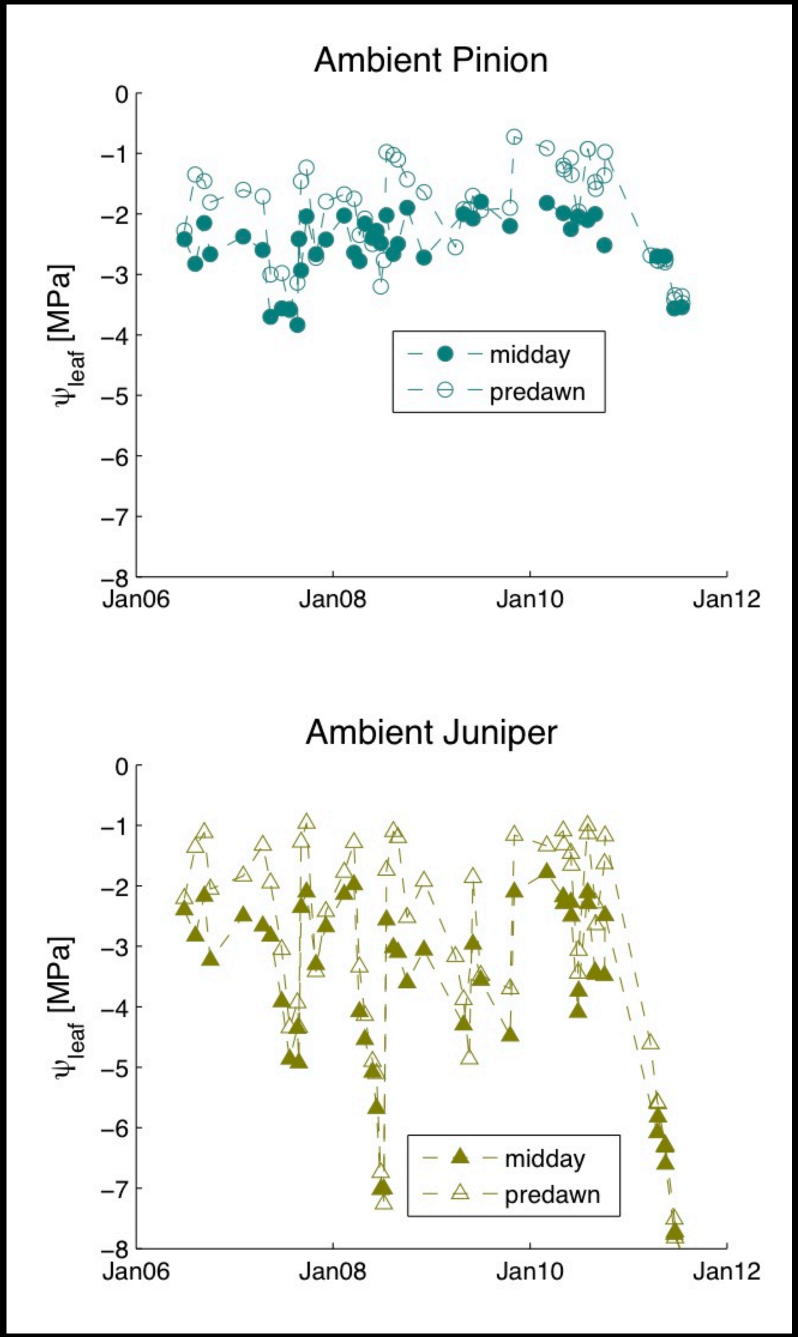
Xylem cavitation



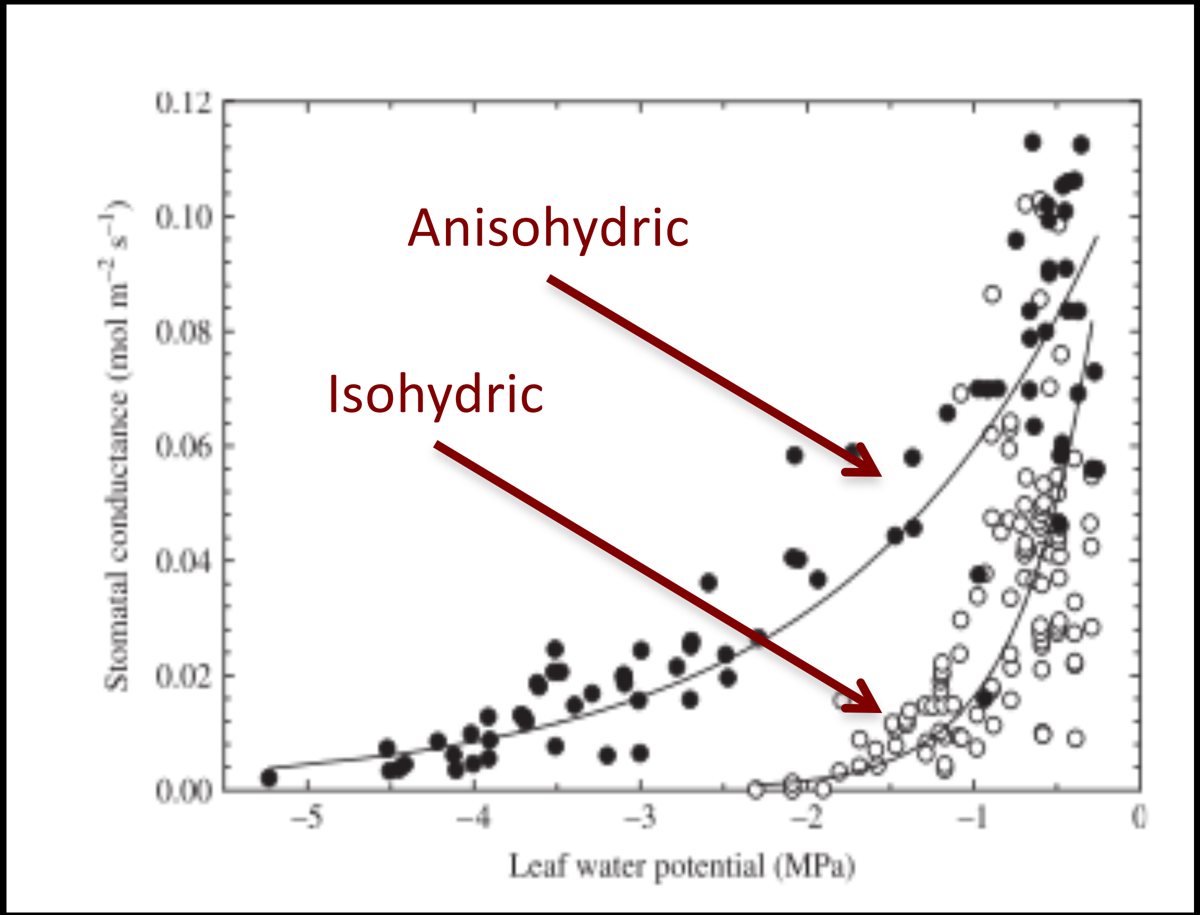
Isohydricity

Isohydric

Anisohydric



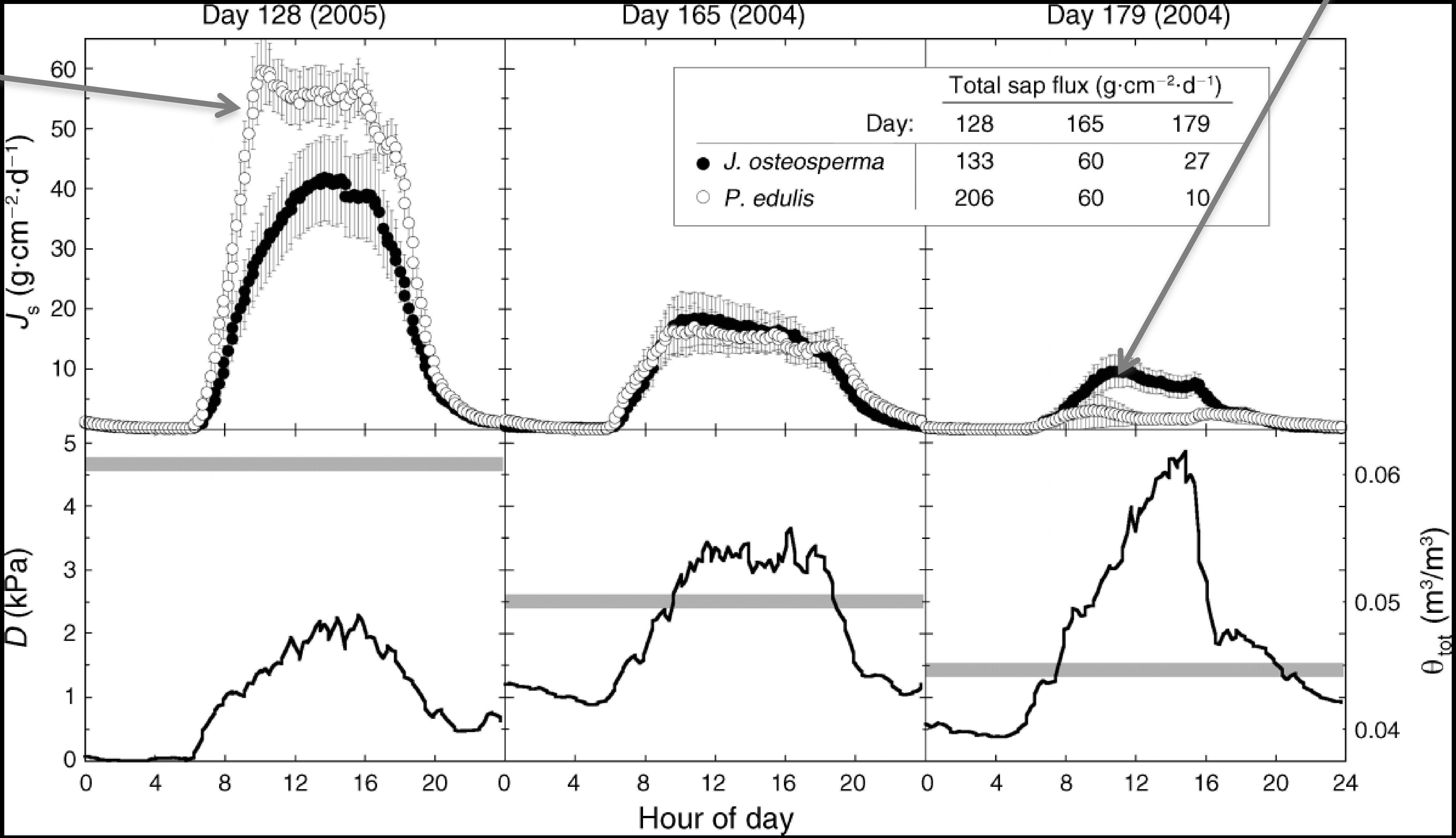
Near-constant Leaf water potential



Isohydricity

Isohydric
Strong
stomata
regulation

Anisohydric - Xylem control

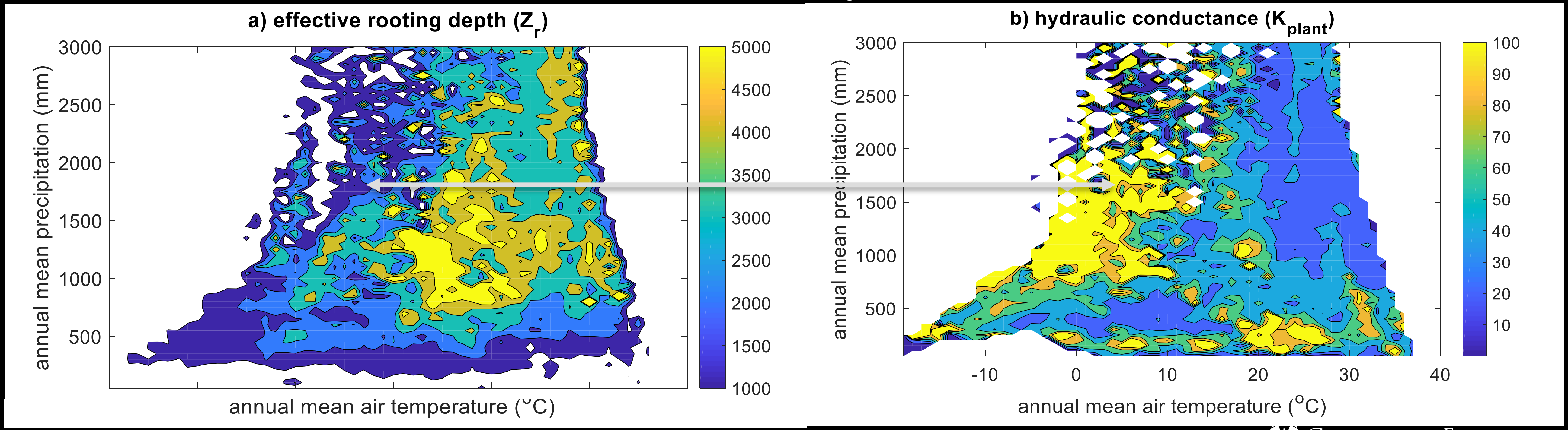


Leaf water potential time scales

Temporal variations in leaf water potential
Diurnal to seasonal

- Physiology regulates diurnal ψ_{leaf}
- Both root moisture & physiology regulate seasonal ψ_{leaf}

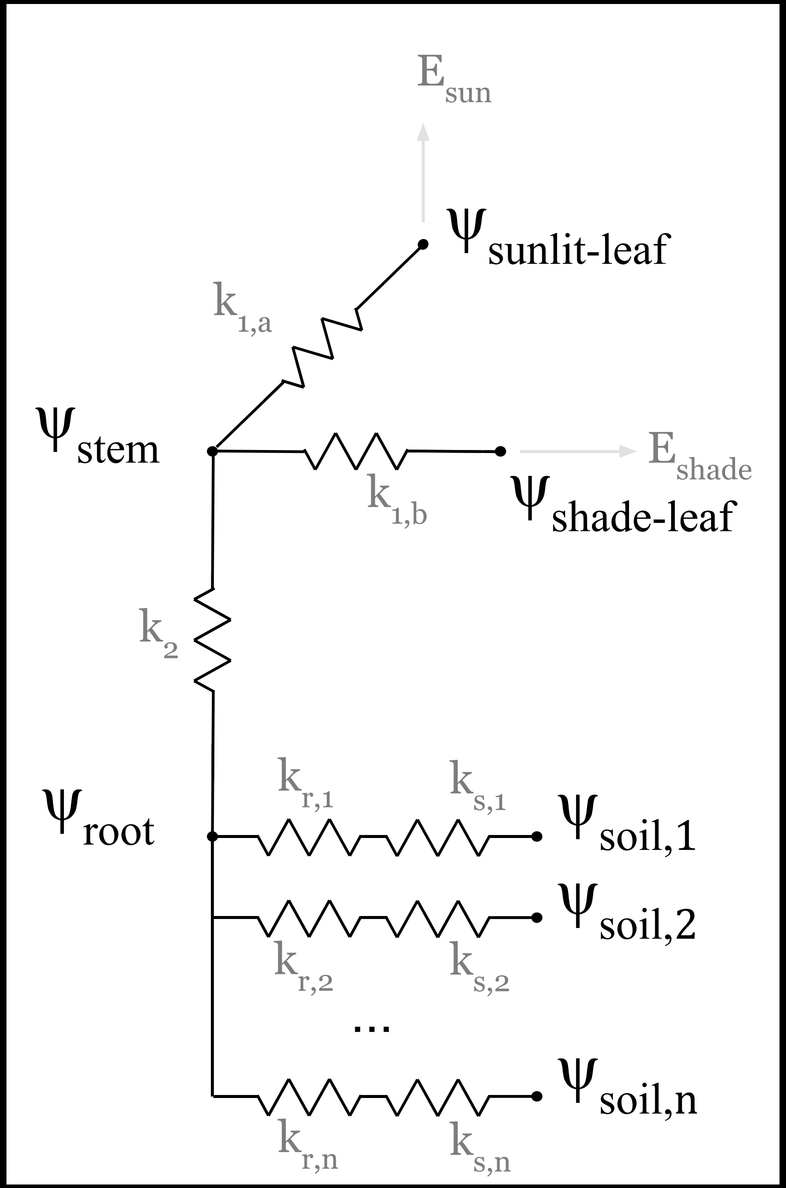
Coordination at global scale?

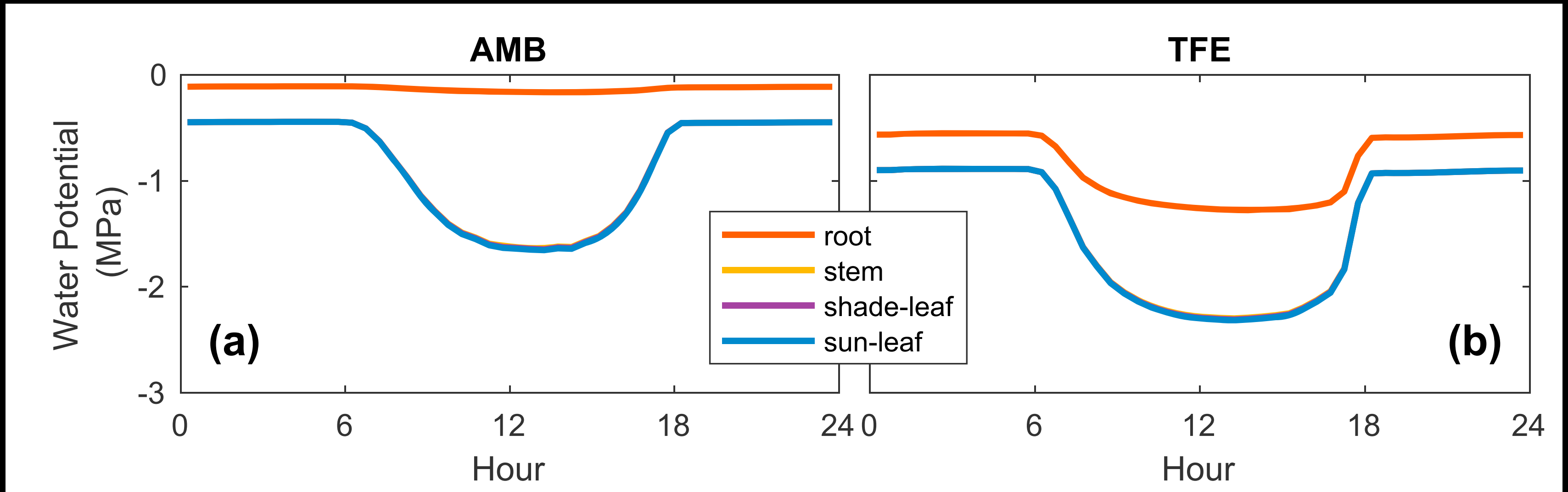


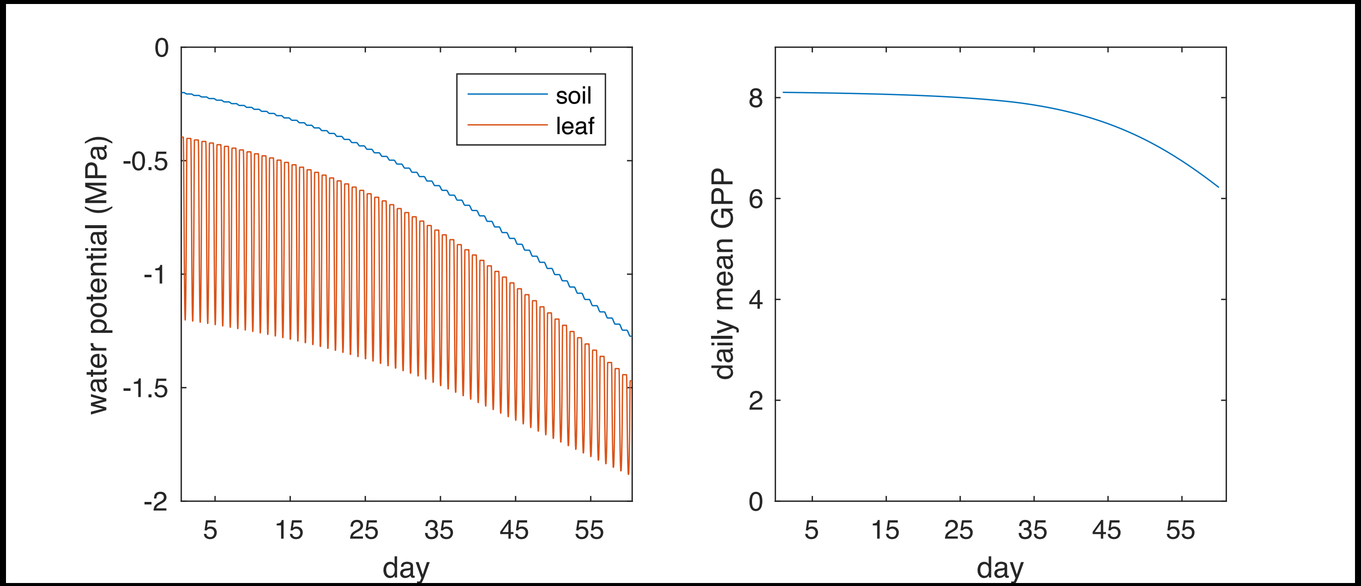
Liu, Konings & Gentine *submitted*, Mursinna et al., Matheny, Forests 2018

Implementation of plant hydraulics in global model

Community Land Model 5.0
Many other examples e.g. JULES

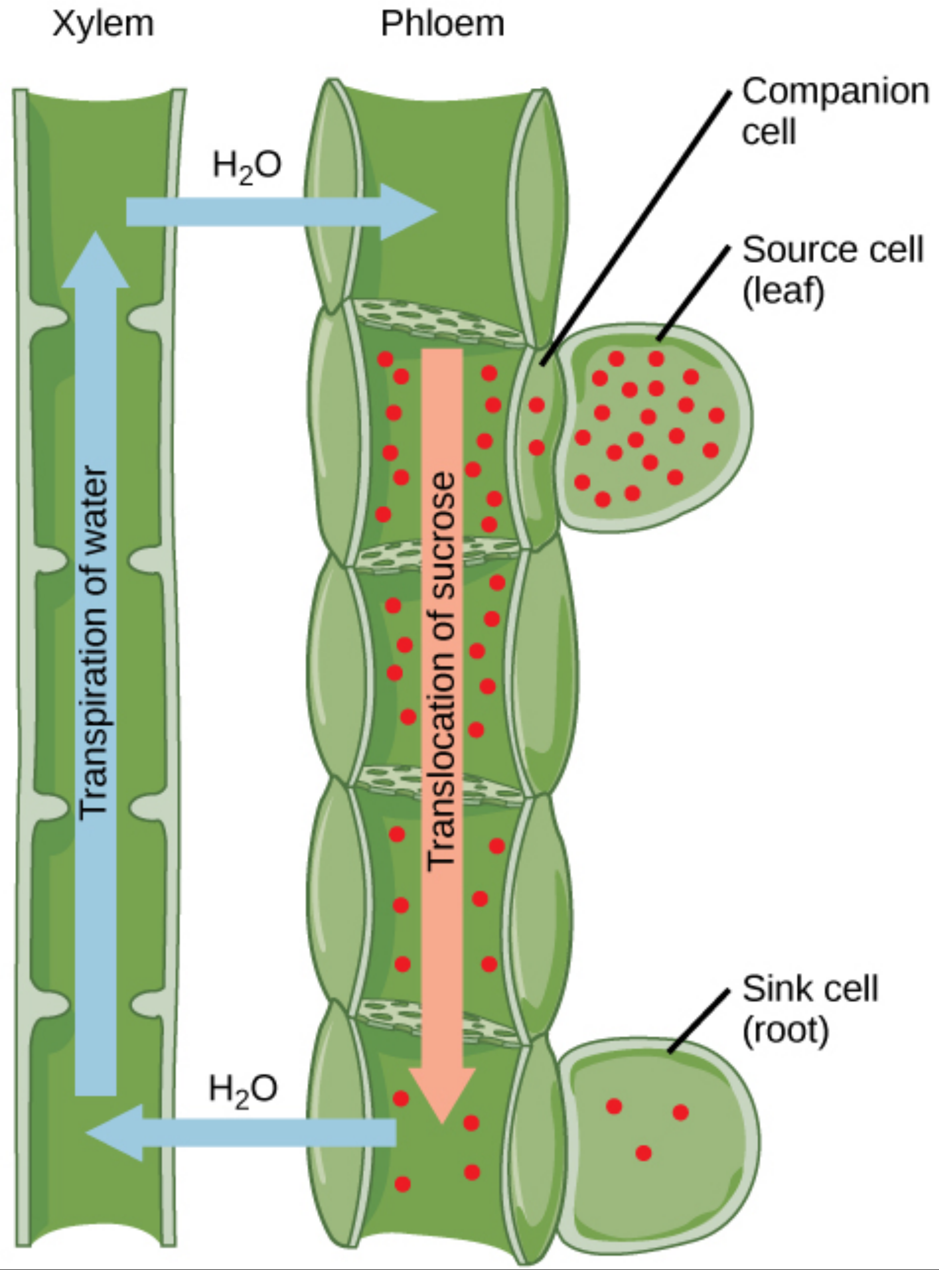






Kennedy et al. *JAMES* 2019

3. Phloem



Münch hypothesis (1927-1930)

- Phloem transports carbohydrates to sink tissues for growth, respiration and storage
- Carbohydrates (GPP) raise solute concentration, create osmosis $\psi_{\text{osmosis}} = -RT\ln(C)$.

→ raises turgor pressure and draw water from xylem through osmosis.

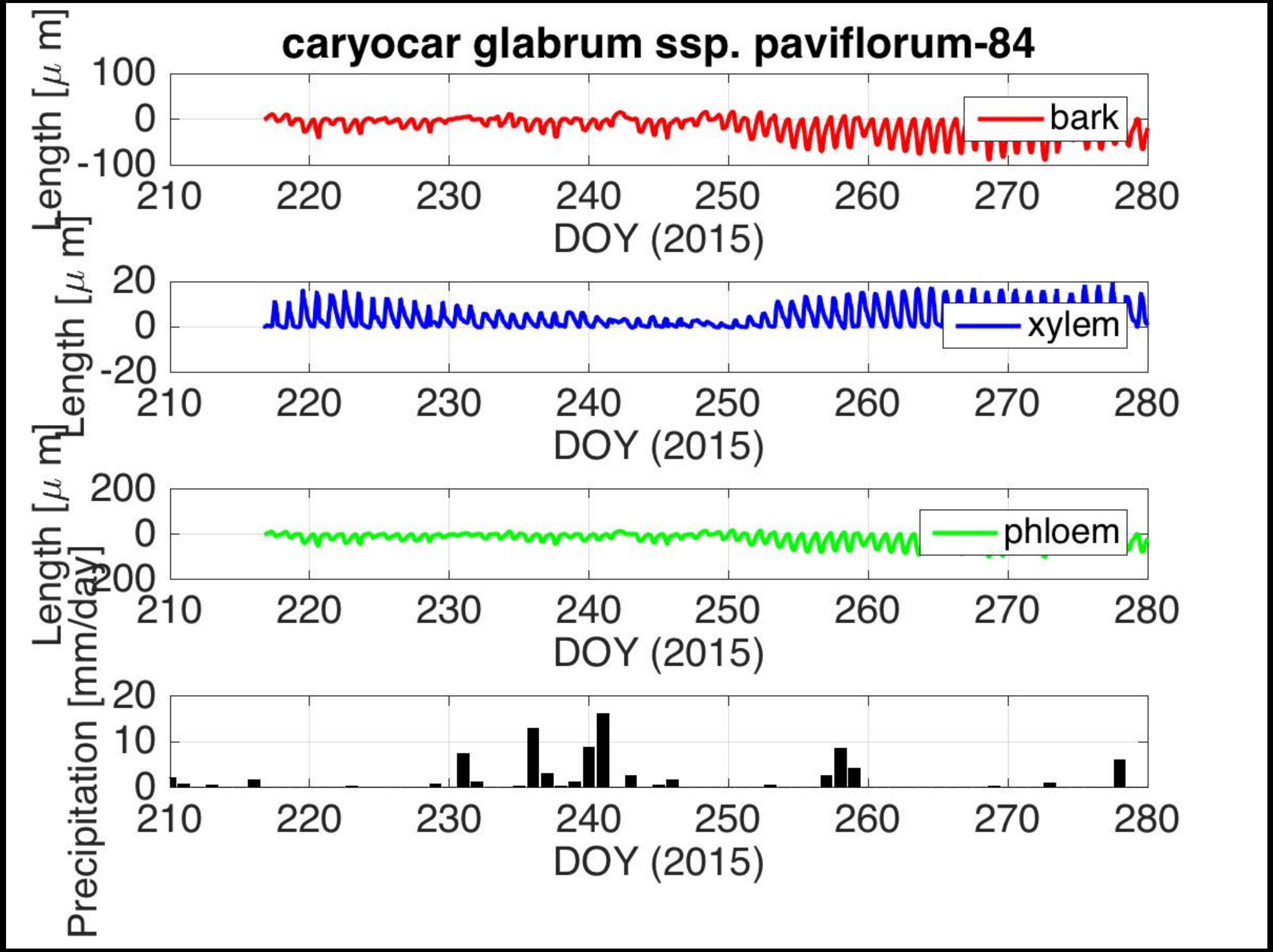
- At growth and storage sinks, carbohydrates are unloaded or passively leak out of phloem, lowering the solute concentration.
- Connects source and sink tissues delivering photosynthate where needed
- Theory has issues over long distances

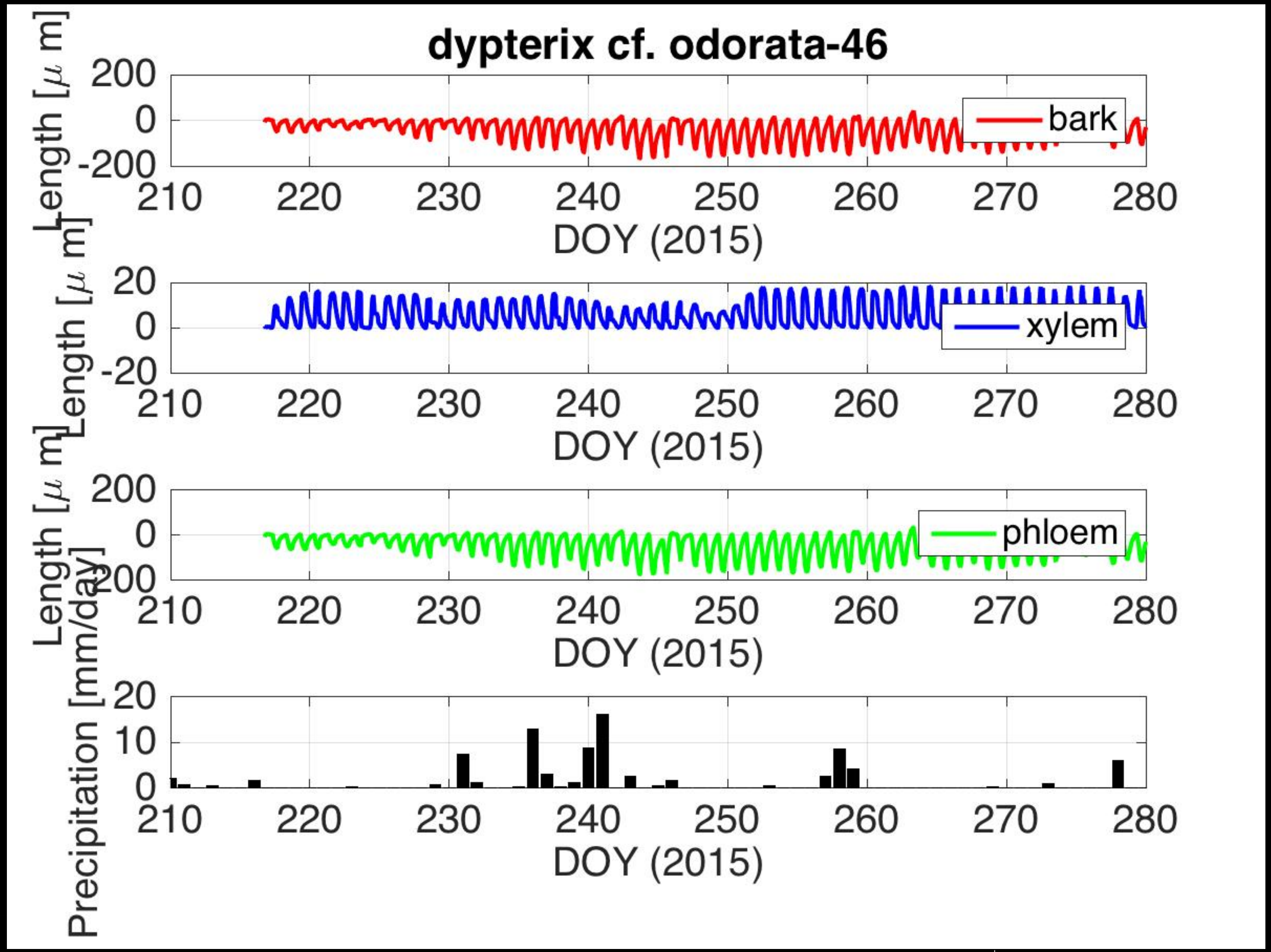
Rennie and Turgeon 2009, Thompson and Holbrook 2003, Mencuccini and Hollta 2010, Huang … Katul 2018

Example of diurnal fluctuation in xylem & phloem radii in the Amazon (K34)

P. Bittencourt, R. Oliveira

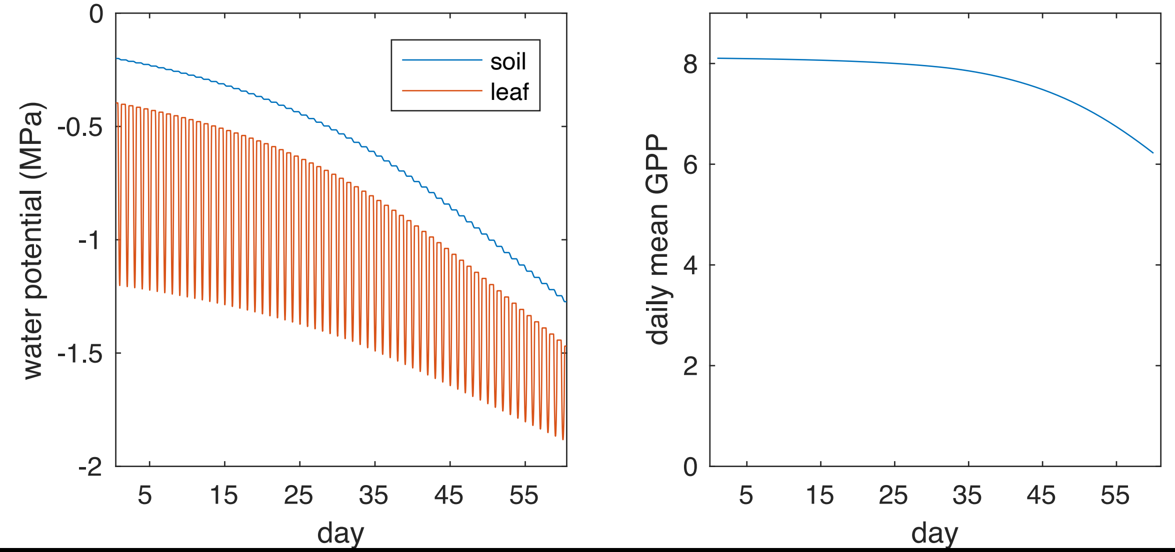
Amazing diversity in xylem and phloem response as well as growth!

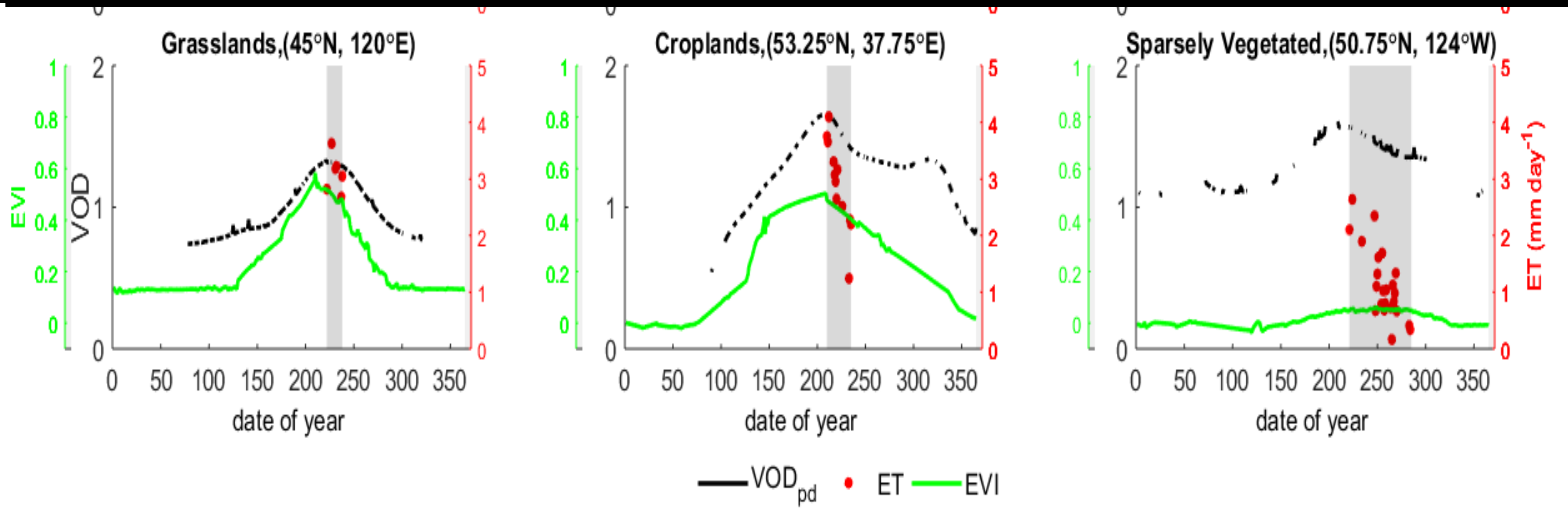




Leaf-gas exchange, xylem, phloem, growth time scales

- **Daily time scale:**
  Xylem, phloem flow & leaf-gas exchange
- **Monthly time scales:**
  These
  + rooting depth
  + growth
- How can we **differentiate processes?**

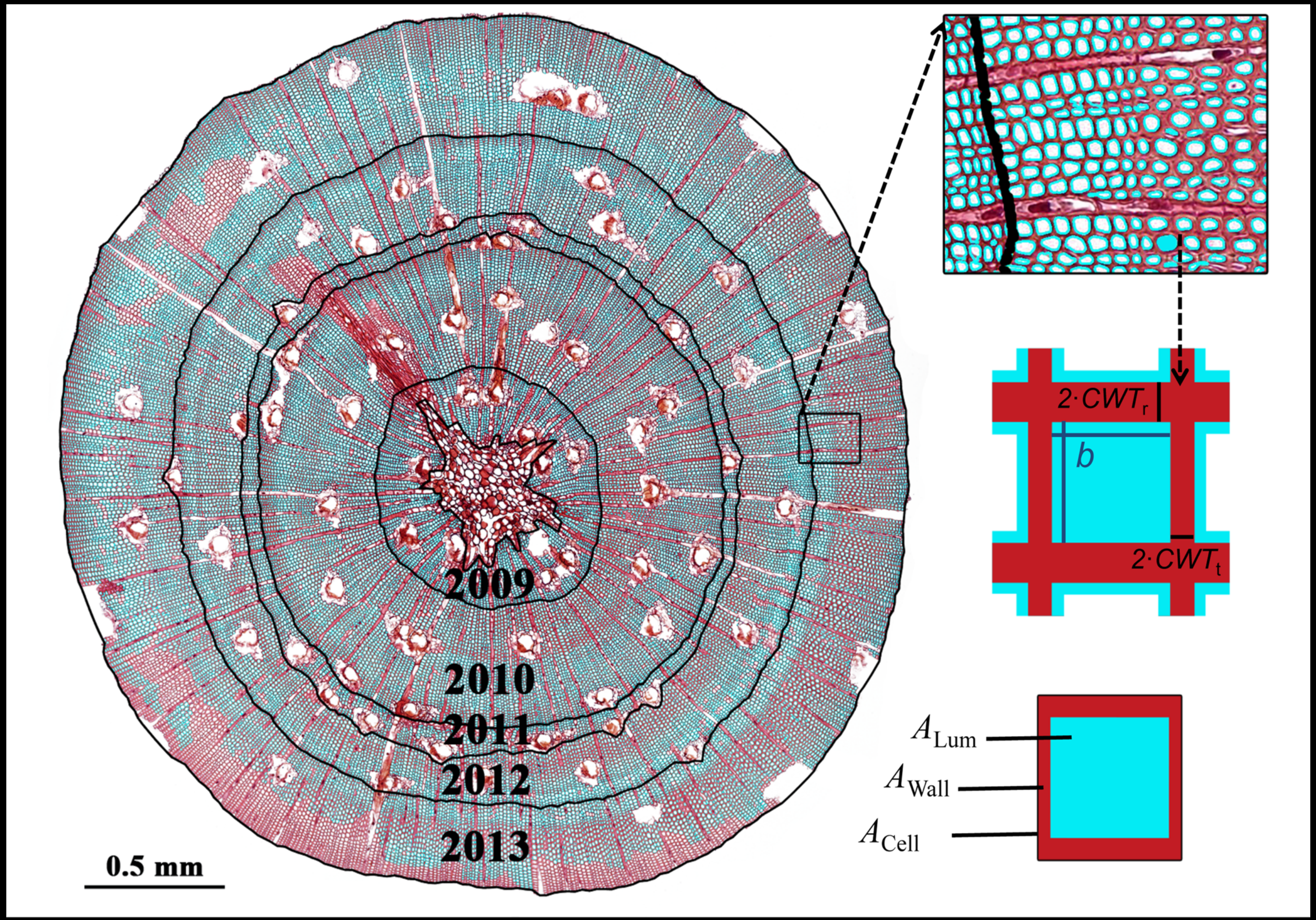


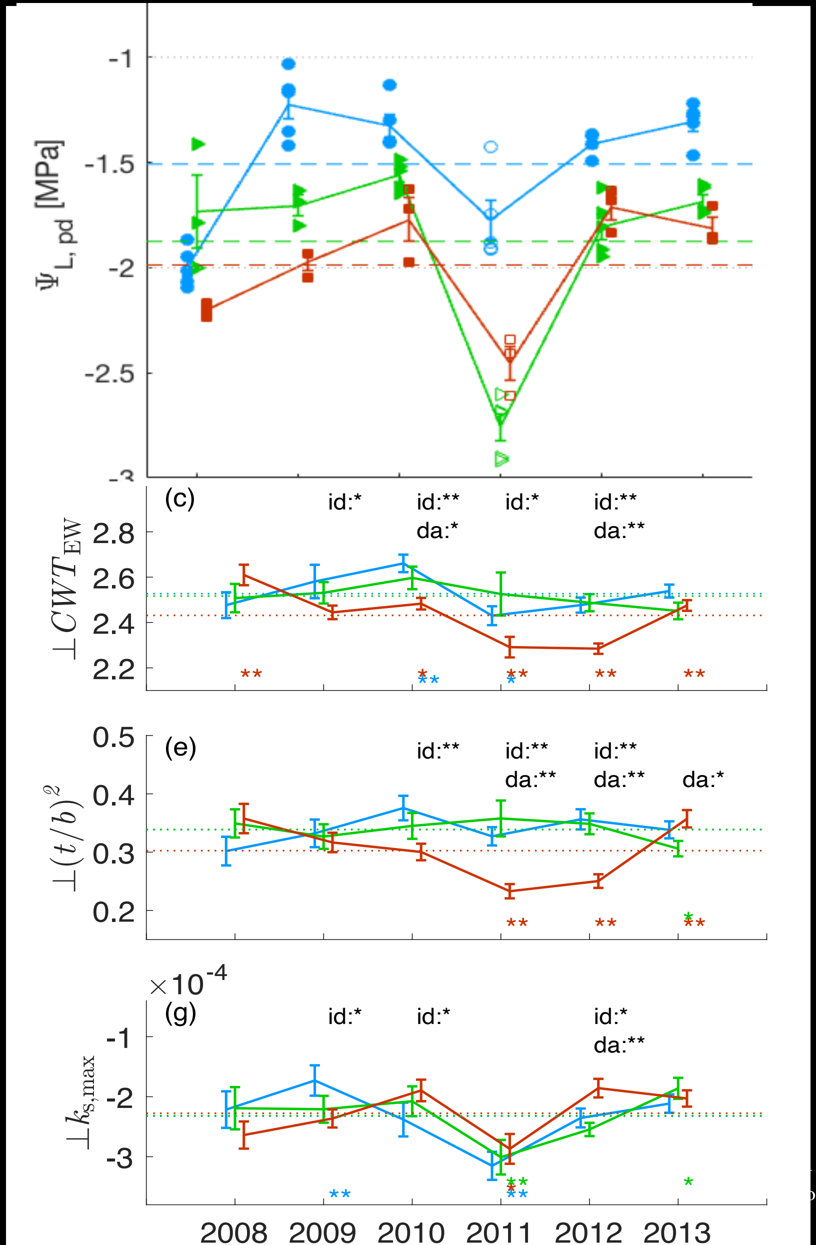


Liu, Konings, Gentine *submitted*

Interannual time scales?

Tree ring - annual growth
We know it is related to water!
Feedback on water cycle (transpiration)

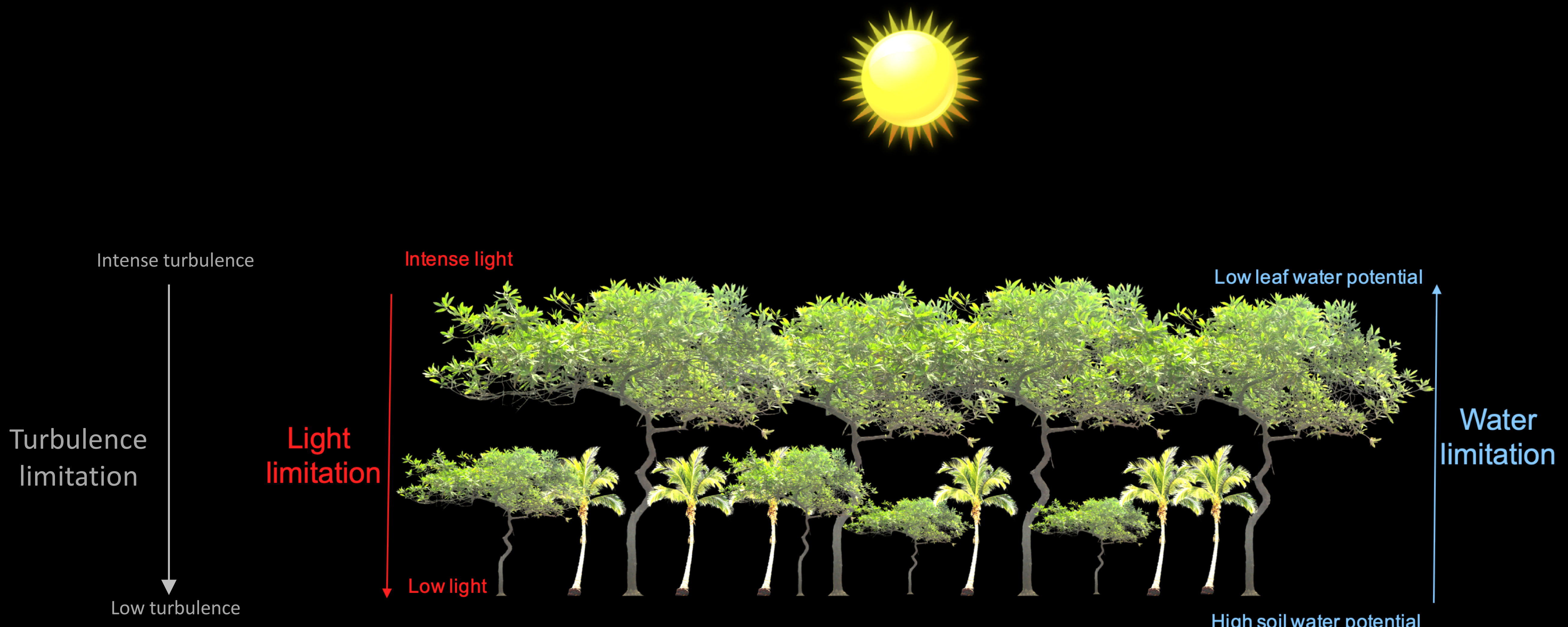




Guérin, Gentine et al *in revision*

Vertical/horizontal microclimate and state gradients

Gradient in SPAC + microclimate + species composition
What is the ecosystem/landscape emergent behavior?



Gentine et al., HESS 2019

Thank you for your attention

Questions?