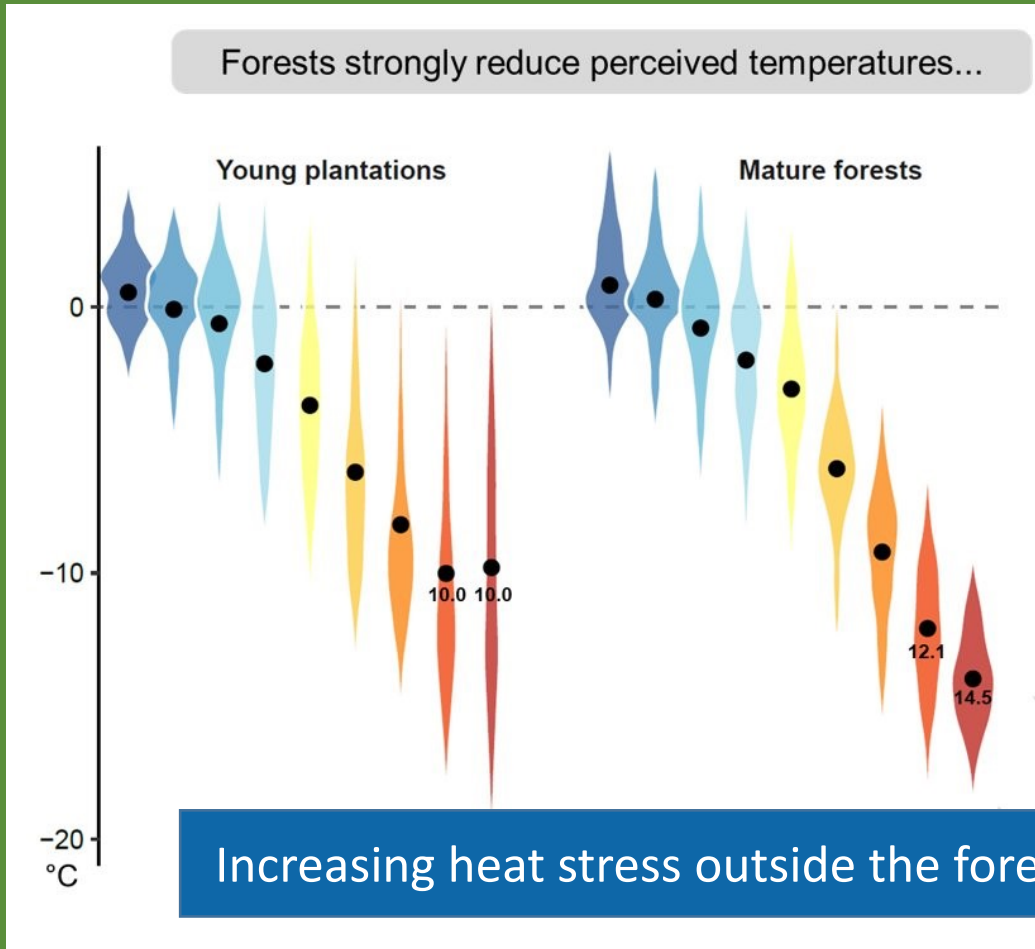


DYNAMIC PROCESSES REQUIRE APPROPRIATE METHODS TO CAPTURE THEM: WHY IN-SITU WATER STABLE ISOTOPE MONITORING NEEDS TO BECOME A STANDARD METHOD IN FOREST HYDROLOGICAL RESEARCH

MATTHIAS BEYER, KATHRIN KUEHNHAMMER, JOOST VAN HAREN, ANGELIKA KUEBERT, CHRISTIAN BIRKEL, RICARDO SANCHEZ-MURILLO, AND JOHN MARSHALL



Forests regulate our climate...



Climate + too many shallow-rooters
+ lack of niche separation

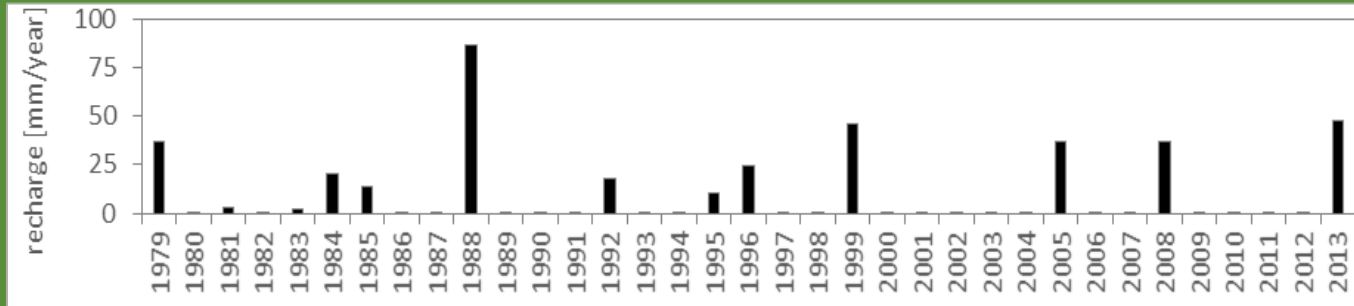
[Gillerot et al., 2022]

Humans also need water: groundwater recharge & trees

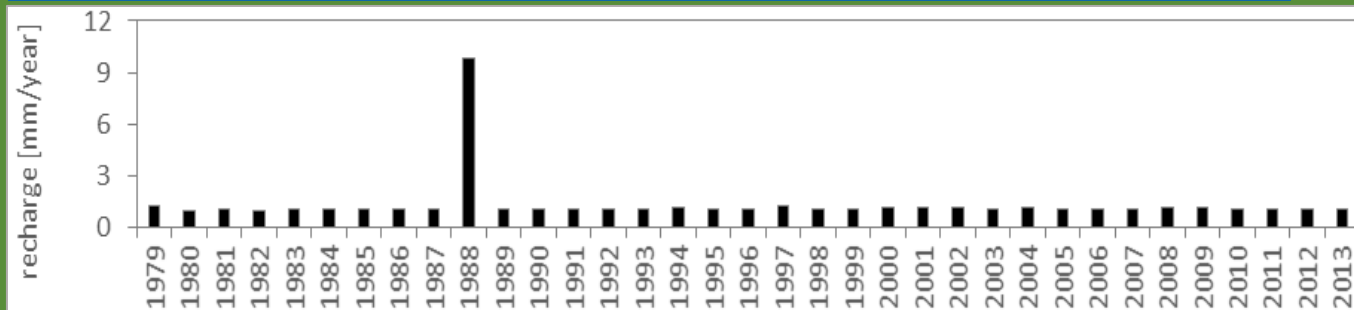


[Ohangwena Region, northern Namibia]

Model calculation (Hydrus1D): max. root depth 2.3m



Model calculation (Hydrus1D): max. root depth 4m



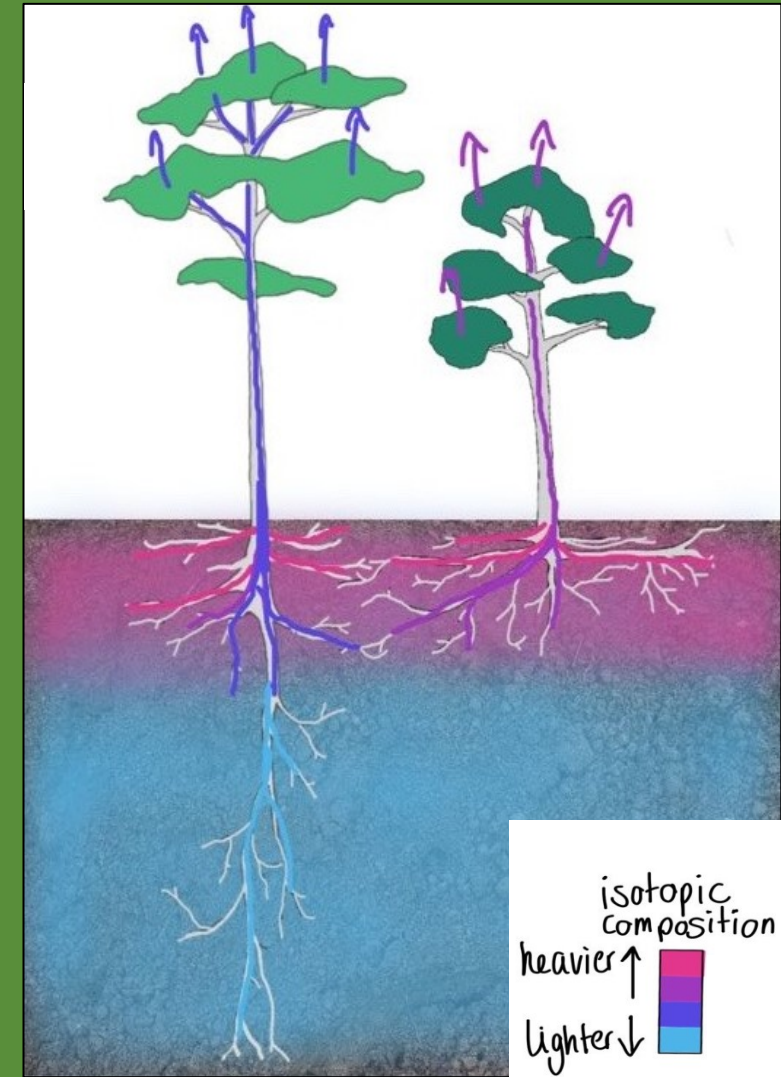
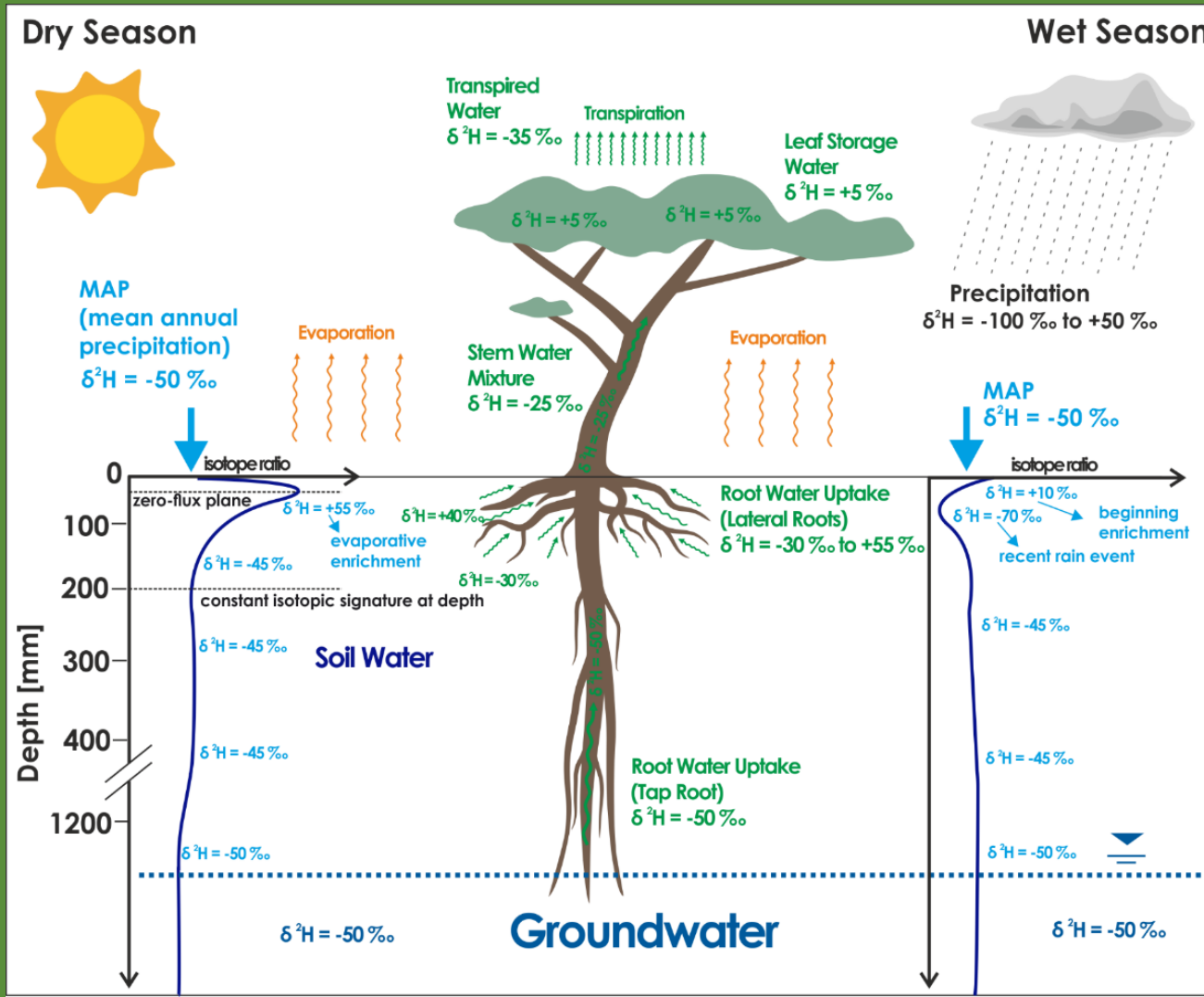
What's really happening below ground?



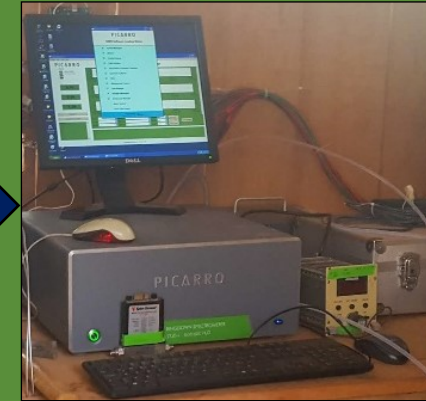
[Stocker et al., 2023, *Nat.Geosc.*]

- rooting-zone water-storage capacity varies spatially, is largely unknown and not directly observable
- plant-available water stores >2-m-depth: 37% of Earth's vegetated surface
- water stored at depth and along the entire critical zone is not fully represented in models
- evident plasticity of root zone depth & water storage are often ignored

Water isotopes

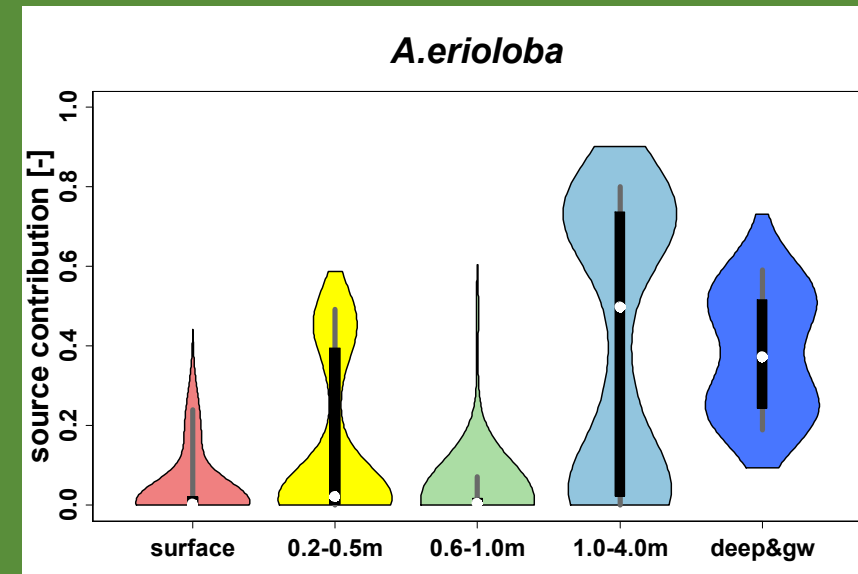


...but traditional methods are increasingly questioned



Mixing Model

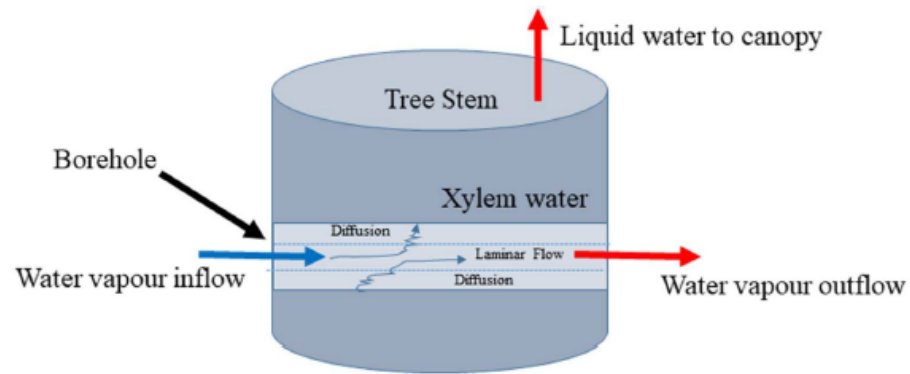
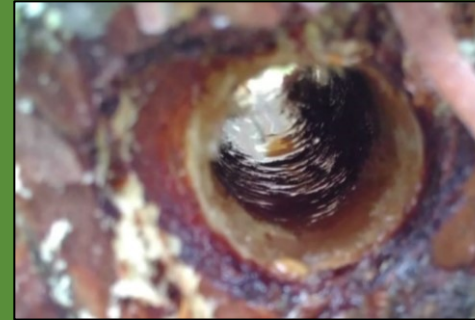
- laborious & error-prone
- not measuring mobile water pool only
- snapshot: one point in time
- tree is damaged: How often can we sample? Branches accessible?
- methodological artefacts and organic interference
- water extraction + subsequent vaporization: obsolete



Development and application of novel in situ monitoring techniques

Borehole Equilibration: Testing a New Method to Monitor the Isotopic Composition of Tree Xylem Water *in situ*

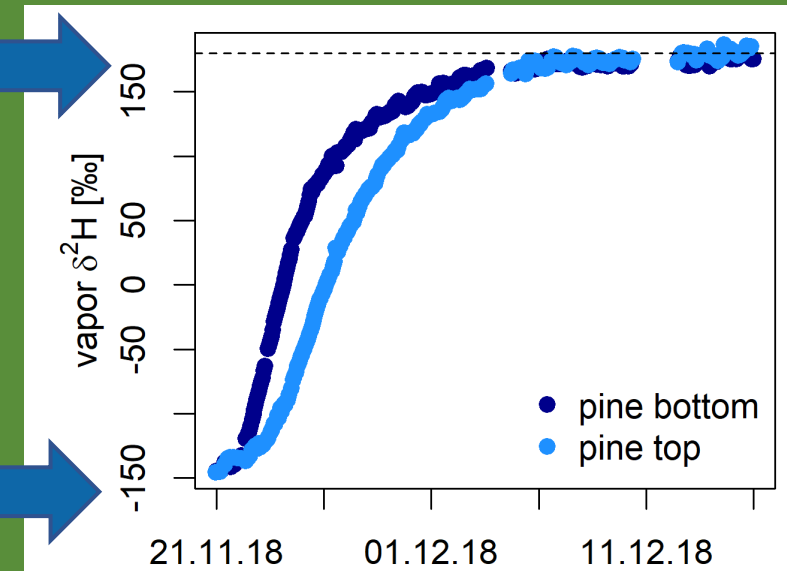
John D. Marshall^{1*}, Matthias Cuntz^{2†}, Matthias Beyer^{3,4†}, Maren Dubbert^{5,6†} and Kathrin Kuehnhammer^{3,5†}



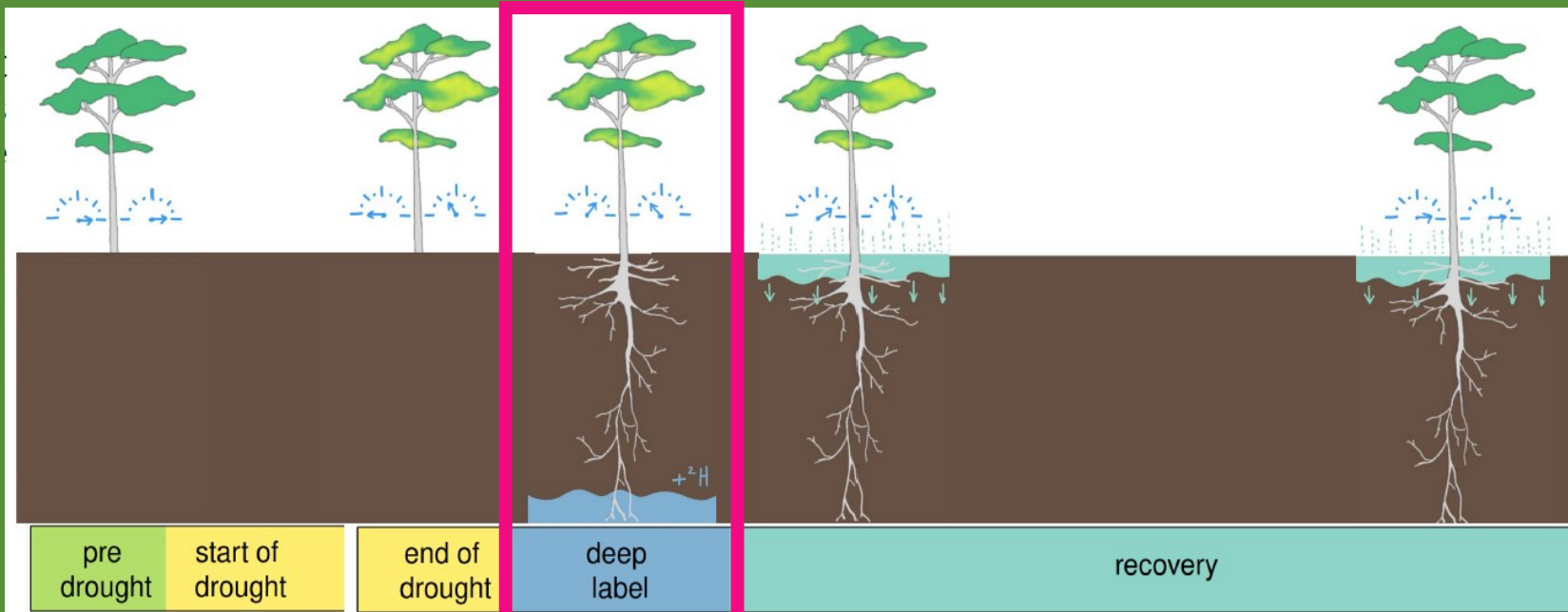
Measures water vapor, infers liquid value via eq. fractionation

Changed source water

Initial source water



B2WALD: A tropical rainforest under drought



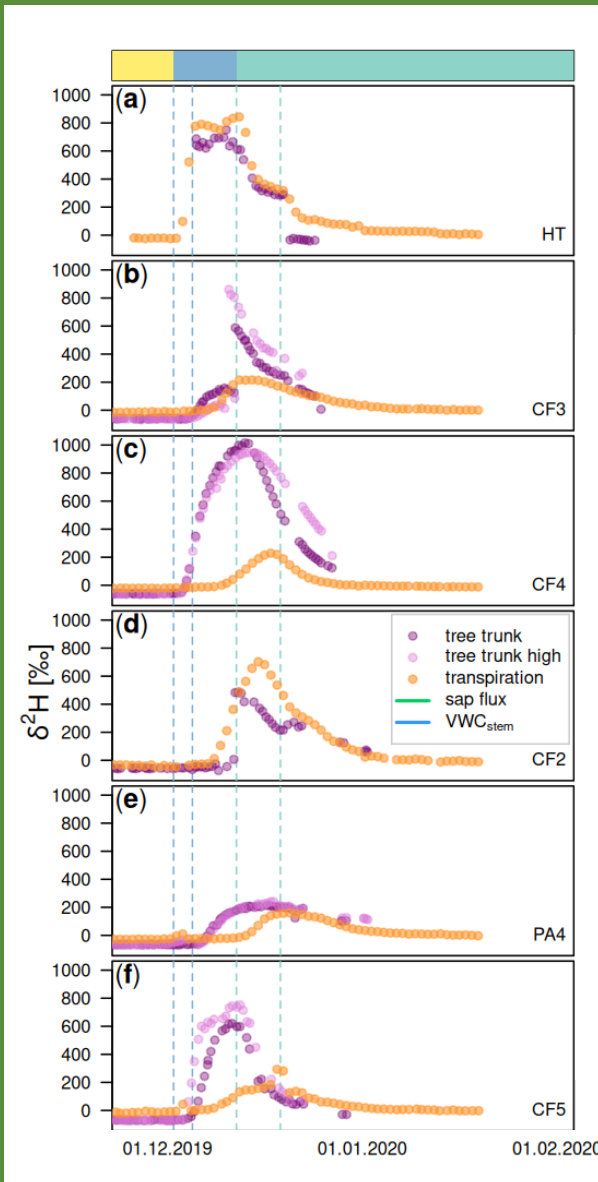
3000 L of deuterium-enriched water applied via drainage pipes

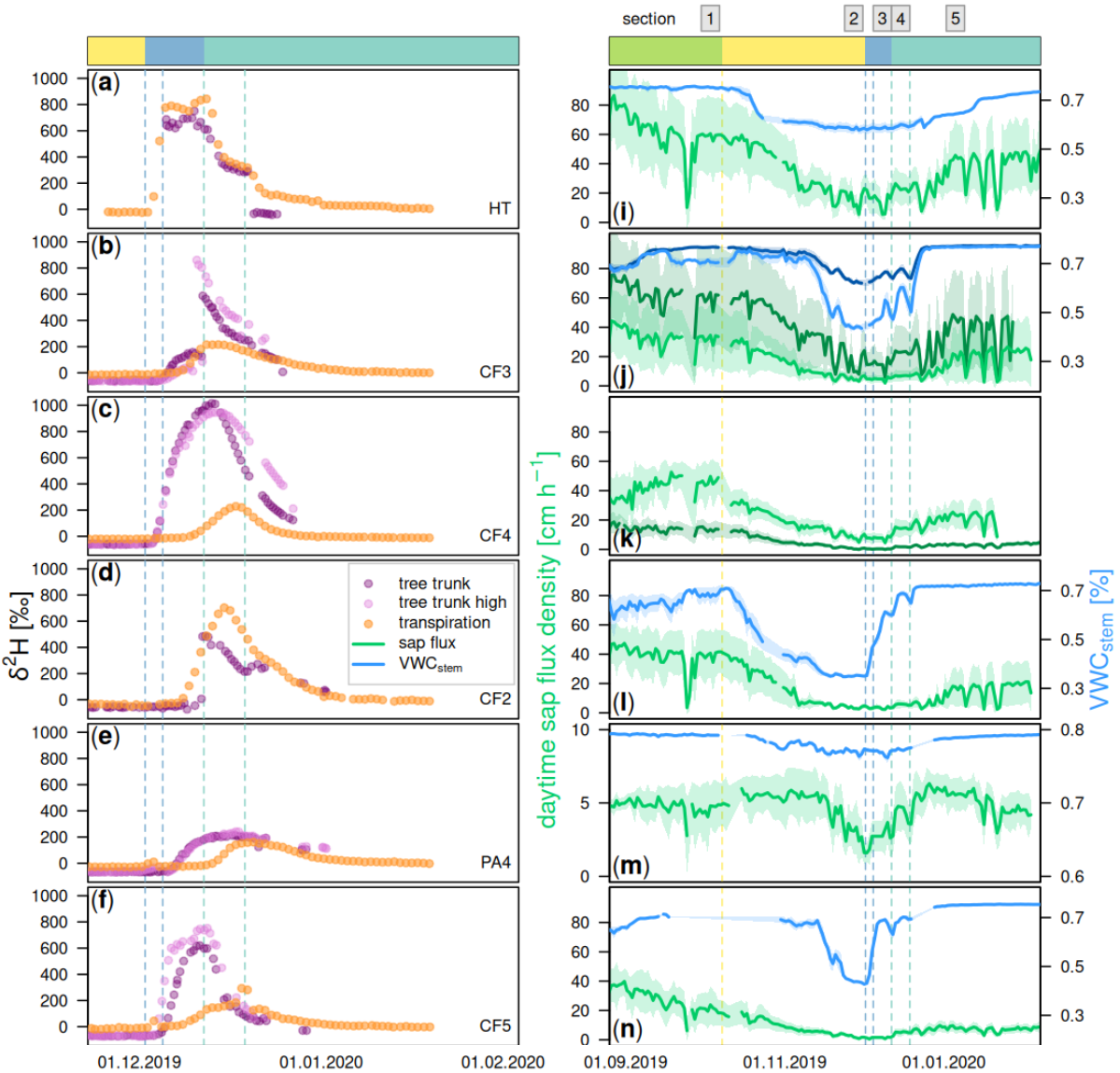
Biosphere 2, Tucson, Arizona



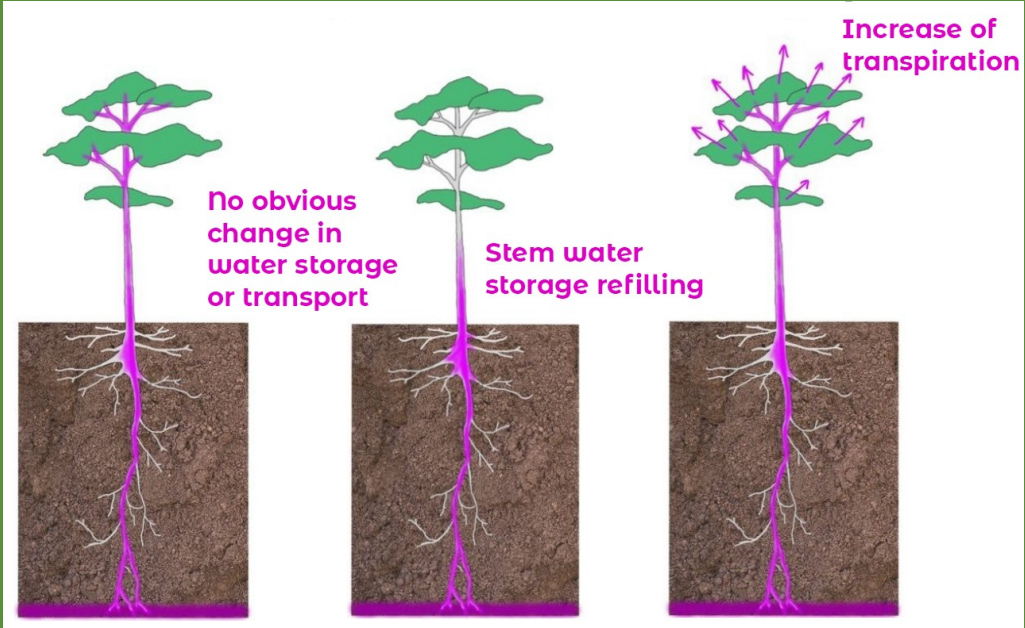
[Werner et al. 2021, *Science*]

- *All studied tropical canopy trees access water at soil depths up to 3.3 m.*



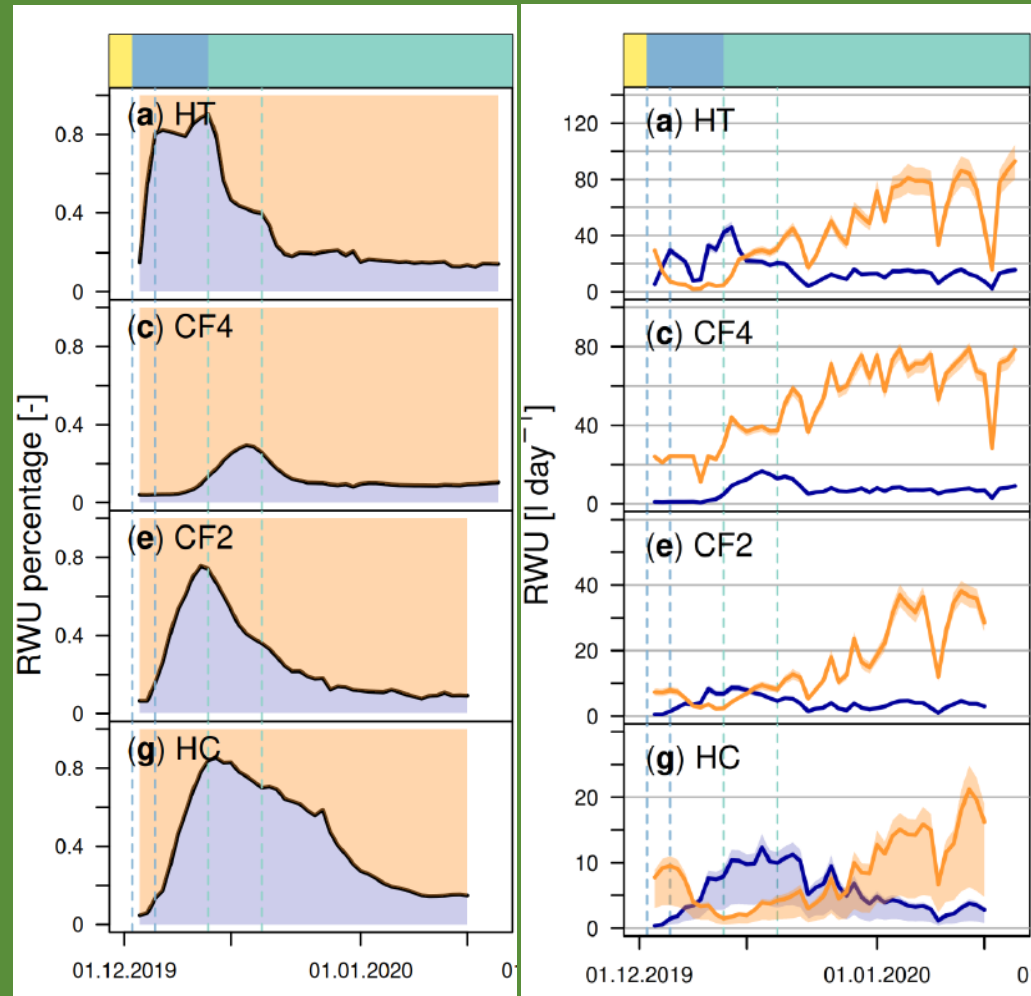


■ All studied tropical canopy trees access water at soil depths up to 3.3 m.



[Kühnhammer et al., 2023, STOTEN, under review]

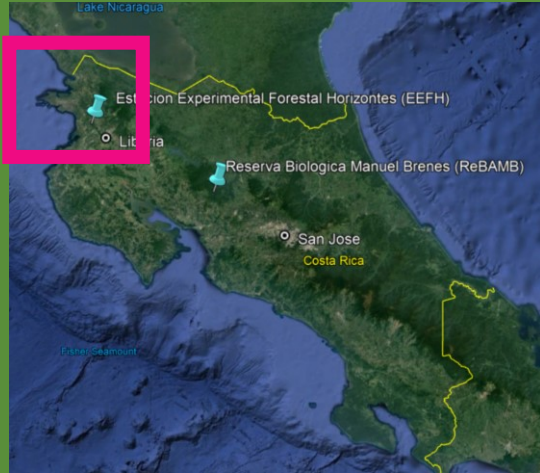
B2WALD: A tropical rainforest under drought



- *Deep roots help tropical trees endure droughts but total transpiration fluxes are driven by precipitation*

[Kühnhammer et al., 2023, *STOTEN*, under review]

Water use strategies of dry forest trees



Water use strategies of dry forest trees



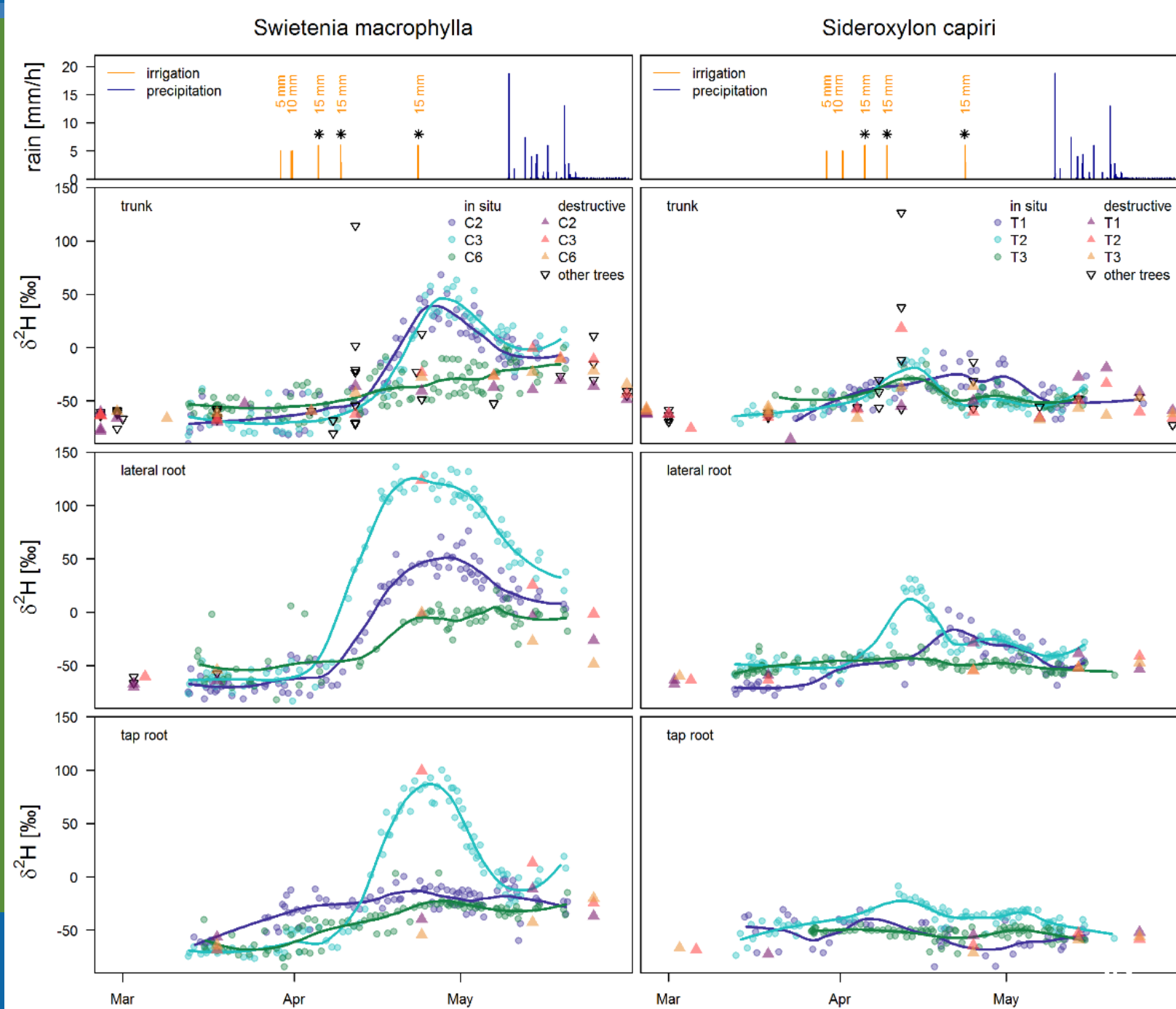
Isotopic labeling



In situ tree xylem water

- immediate uptake by *Swietenia macrophylla* (Caoba)
- no to weak reaction of *Sideroxylon capiri* (Tempisque)
- in situ vs. destructive: fits well

Kühnhammer et al. (2021), *Continuous in situ measurements of water stable isotopes in soils, tree trunk and root xylem: Field approval*



....my five cents

- *in situ methods*

- Continuous monitoring of water uptake depths
- Measure the mobile fraction of water
- Less organic contamination
- Great potential when combined with labeling
- Improve model performance [Munksgaard et al. ,2019; Gaj et al, 2017; Yang et al., 2021]

- *Criticism*

- Complicated, laborious and high-maintenance – **Absolutely true [but see next slide].**
- Natural abundances possible? - **Yes.** [Kühnhammer et al., 2021]
- How long can we monitor? - **Up to two years in trees.** [Marshall, 2022]
- Expensive: “not everybody has a laser spec to take to the field!” [... see next slide]
- Do we destroy the trees? - **No.**

...in situ vapor sampling...



[Havranek, 2020, RCM;
Magh et al., 2022, HESS]







....in situ vapor sampling....



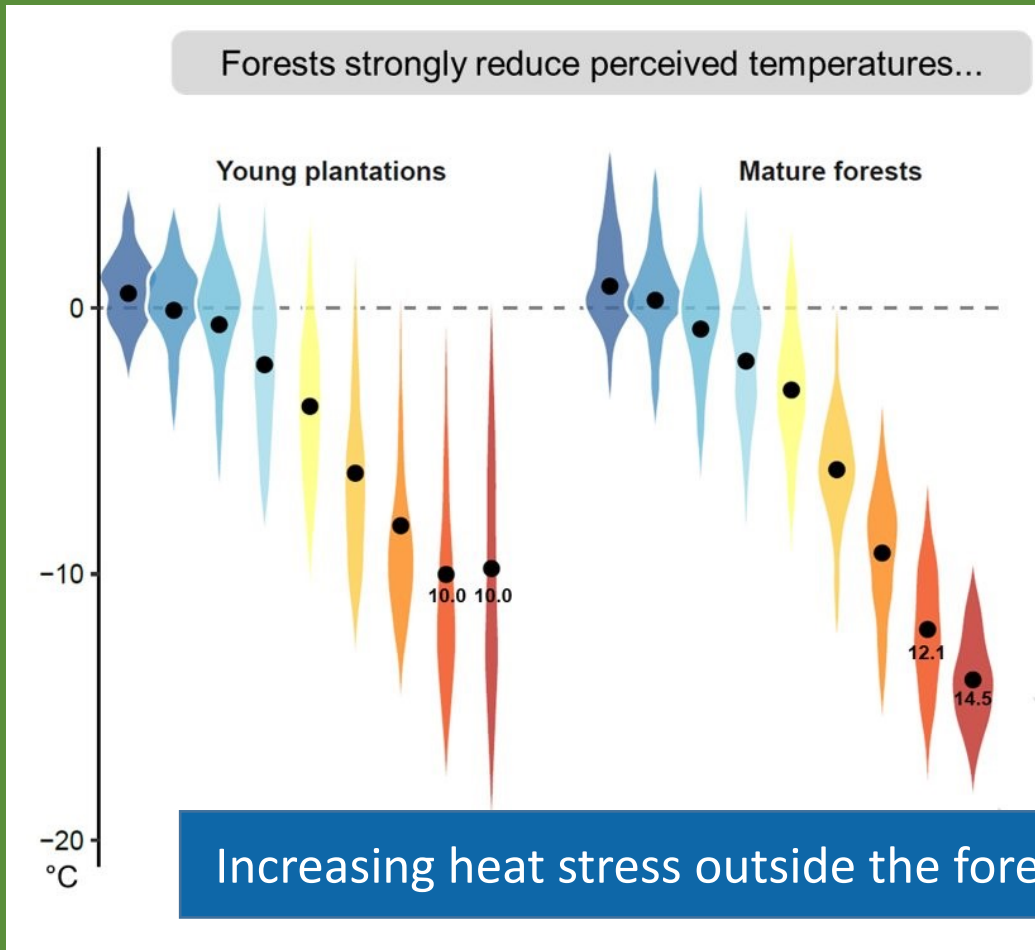
Thank you!



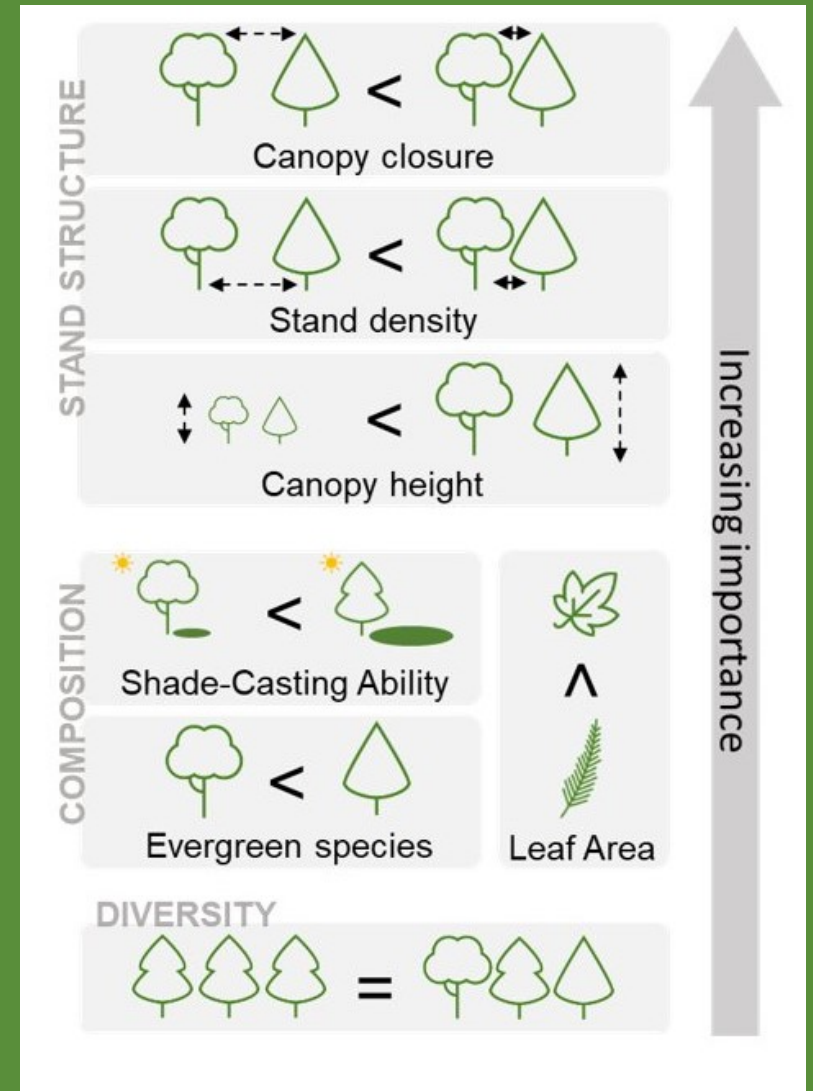
 isodrones.com
  Isodrones Project
  @Isodronesproject



Forests regulate our climate...



[Gillerot et al., 2022]

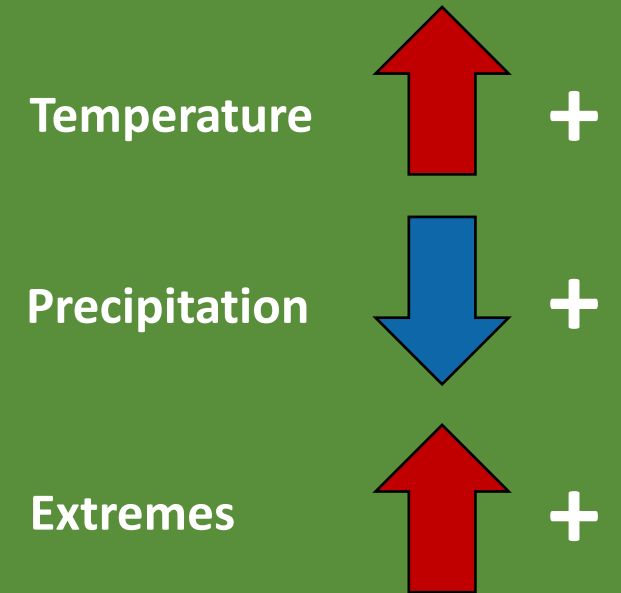


[Gillerot et al., 2022]

...but they need sufficient water.

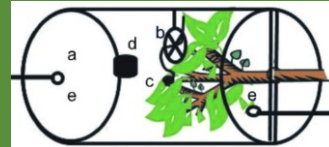
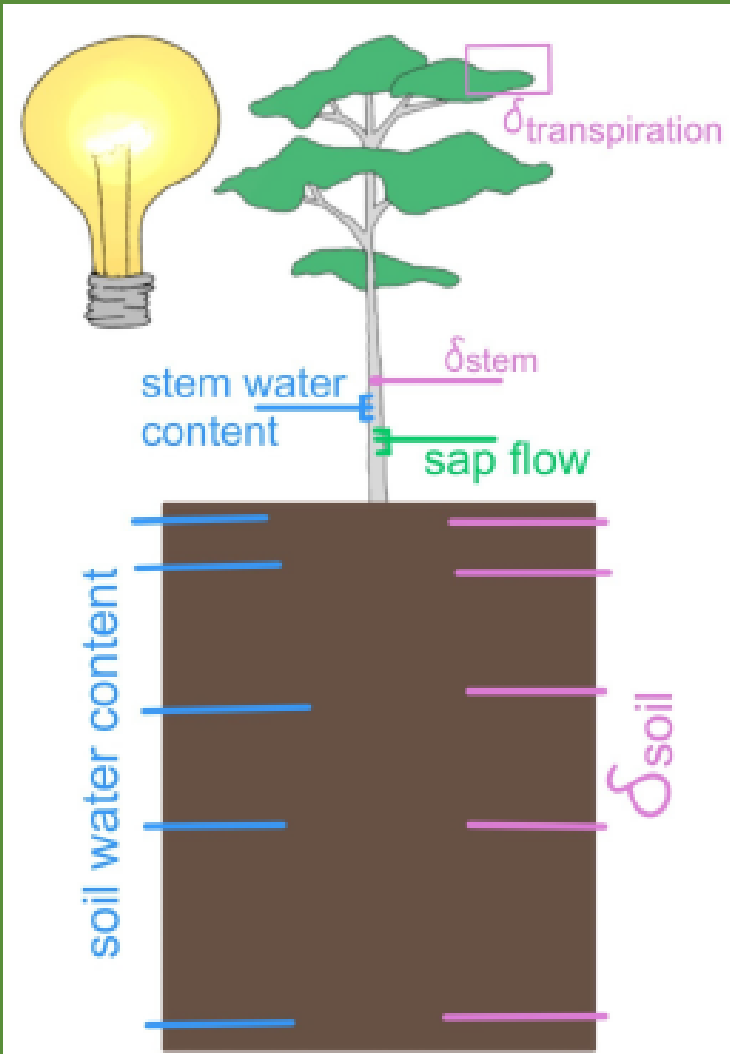


The climate dilemma

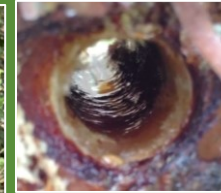


Too many shallow-rooters
& lack of niche separation

...towards continuous/*in situ* isotope measurements



[Dubbert et al., 2013, 2014, *JoH*]



Reviews & Perspectives:

[Beyer et al., 2020, *HESS*]

[Beyer & Penna, 2021, *Front. Pl. Sc.*]

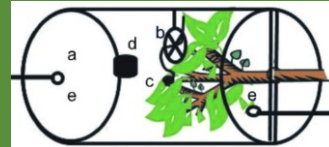
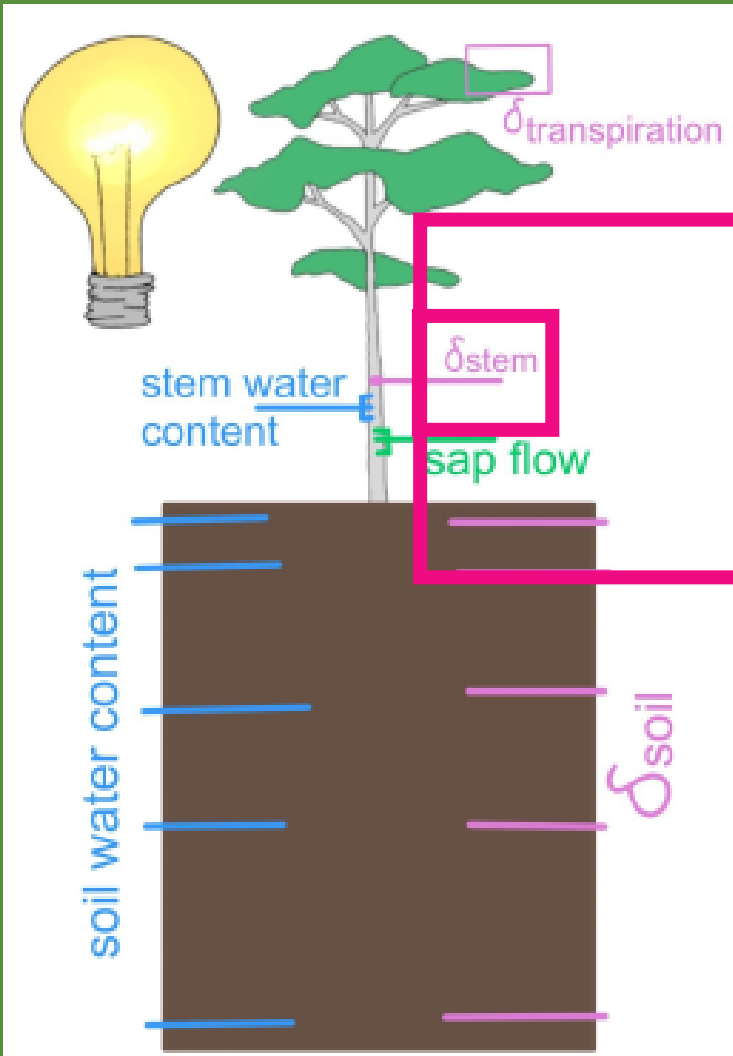
[Orlowski et al., 2023, *STOTEN*]

[Volkman et al., 2016, *PCE*;
Kühnhammer et al., 2021, *RCM*;
Mennekes et al., 2021, *HESS*; Seeger
& Weiler 2021, *Biogeosciences*]

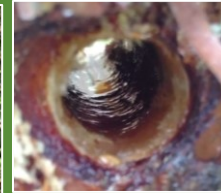


[Rothfuss et al., 2013, *WRR*; Volkman &
Weiler, 2014, *HESS*; Gaj et al., 2016, *HESS*;
Oerter et al., 2017, *RCM*]

...towards continuous/*in situ* isotope measurements



[Dubbert et al., 2013, 2014, *JoH*]



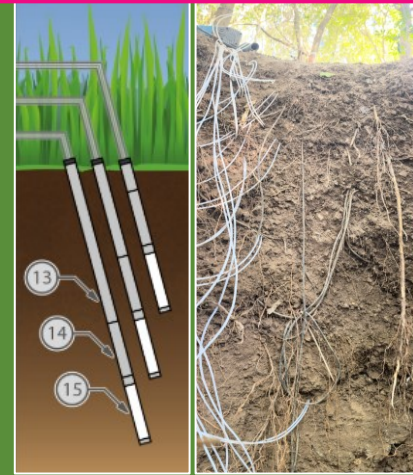
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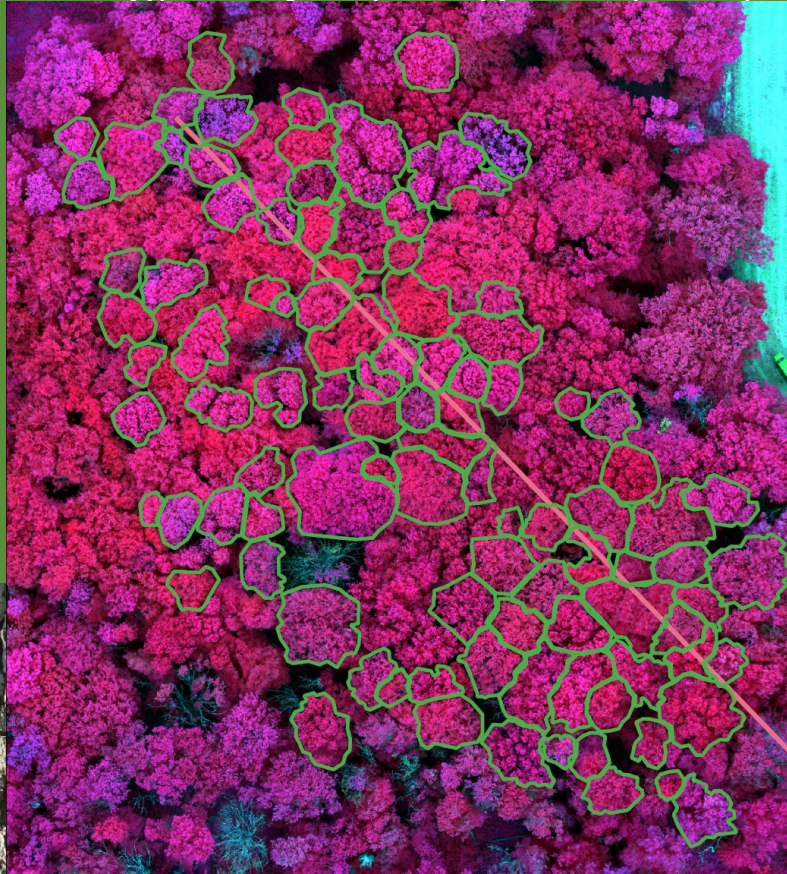
[Volkman et al., 2016, *PCE*;
Kühnhammer et al., 2021, *RCM*;
Mennekes et al., 2021, *HESS*; Seeger
& Weiler 2021, *Biogeosciences*]



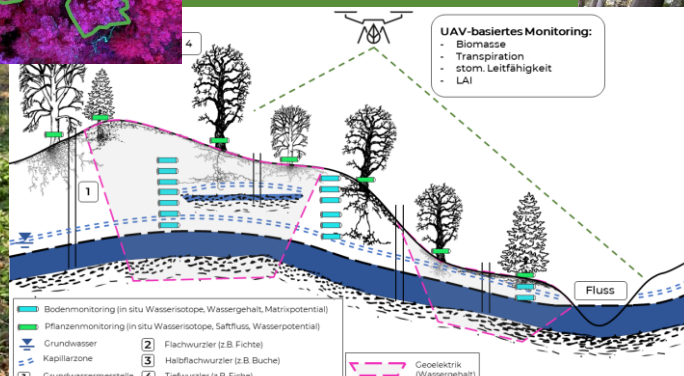
[Rothfuss et al., 2013, *WRR*; Volkman &
Weiler, 2014, *HESS*; Gaj et al., 2016, *HESS*;
Oerter et al., 2017, *RCM*]

...Ausblick...

what we do there...

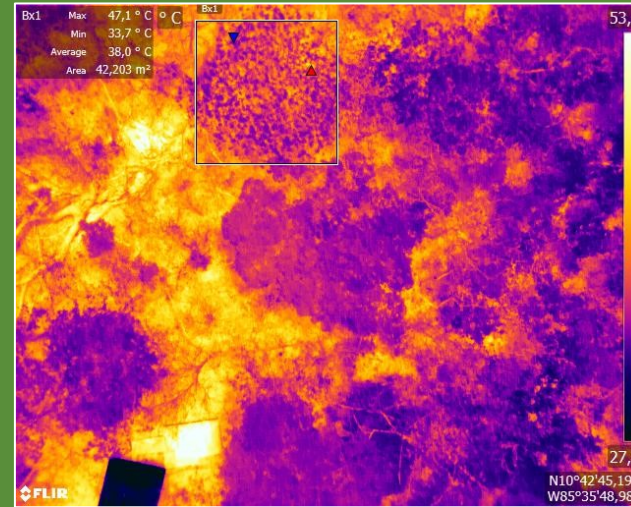


ch



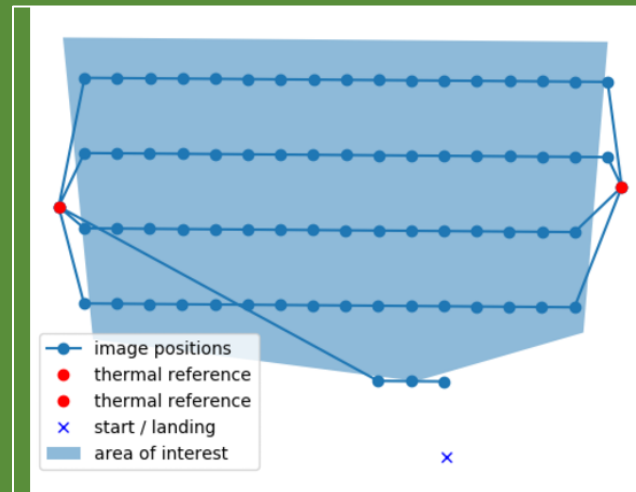
Drones (UAV)

- Thermal imaging:
 - Transpiration
 - Stom. Conductance
 - Crop/plant water stress index



Novel method for calibration and flight planning allows to calculate transpiration on single leaf scale

[Gerchow et al., in prep.]



Flight planning online:
www.isodrones.com/flightplanner

Drones (UAV)

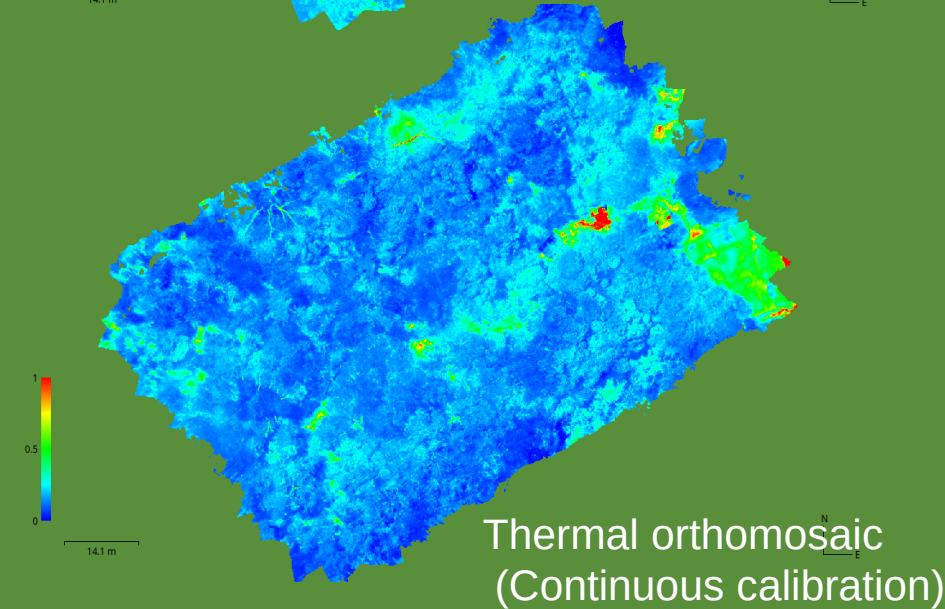
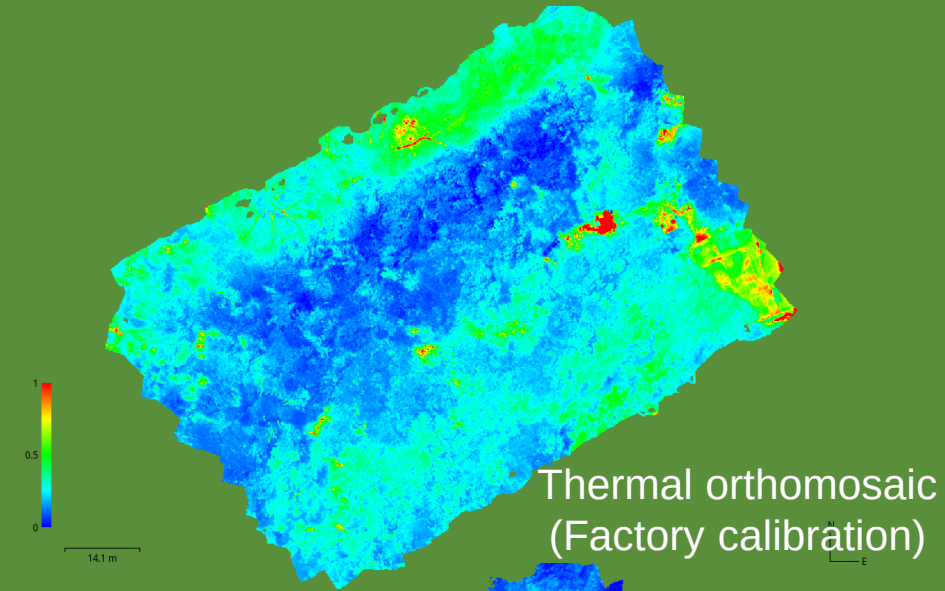
- Thermal camera poses are estimated from RGB photos to form the thermal orthomosaic (dual sensor)
- Comparison of different calibration methods

Most accurate



Calibration accuracy (mean \pm std)

Flight Conditions	1) Factory Calibration (°C)	2) Empirical line method (°C)	3) Factory Calibration + Drift correction (°C)	4) Continuous empirical line method (°C)
Cloudy	4.3 \pm 1.8	1.7 \pm 1.2	0.9 \pm 1.2	0.9 \pm 0.6
Sun	6.2 \pm 1.7	5.8 \pm 2.3	3.5 \pm 2.4	1.5 \pm 1.9
Partly Cloudy	2.9 \pm 3.3	2.9 \pm 2.9	2.5 \pm 3.3	2.3 \pm 3.0
Overall	4.5 \pm 2.4	3.5 \pm 2.2	2.3 \pm 2.5	1.6 \pm 2.1

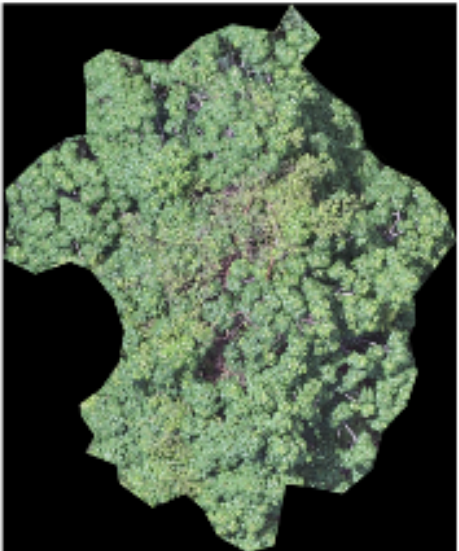


Drones (UAV)

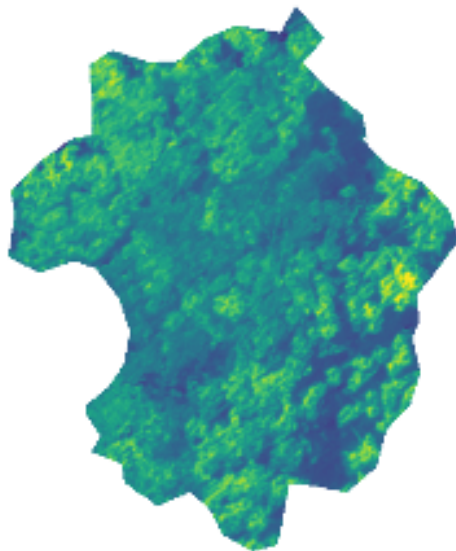
- Thermal imaging:
 - Transpiration
 - Stom. Conductance
 - Crop/plant water stress index

→ Enables single-leaf-scale analysis
→ UAV-borne estimation of T

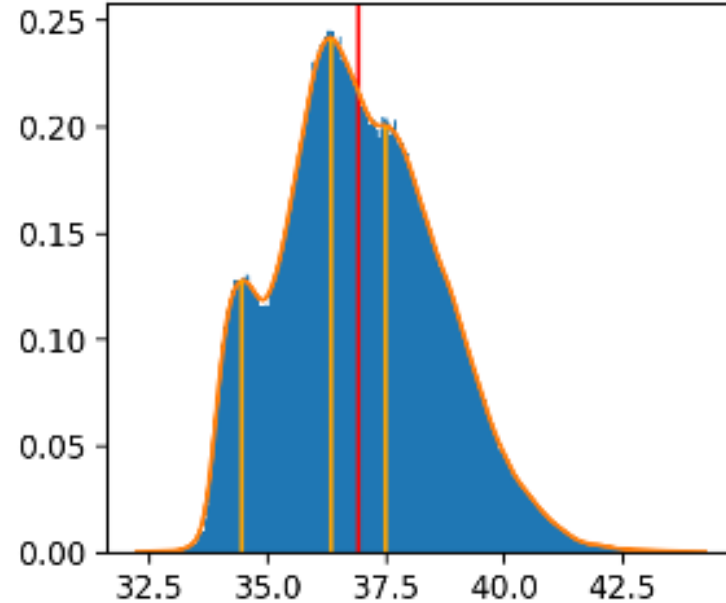
Extracted canopy RGB



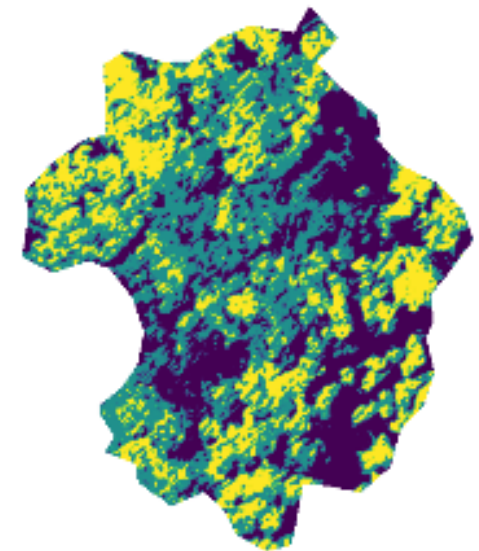
Extracted canopy thermal



Mean canopy temperature: 36.9°C



Temperature classification

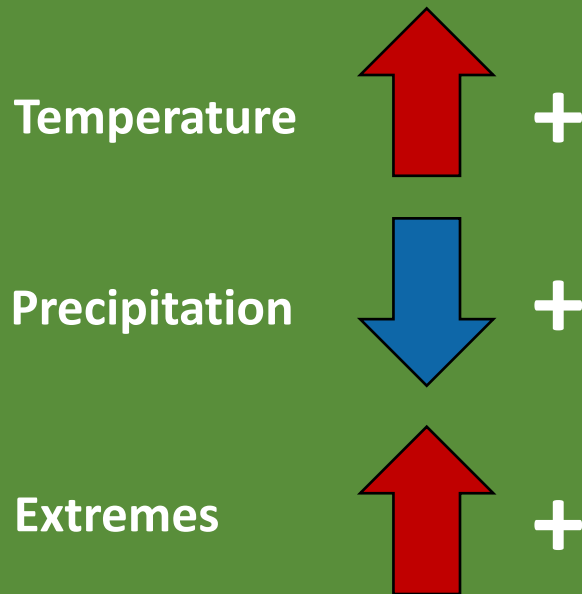


...but they need sufficient water.

The World's Roots Are Getting Shallower

Root-filled soils are hot spots of nutrient cycling and carbon storage. New research finds that the world has lost millions of cubic meters of rooted soil volume—and we're on track to lose much more.

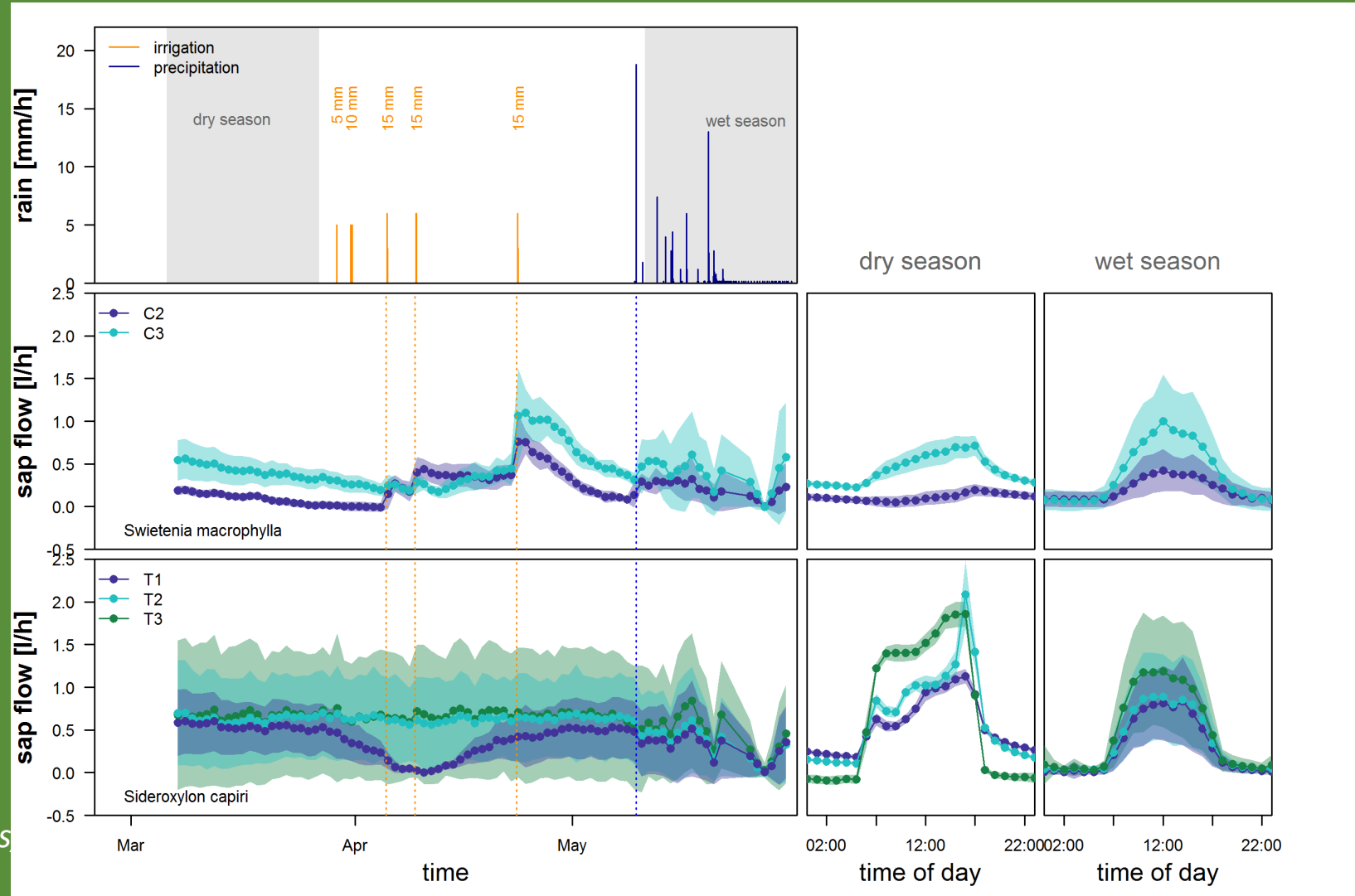
The climate dilemma



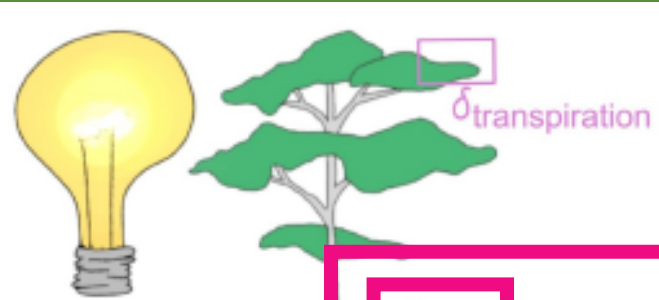
Too many shallow-rooters & lack of niche separation

tree water uptake – sap flow

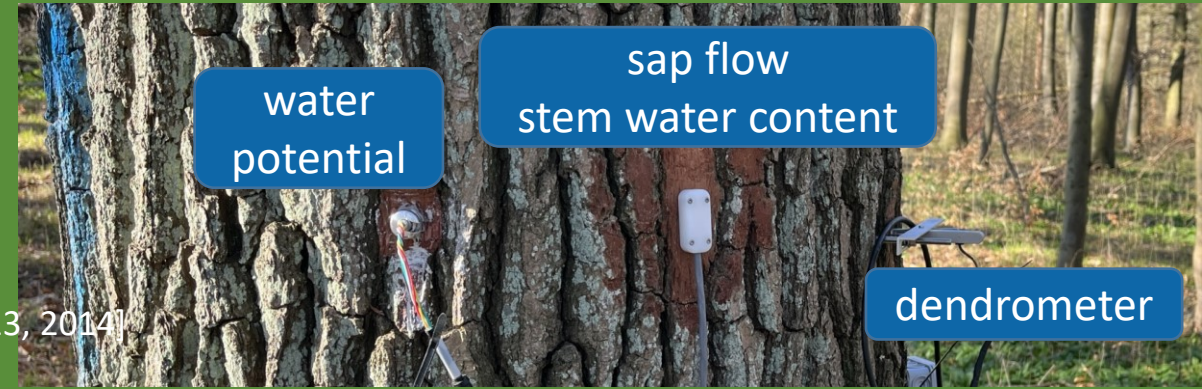
- immediate uptake by *Swietenia macrophylla* (Caoba)
- no reaction of *Sideroxylon capiri* (Tempisque)



Kühnhammer et al. (2021), *Continuous in situ measurements of water stable isotopes in soils tree trunk and root xylem: Field approval*



[Dubbert et al., 2013, 2014]



stem water content

δ_{stem}

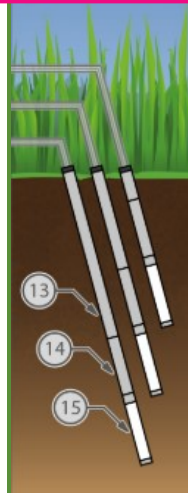
sap flow



[Volkman et al. 2016, Seeger & Weiler 2021]

soil water content

δ_{soil}



[Volkman & Weiler, 2014; Gaj et al., 2016]

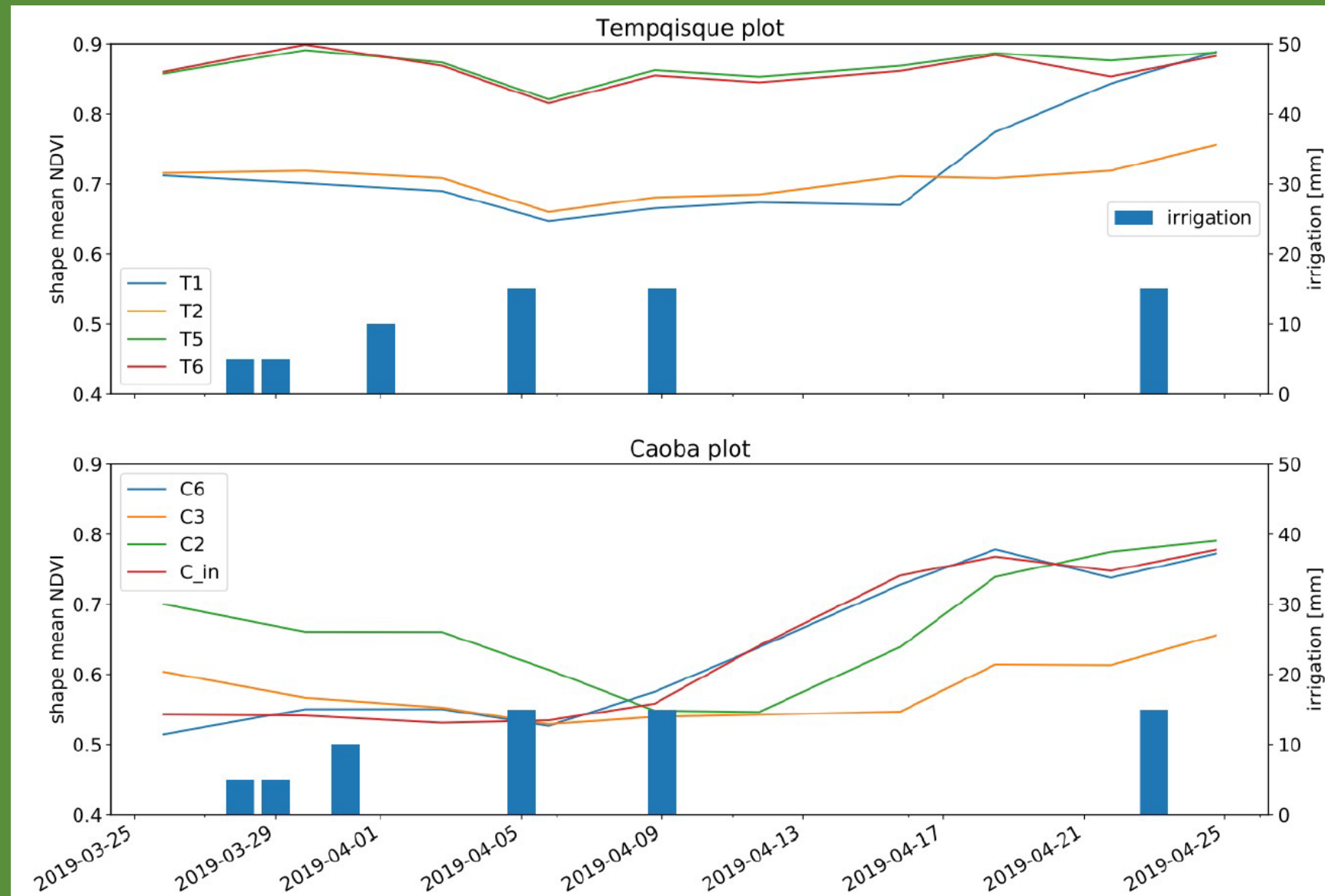
Drones (UAV)

- Vegetation indices:
NDVI

- Tempisque unaffected by irrigation

→ indicator for deep water uptake by Tempisque?

This would be easy to identify and investigate!



Drones (UAV)

- **Vegetation indices:
Composite**

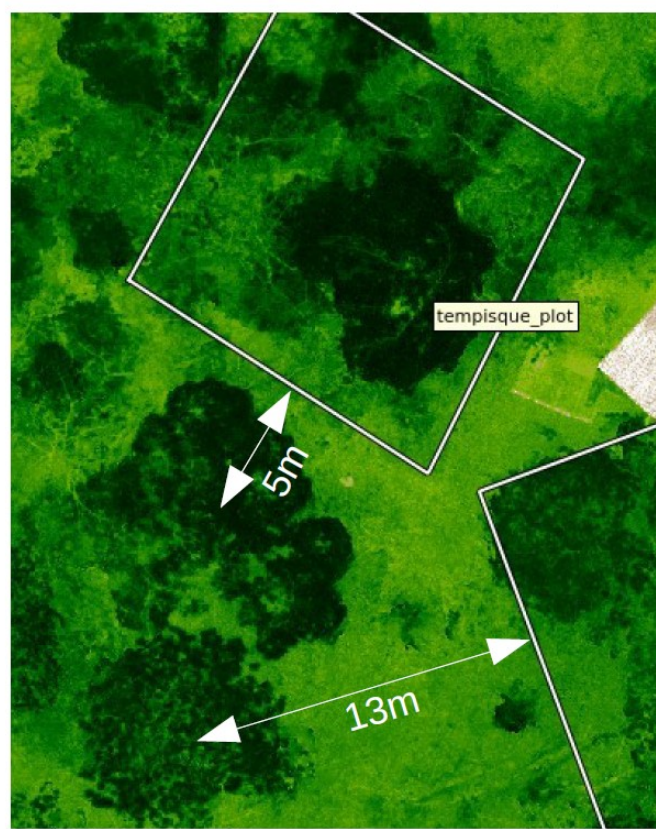
- Near-infrared spectral information visualized (healthy leaves reflect more)
- Healthy vegetation:
 - **Bright Pink**
- Non-Healthy vegetation:
 - **Dark Purple**



...some more UAV stuff



NDVI map before irrigation



NDVI map after irrigation

- Lateral water uptake



- Sampling drone

