Understanding Drought Response of Ecosystems with a Soil-Plant Digital Twin Based on STEMMUS-SCOPE

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With contributions from:

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Zengjing Song	– STEMMUS-SCOPE & Plant Hydraulics
Danyang Yu	– STEMMUS-SCOPE & Crop Growth
Enting Tang	– STEMMUS-SCOPE & Nutrients
Qianqian Han	– STEMMUS-SCOPE & ML-Based Emulator
Prajwal Khanal	– STEMMUS-SCOPE & ML, Satellite Upscaling
Lianyu Yu	– STEMMUS-SCOPE & Groundwater
Christiaan van der Tol	– SCOPE developer
Fakhereh Alidoost	– High Performance Computing

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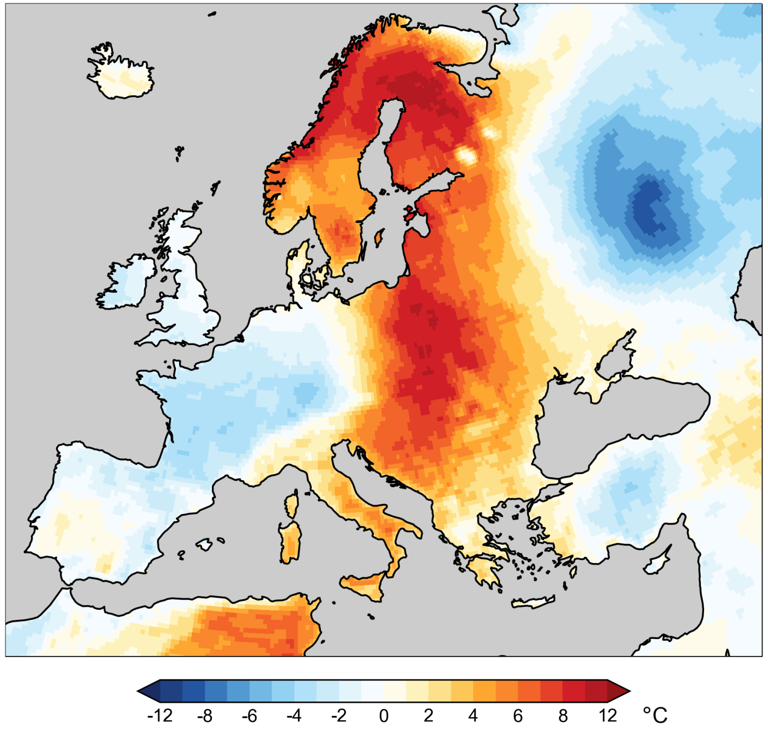
Science Questions:

- Droughts and heatwaves impact ecosystem water, energy and carbon fluxes, and jeopardize terrestrial ecosystem carbon sequestration.
- What is the mechanism controlling the drought response of ecosystem?
- How does the drought response of ecosystems vary in space and time?

Surface temperature anomaly for 01 July 2022



Reference period: 1991-2020 • Data: ERA5 • Credit: C3S/ECMWF

PROGRAMME OF THE EUROPEAN UNION Copernicus ECMWF Climate Change Service

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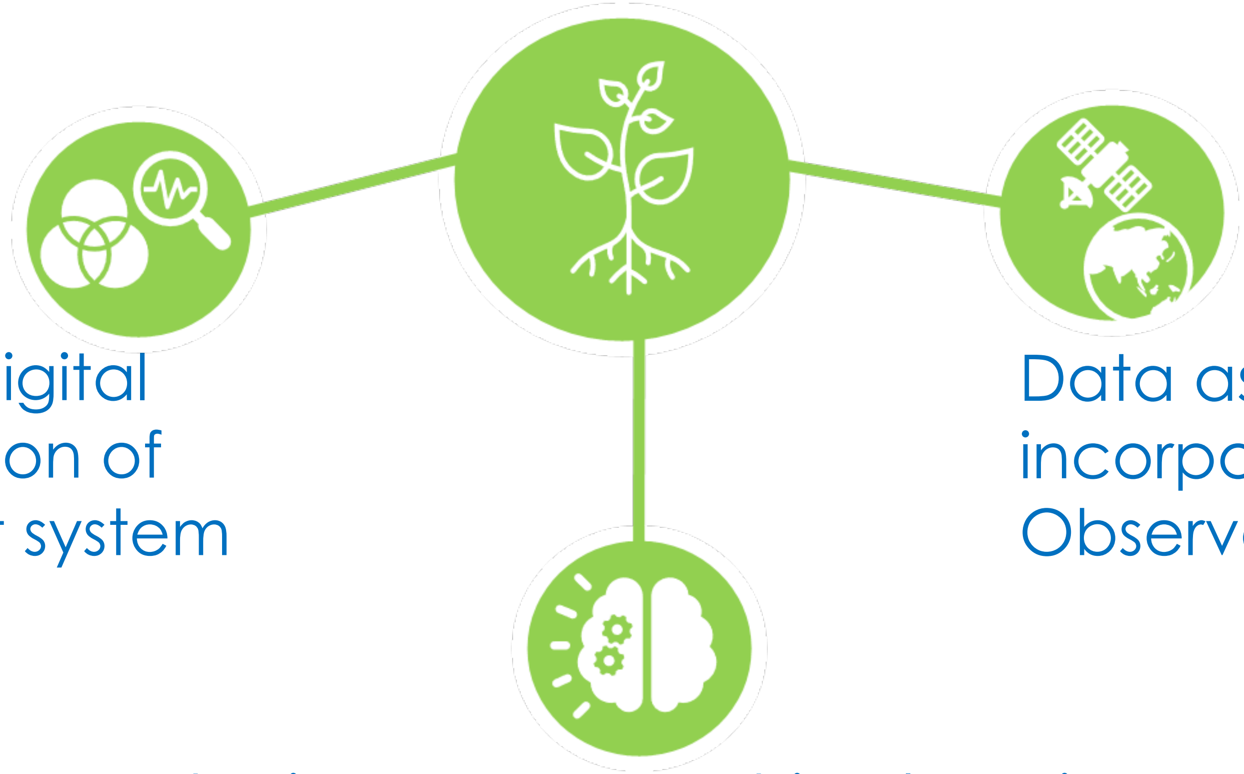
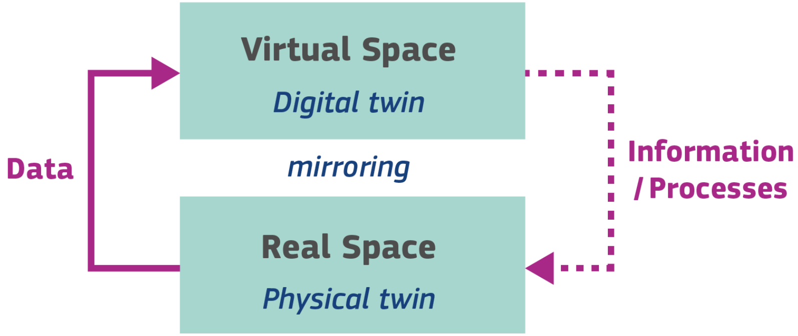
A Digital Twin for Soil-Plant System based on STEMMUS-SCOPE



Develop a Digital Representation of the soil-plant system

Data assimilation to incorporate Earth Observation data

Physics-aware machine learning to approximate the coupled model



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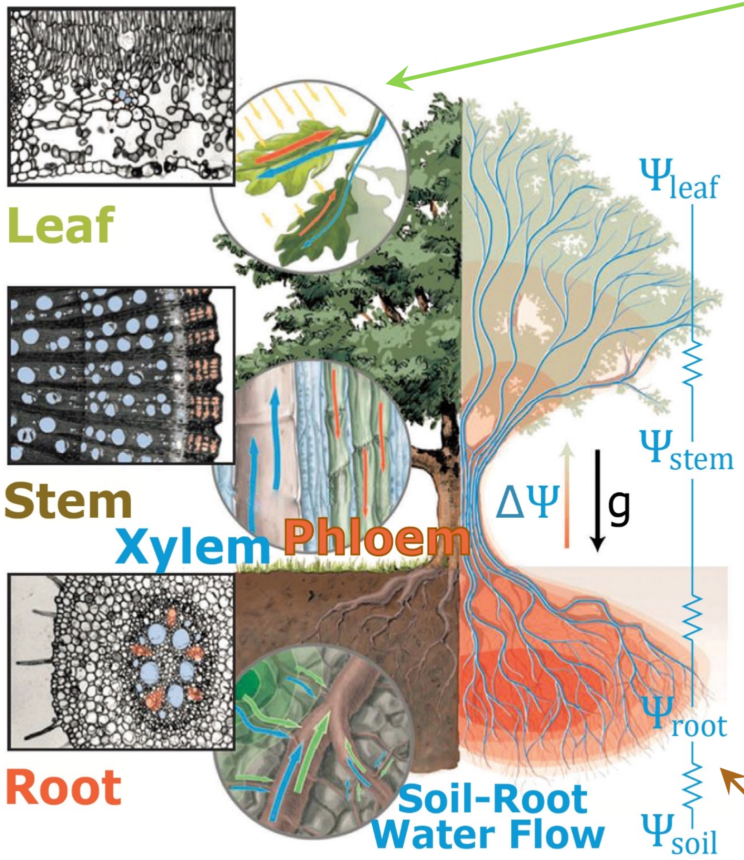
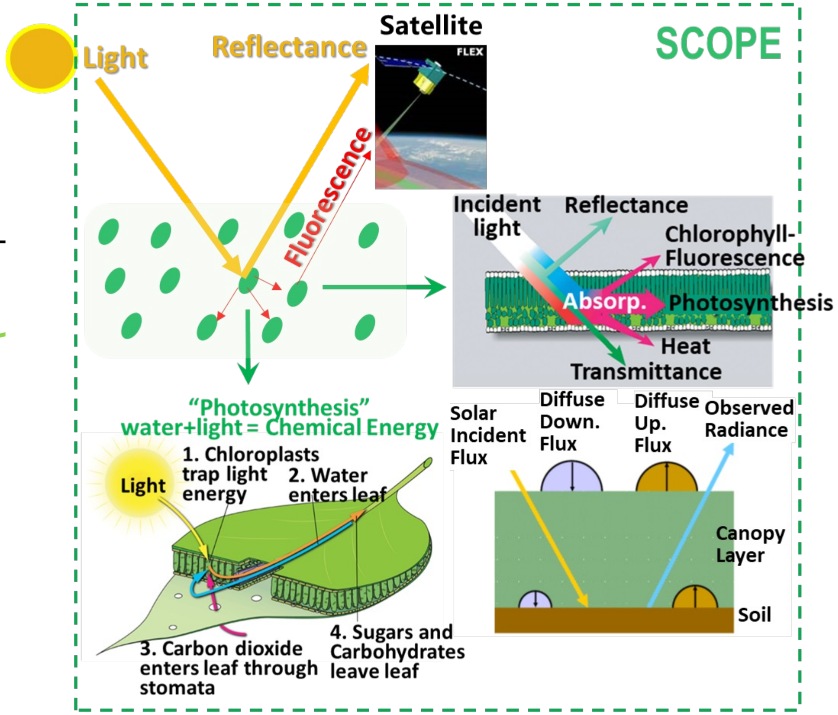
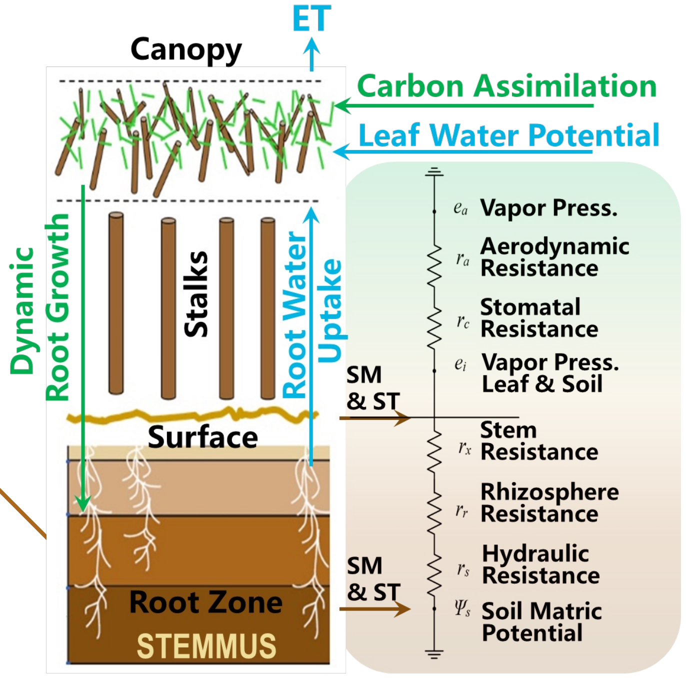
A Digital Twin for Soil-Plant System based on STEMMUS-SCOPE

STEMMUS-SCOPE:

Integrated modelling of canopy photosynthesis, fluorescence,
and the transfer of energy, mass, and momentum in
the SPAC continuum.







Linking SIF (Solar-Induced Fluorescence) to Soil-Water-Plant-Energy Interactions

OUTLINE

Understanding Drought Responses with STEMMUS-SCOPE

- Agriculture and Nature Ecosystems
- SIF vs. GPP and Role of Water Potential

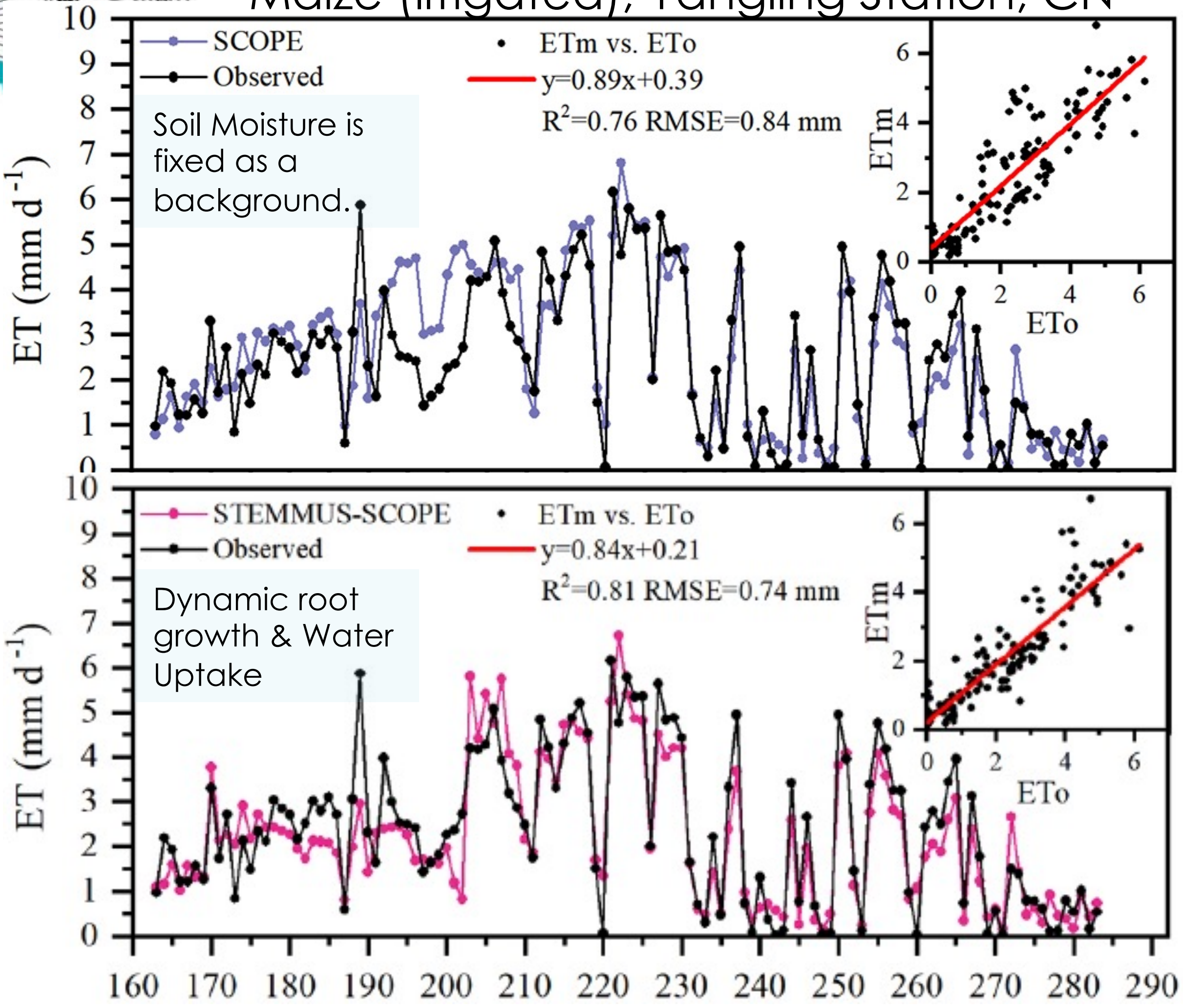
Opportunities & Challenges & Outlooks

- STEMMUS-SCOPE Coupled with Plant Hydraulics
- STEMMUS-SCOPE Coupled with Crop Growth Model

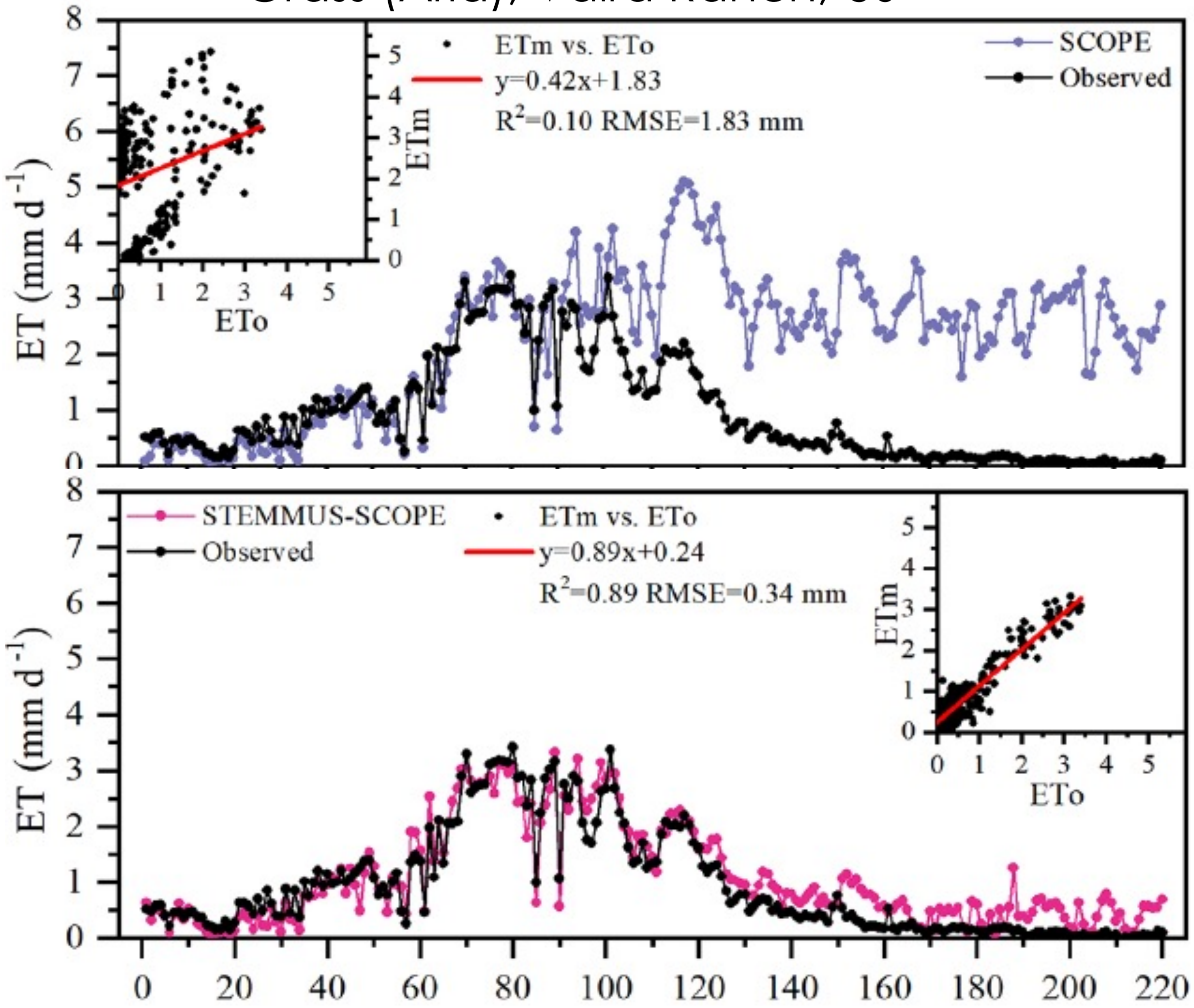
1. Drought Responses: Evapotranspiration

(Wang et al. 2021, GMD)

Maize (Irrigated), Yangling Station, CN



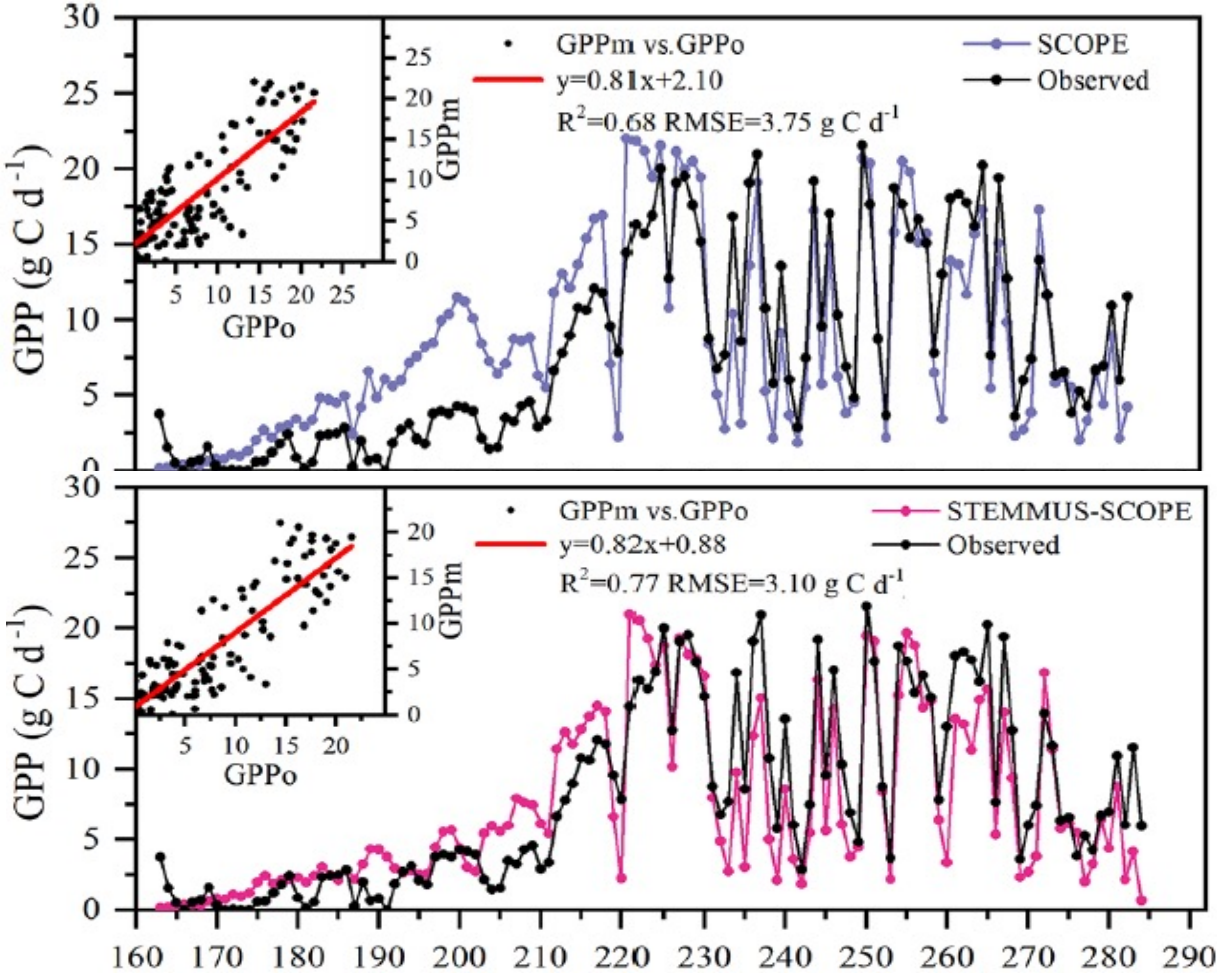
Grass (Arid), Vaira Ranch, US



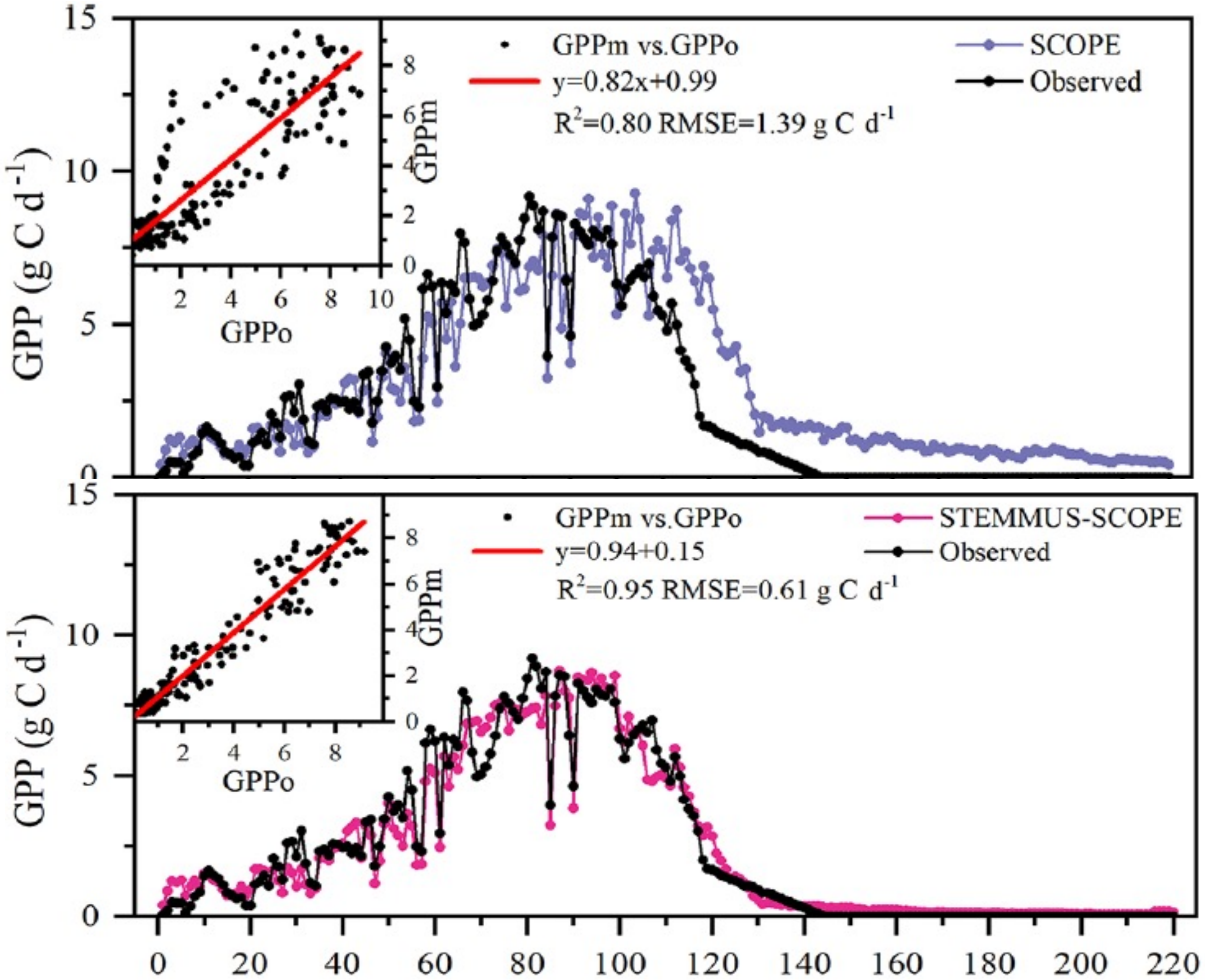
1. Drought Responses: GPP

(Wang et al. 2021, GMD)

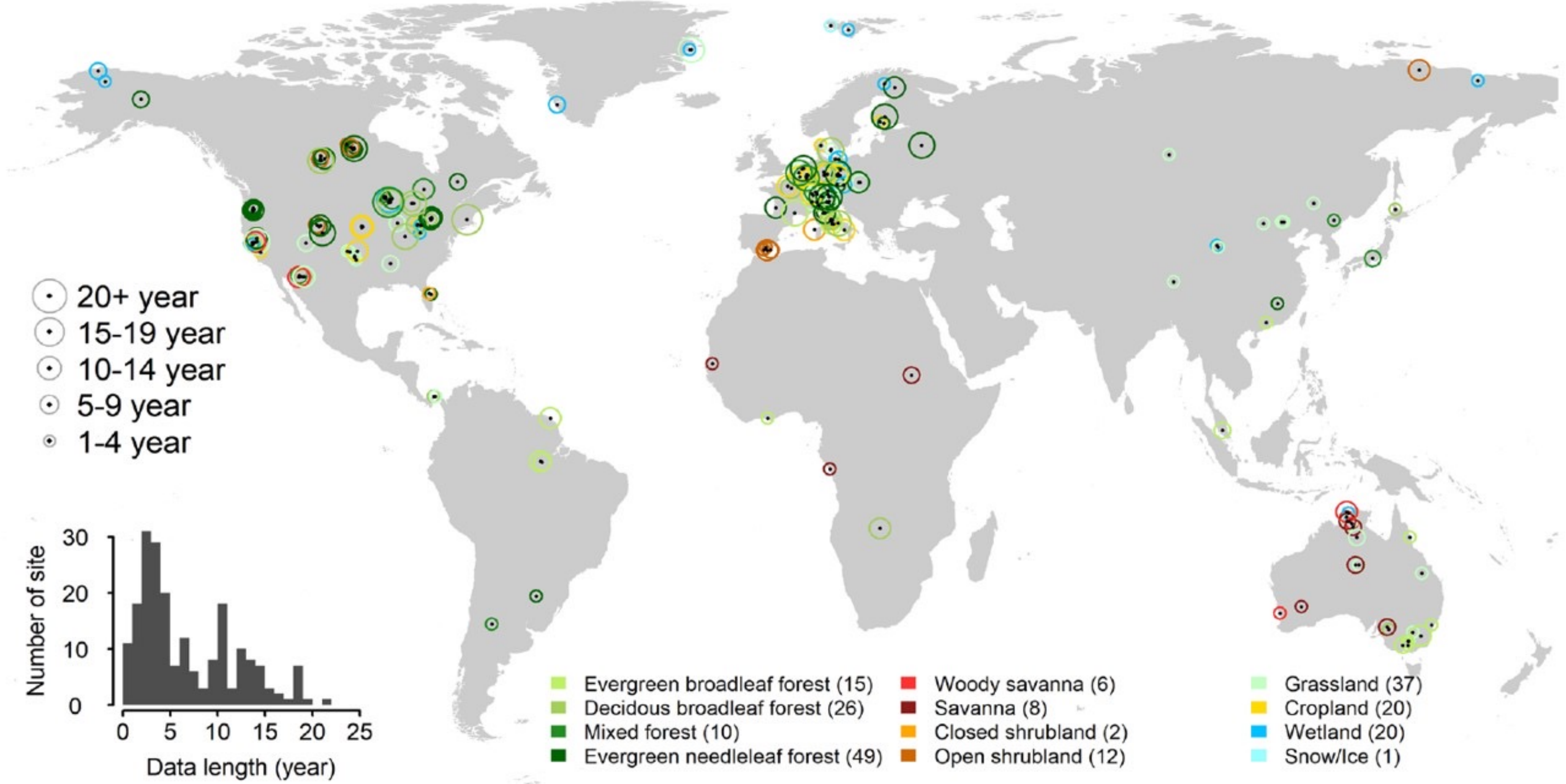
Maize (Irrigated), Yangling Station, CN



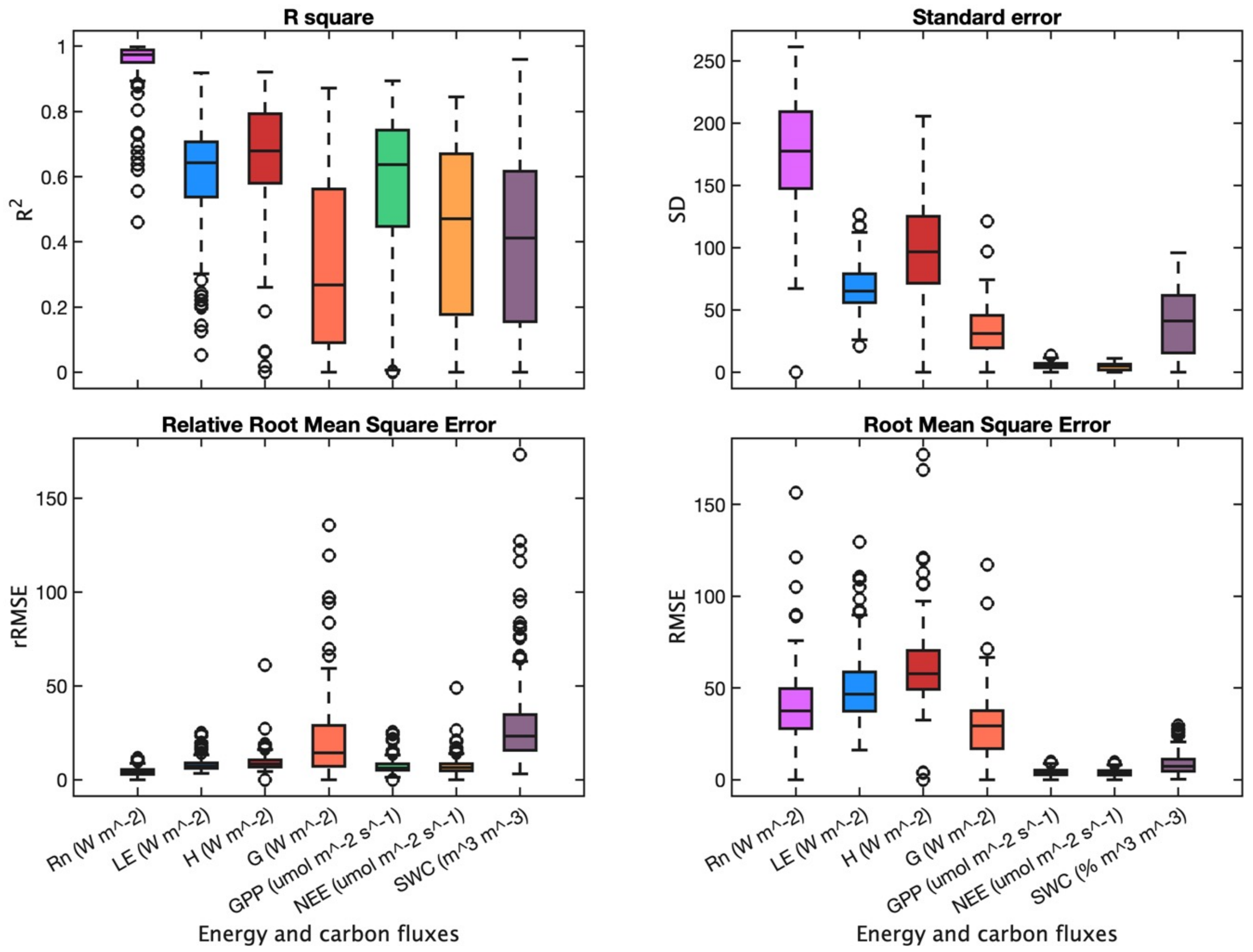
Grass (Arid), Vaira Ranch, US



1. Drought Response: GEWEX-PLUMBER2



1. Drought Response: GEWEX-PLUMBER2 - General Performance



General performance of STEMMUS-SCOPE in simulating energy-carbon fluxes and soil water content.

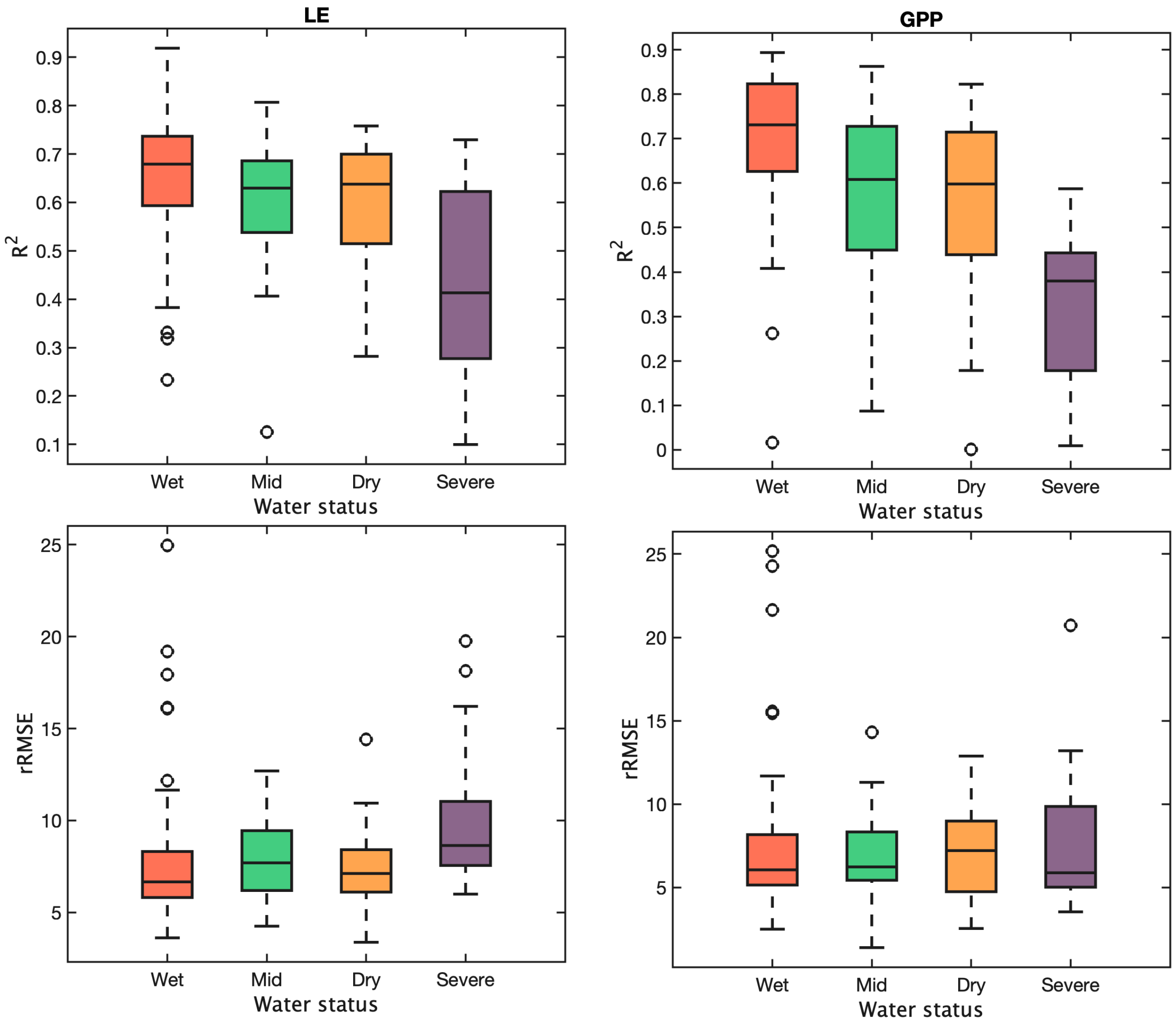
Model Inputs/Driving:

- MODIS LAI
- ERA5 & PLUMBER2
- Soil Hydraulic Parameters (Montzka et al. 2017)
- SoilGrids
- … …

Without tunning … …

(Wang, et al. 2023 unpublished)

1. Drought Response: GEWEX-PLUMBER2 - General Performance



(Wang, et al. 2023 unpublished)

SESSION SUMMARY

- Without considering soil water stress with a process-based soil water and heat transport model, Water-Energy-Carbon Fluxes (ET, GPP, NEE, etc.) are overestimated;

- STEMMUS-SCOPE enables the mechanistic consideration of soil water stress, and capture the drought responses of ecosystem functioning;

- STEMMUSE-SCOPE is applied for GEWEX-PLUMBER2 project (170 Fluxnet sites), the general performance is reasonable without model tunning;

- For severe dry conditions, model performance is still to be improved …

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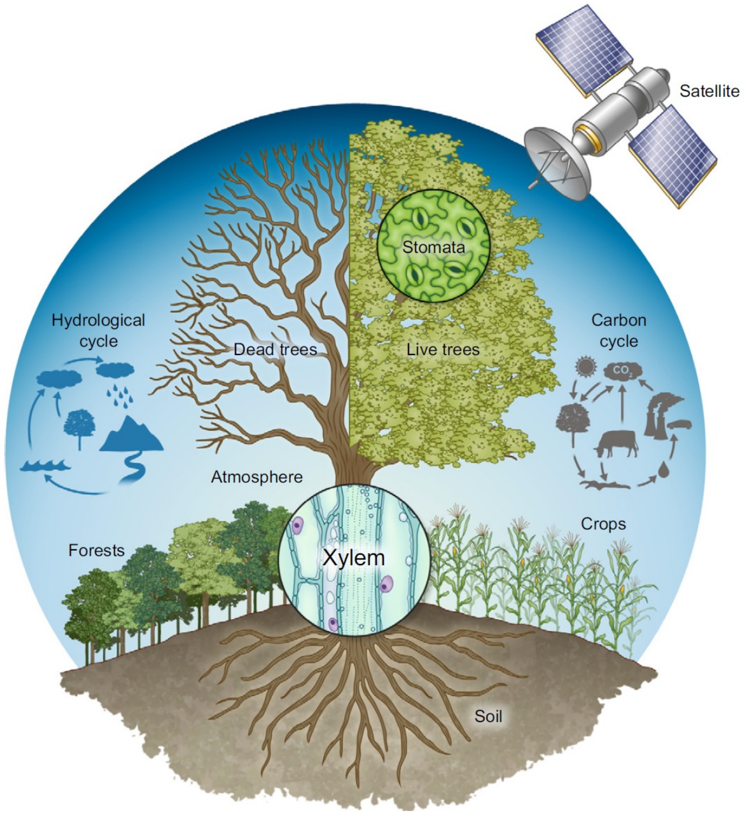
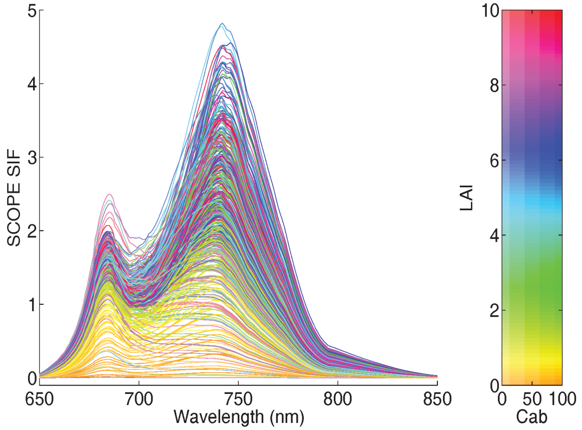
- STEMMUS-SCOPE Coupled with Crop Growth Model

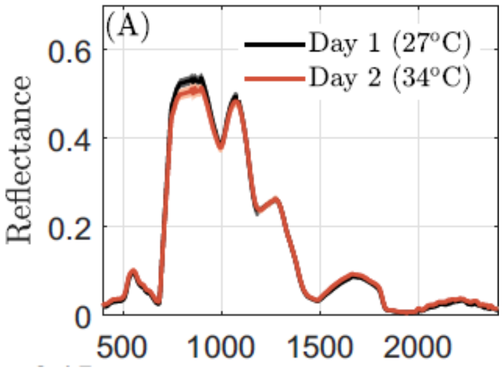
2. SIF vs GPP and Roel of Water Potential

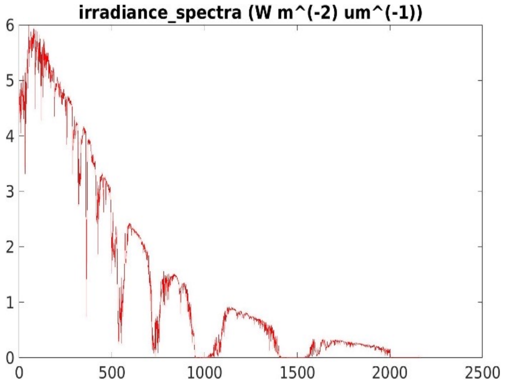
STEMMUS-SCOPE links satellite observables in the visible, infrared, and thermal domains to water-energy-carbon processes above- and below-ground. (OSSEs - Observation System Simulation Experiments)

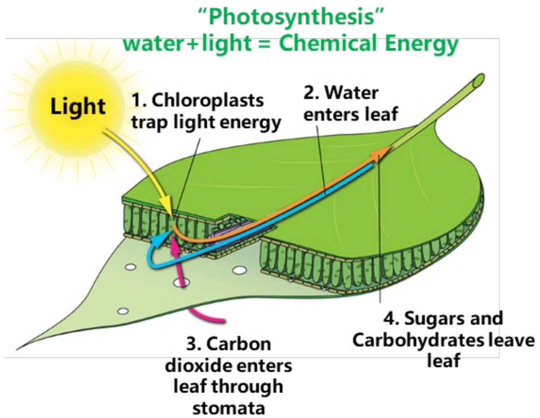


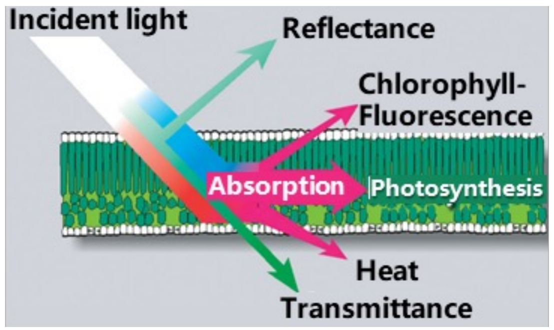


Top of Canopy Solar-Induced Fluorescence (SIF)

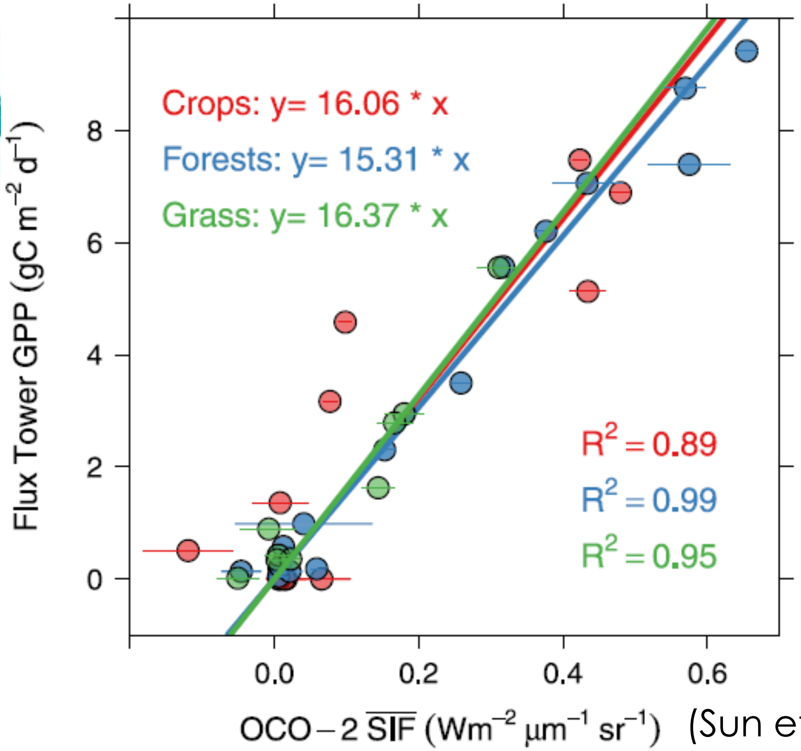




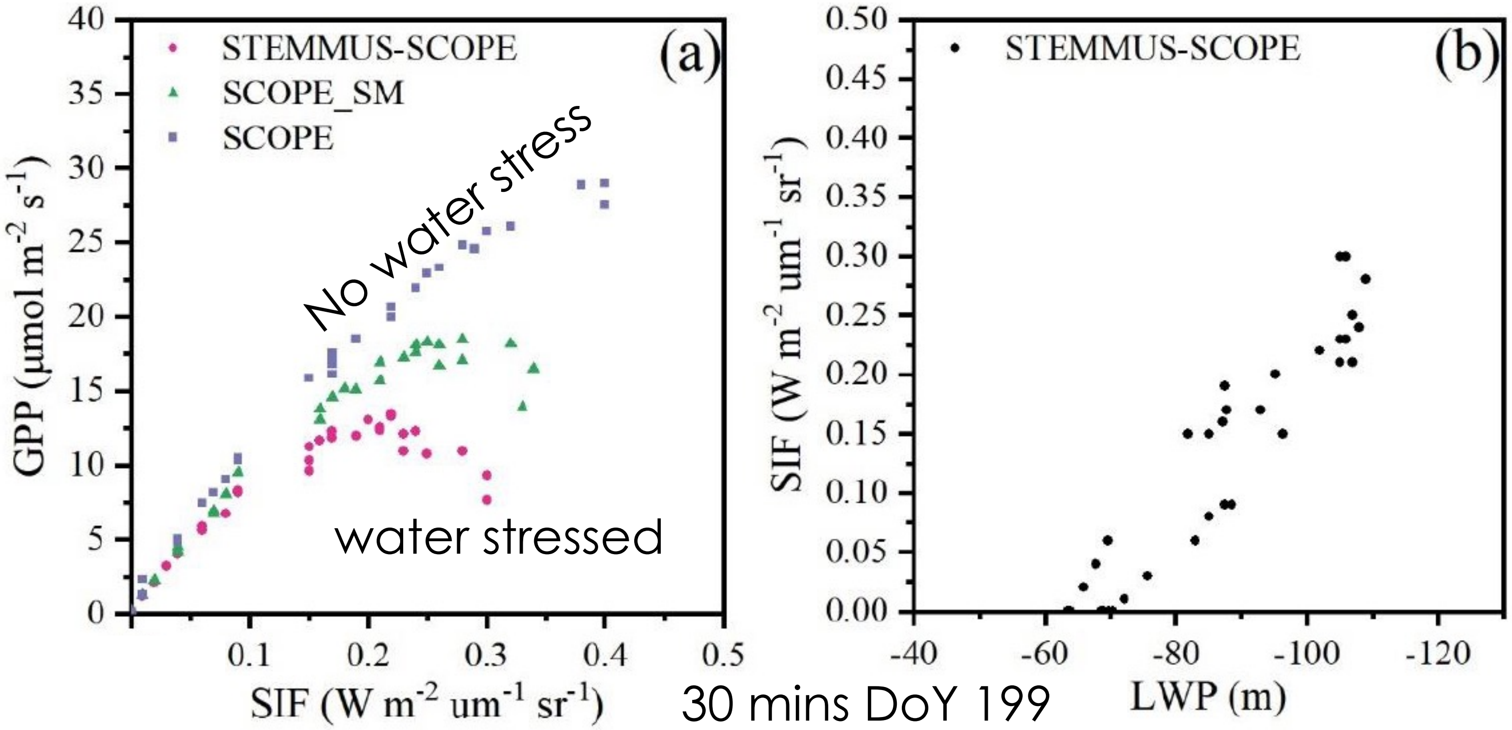




2. SIF vs GPP and Roel of Water Potential



(Sun et al. 2017)



$$GPP = PAR \times fAPAR \times LUE_{Photochemistry}$$

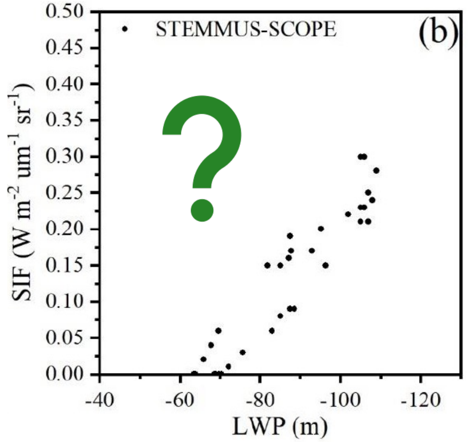
$$SIF = PAR \times fAPAR \times LUE_{Fluorescence}$$

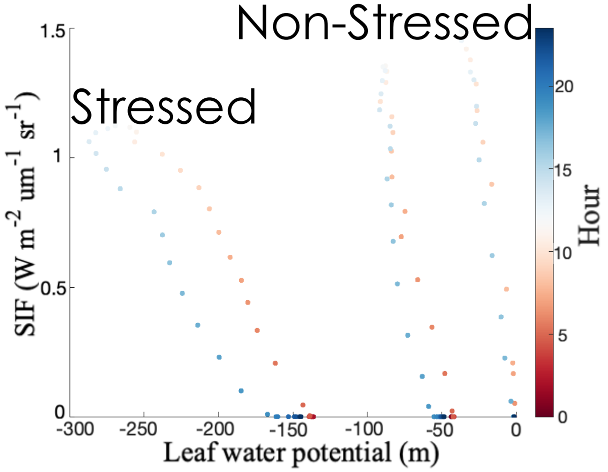
The ***apparent*** linear "SIF vs. GPP" between flux tower GPP and SIF has stimulated the development of SIF remote sensing.

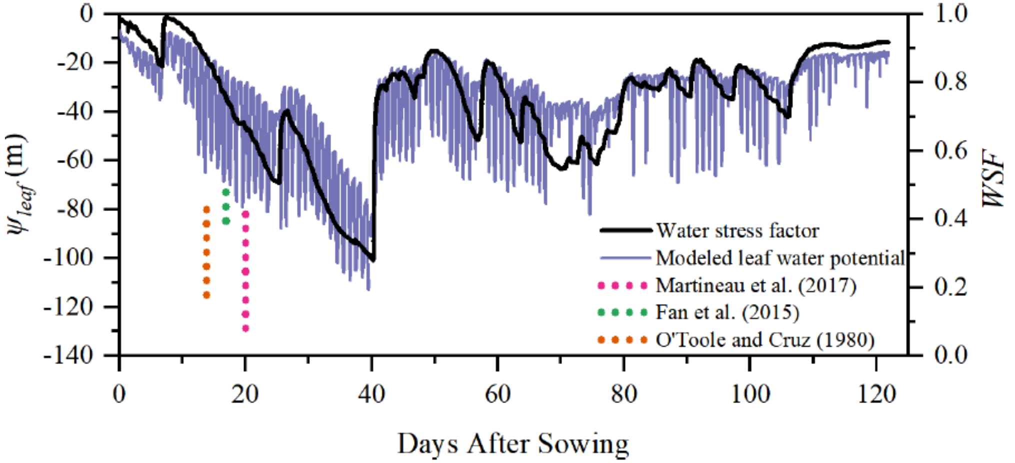
- STEMMUS-SCOPE shows that this apparent linear "SIF vs. GPP" is valid when there is no water stress
- When the plant is water stressed, "SIF vs. GPP" appears nonlinear.
- There seems a linear relationship "SIF vs. Leaf Water Potential"

(Wang, et al. 2021, GMD)

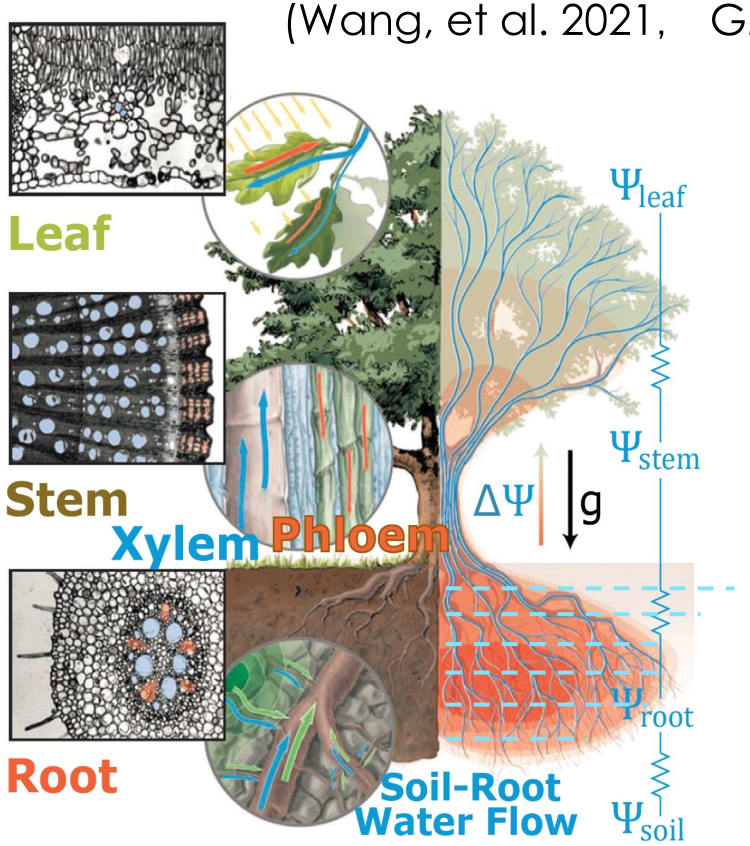
2. SIF vs GPP and Roel of Water Potential







(Wang, et al. 2021, GMD)



$$\mathrm{WSF} = \sum_{i=1}^{n} \mathrm{RF}(i) \cdot \mathrm{WSF}(i)$$

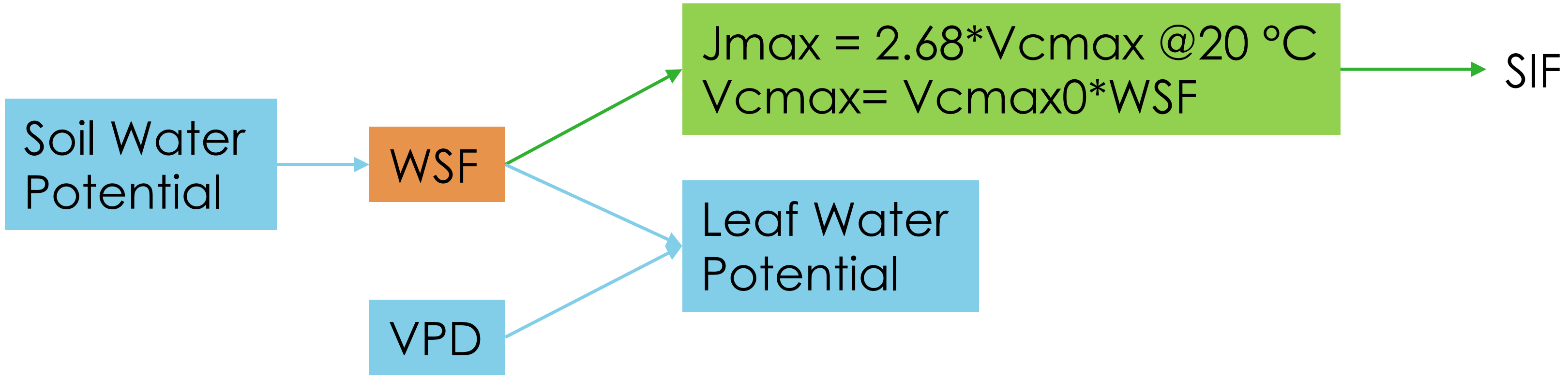
$$\mathrm{WSF}(i) = \frac{1}{1 + e^{-100 \cdot \theta_{\mathrm{sat}} \left(\mathrm{SM}(i) - \frac{\theta_f + \theta_w}{2} \right)}}$$

RF- root length fraction

- GPP and SIF are regulated by electron transport rate and rubisco catalytic activity.
- [STEMMUS-SCOPE uses Jmax = 2.68*Vcmax @20 °C & Vcmax= Vcmax0*WSF]
- Soil water potential & VPD co-regulate leaf water potential.
- **Role of Soil-Plant Hydraulics is critical in better explaining SIF-GPP relationship.**

SESSION SUMMARY/DISCUSSION

- SIF-GPP is not necessarily linear, and is subjected to confounding factors, including soil water stress and leaf water potential;
- SIF is a robust proxy of leaf water potential, or the other way around;



- The interpretation of SIF requires (and will advance) the full spectrum understanding of Soil-Water-Plant-Energy interactions, including soil-plant hydraulics.

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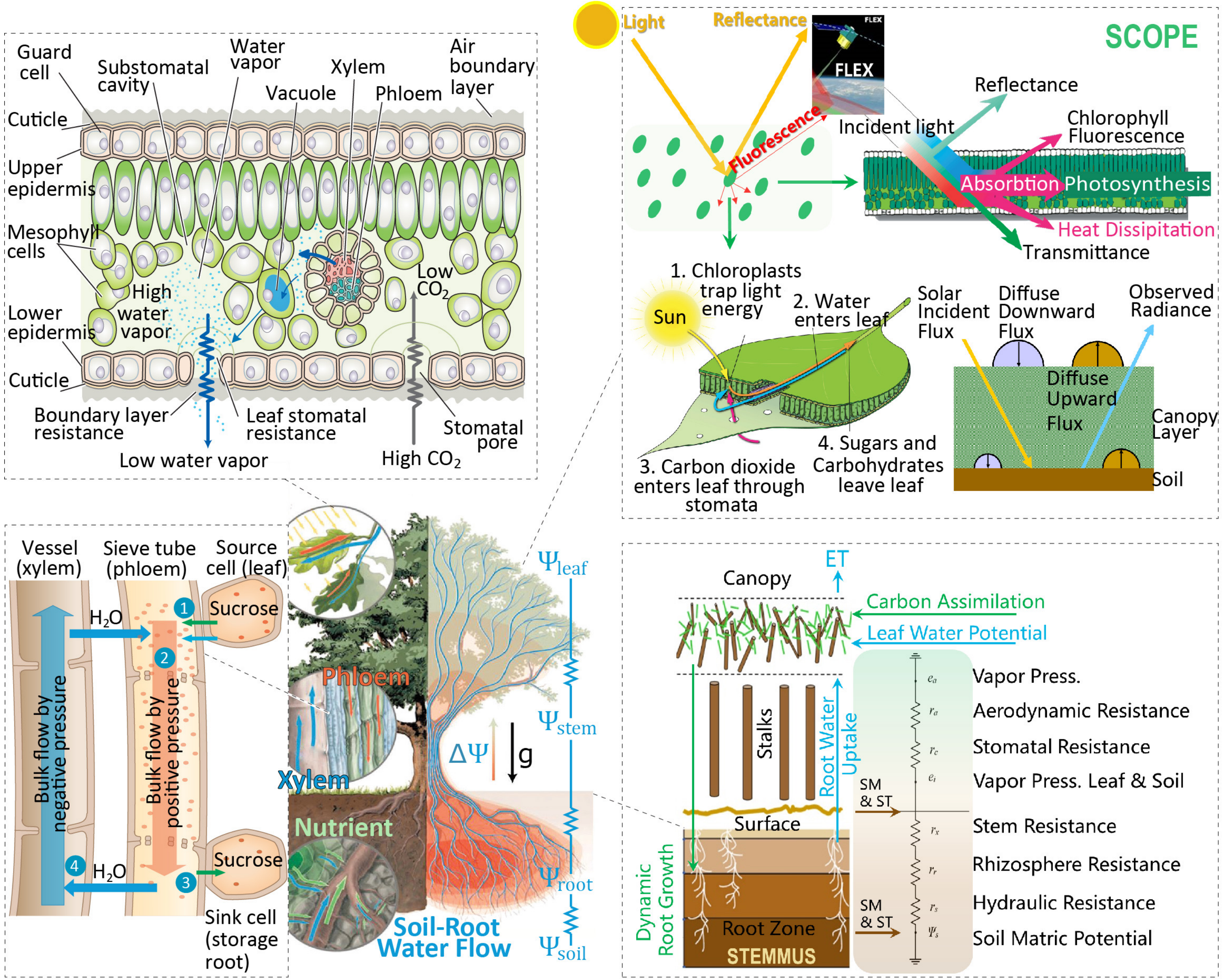
3. Soil-Plant Hydraulics

The soil-plant hydraulic system.

Left panel: the water potential across the SPAC continuum connects the root zone soil to the leaf, influence the bulk water flow in xylem and phloem, as well as affect the water vapor density in the substomatal intercellular airspace of leaves.

It, therefore, impacts gas exchange, photosynthesis activities, energy balance, and radiative transfer at leaf and canopy levels.

(Zeng et al. 2023 Unpublished)



1. Loading of sugar (coral dots, being the output of photosynthetic activities) into the sieve-tube at the source (a mesophyll cell in a leaf) reduces water potential inside the sieve-tube elements, causes a water potential gradient between the vessel and the sieve tube, and induces water flow from the vessel to the tube.
2. The water uptake by the sieve-tube generates a positive pressure that forces the sap to flow along the tube.
3. This positive pressure is relieved by the unloading of sugar to sink cells (e.g., root, organ), which inverses the water potential gradientbetween the vessel and the sieve-tube, and causes the consequent loss of water at the sink.
4. In the leaf-to-root phloem translocation, xylem recycles water from sink to source, and also uptake water from soil via root hairs.

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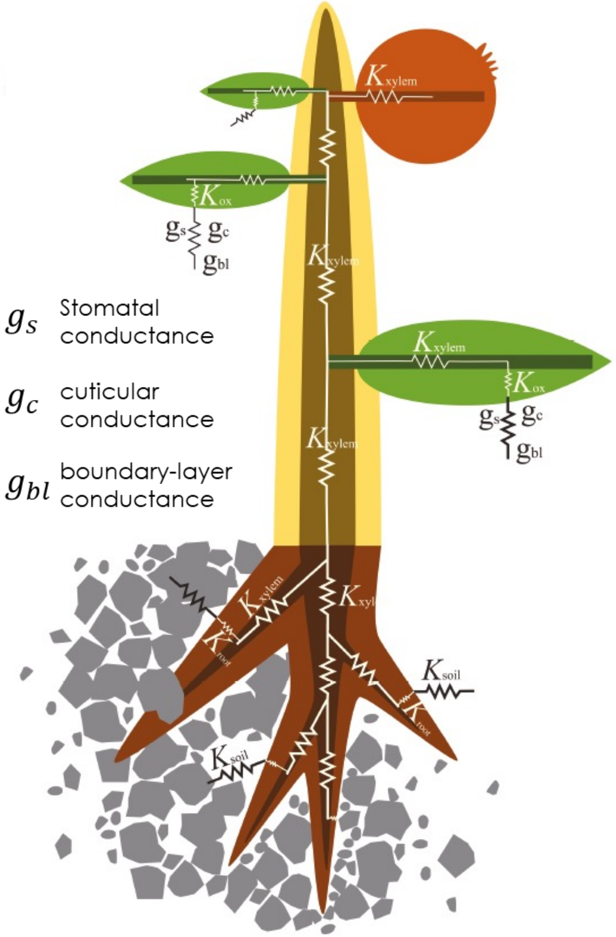
3. Plant Hydraulics



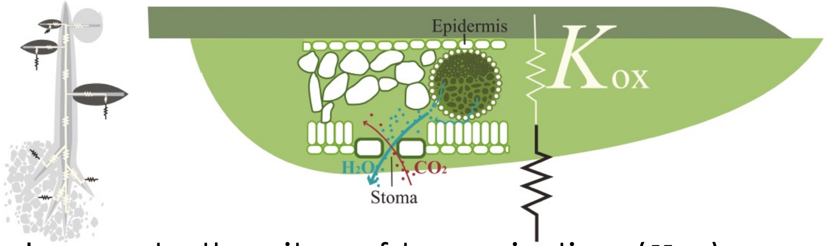
g_s Stomatal conductance

g_c cuticular conductance

g_{bl} boundary-layer conductance

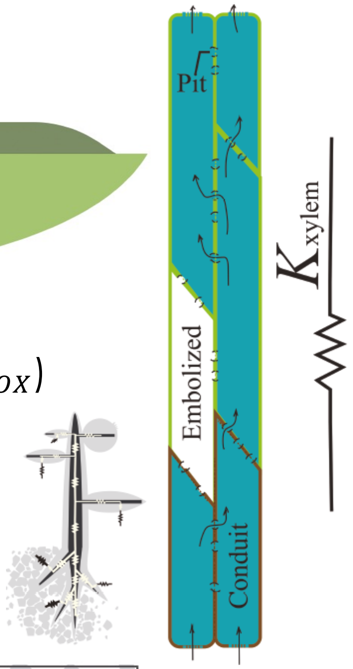
Scheme of water flow:

(i) outside the xylem in the leaves to the sites of transpiration (K_{OX})



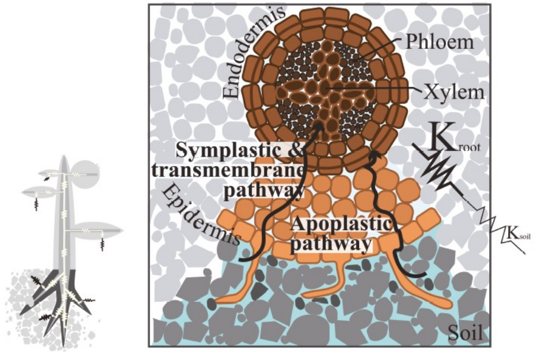
$$K_{\text{leaf}} = (K_{\text{x}}^{-1} + K_{\text{ox}}^{-1})^{-1}$$

(ii) inside the xylem from the roots towards the leaves (K_{xylem})



$$J_v = K \cdot \ \Delta\Psi^{p}$$

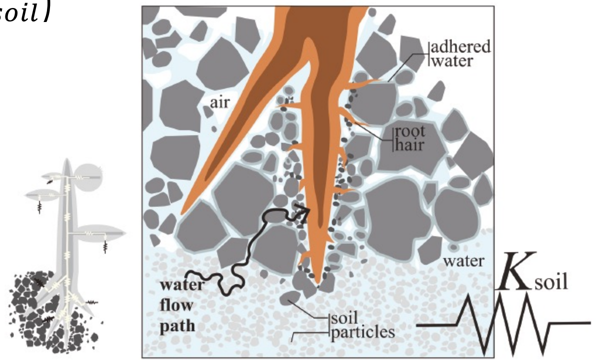
(iii) from the root surface to the xylem (K_{root})



$$J_v = K \cdot (\Delta\Psi^{p} + \sigma \cdot (\Delta\Psi^{\pi}))$$

(iv) from the soil towards the root surface (K_{soil})

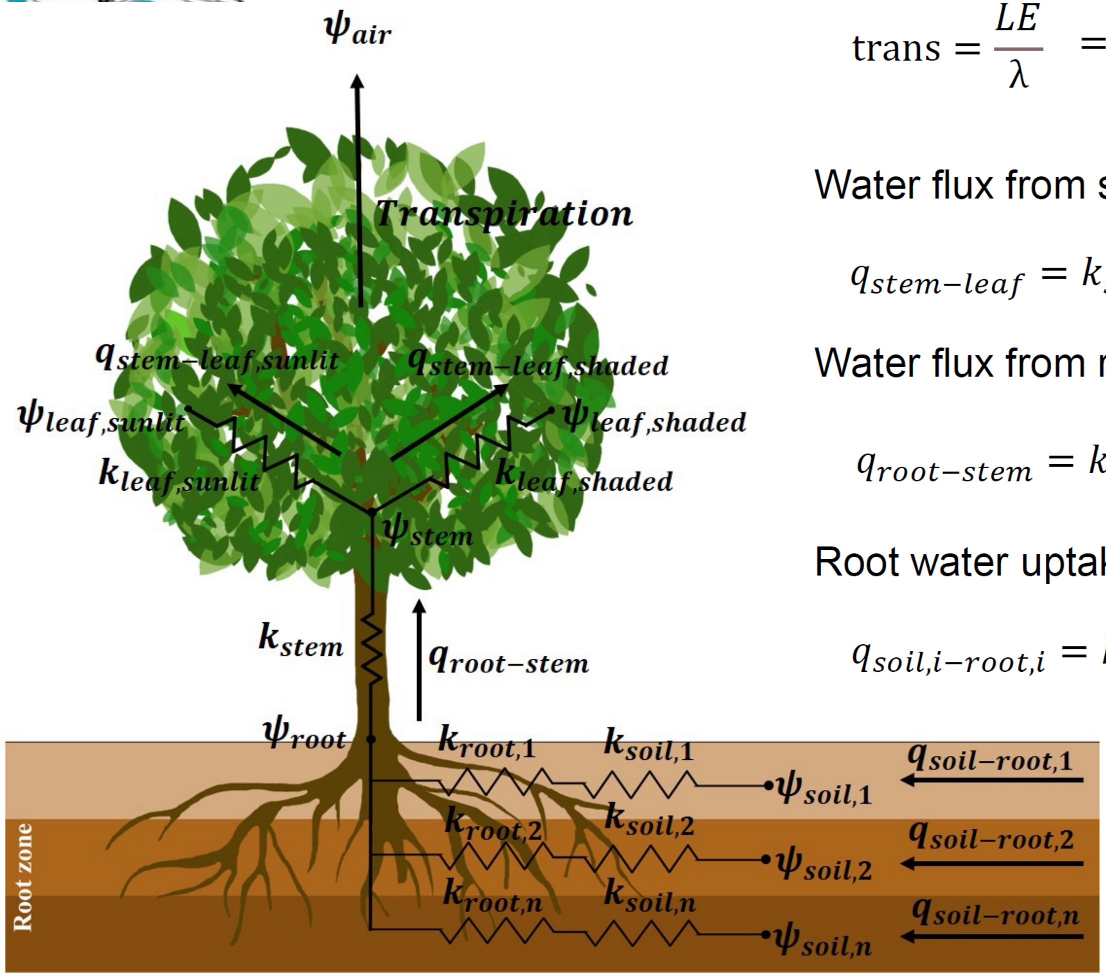
$$q = -\kappa_{\text{soil}}(\theta)\frac{\Delta H}{L}$$



On the pivotal role of water potential to model plant physiological processes

Tom De Swaef, Olivier Pieters, Simon Appeltans, Irene Borra-Serrano, Willem Coudron, Valentin Couvreur, Sarah Garré, Peter Lootens, Bart Nicolaï, Leroi Pols ...

3. STEMMUS-SCOPE with Plant Hydraulics



Transpiration

$$\text{trans} = \frac{LE}{\lambda} = q_{stem-leaf} = q_{root-stem} = \sum q_{soil,i-root,i}$$

Water flux from stem to leaf

$$q_{stem-leaf} = k_{stem-leaf} \times LAI \times (\psi_{stem} - \psi_{leaf})$$

Water flux from root to stem

$$q_{root-stem} = k_{root-stem} \times SAI \times (\psi_{root} - \psi_{stem} - h)$$

Root water uptake

$$q_{soil,i-root,i} = k_{soil-root,i} \times (\psi_{soil,i} - \psi_{root,i} - \Delta z_i)$$

Stomatal conductance

$$g_s = g_0 + 1.6 \cdot \left(1 + \frac{g_1}{\sqrt{D}}\right)\left(\frac{A_n}{c_a}\right)$$

Water stress

$$V_c = V_{cmax} \cdot f_w$$

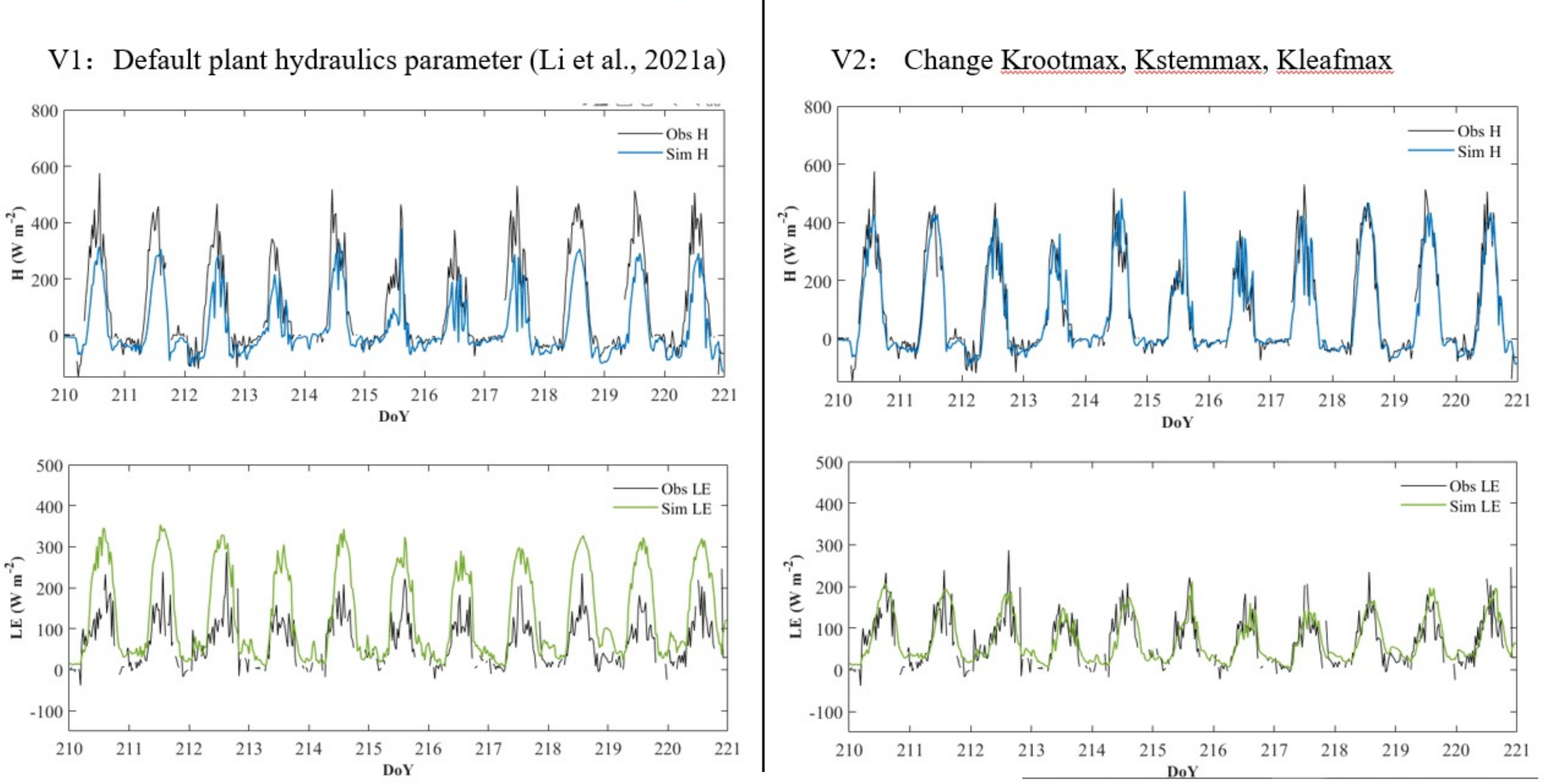
Plant water stress factor

$$f_w = \text{phwsf} = 2^{-\left(\frac{\psi_{leaf}}{P50_{leaf}}\right)^{ck_{leaf}}}$$

(Song, Zeng, et al. 2023, unpublished)

3. STEMMUS-SCOPE with Plant Hydraulics

The effect of plant hydraulic parameters on energy fluxes (obs: original observed LE and H)



(Song, et al. 2023, unpublished)

SESSION SUMMARY/DISCUSSION

- Plant hydraulics can help capture better the dynamics of land surface fluxes;

- Some challenges remained:

  (a) Water capacitance is not considered;

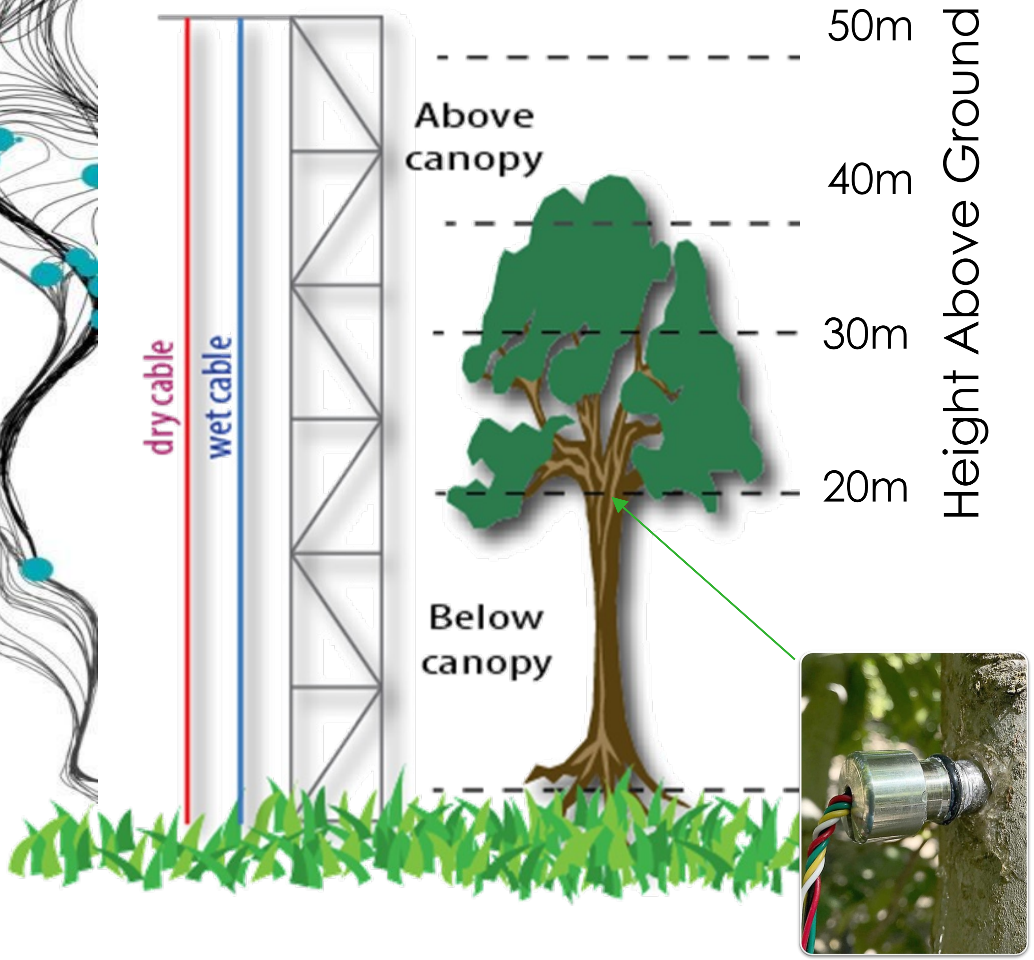
  (b) It is very challenging to get plant hydraulic traits (Kroot, Kstem, Kleaf, etc.)

  (c) It is very challenging to get leaf water potential measurements

  - new technology is emerging (e.g., AquaDust);

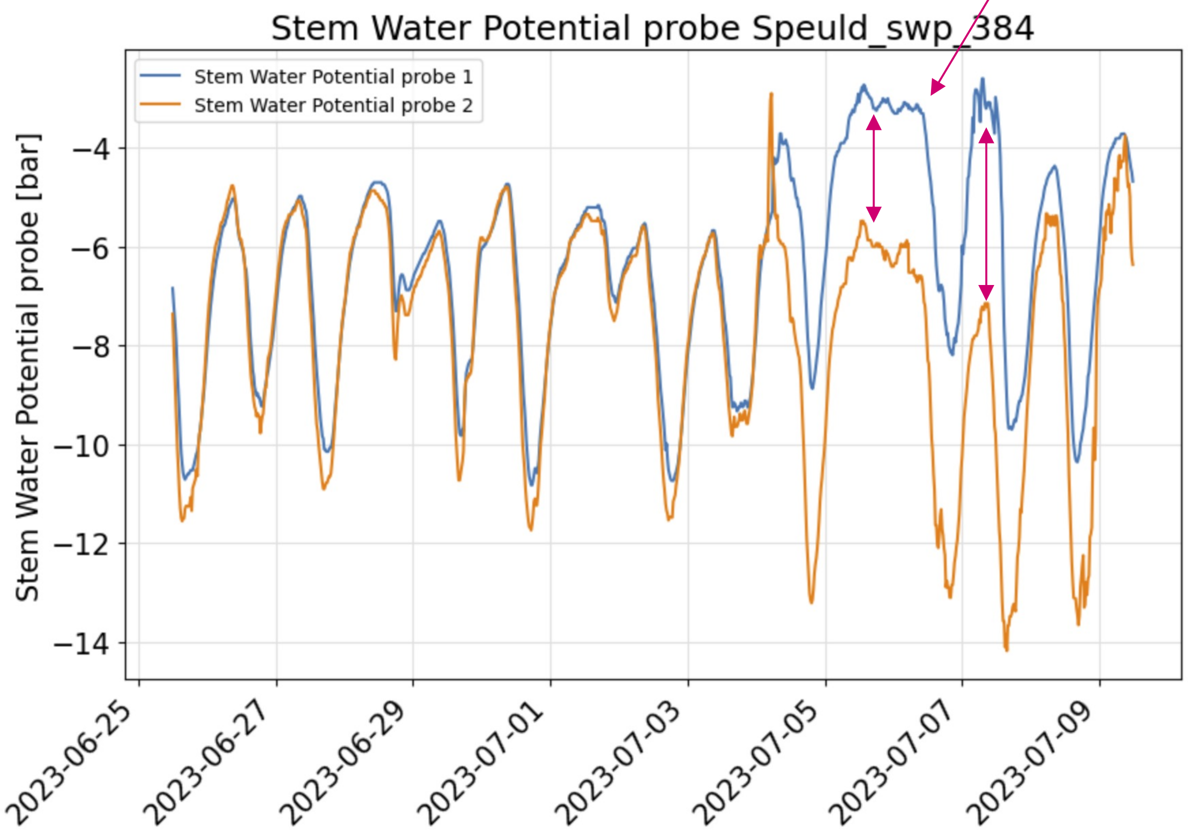
  (d) It is relatively easy to get trunk water potential measurements.

IN-SITU MEASUREMENT OF TRUNK WATER POTENTIAL



FloraPulse
Microtensiometer

Impact by Storm 'Poly'



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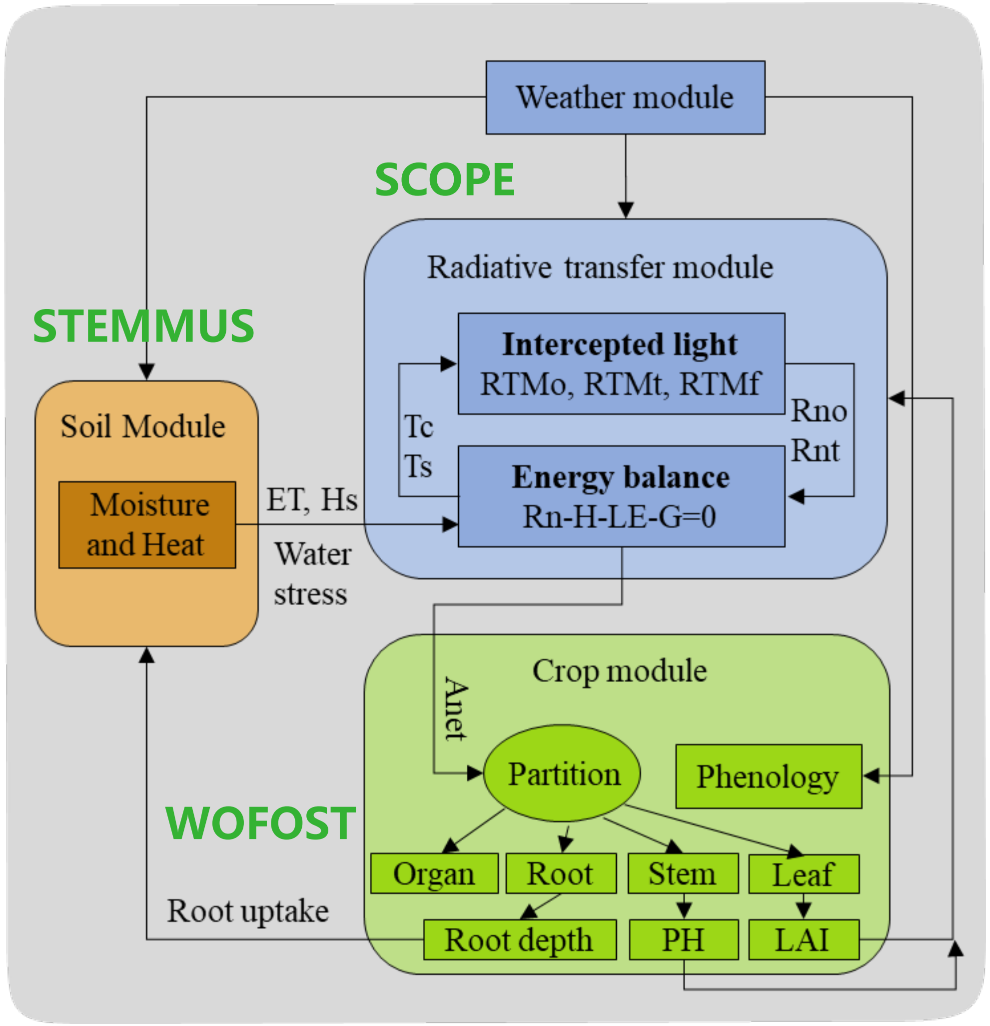
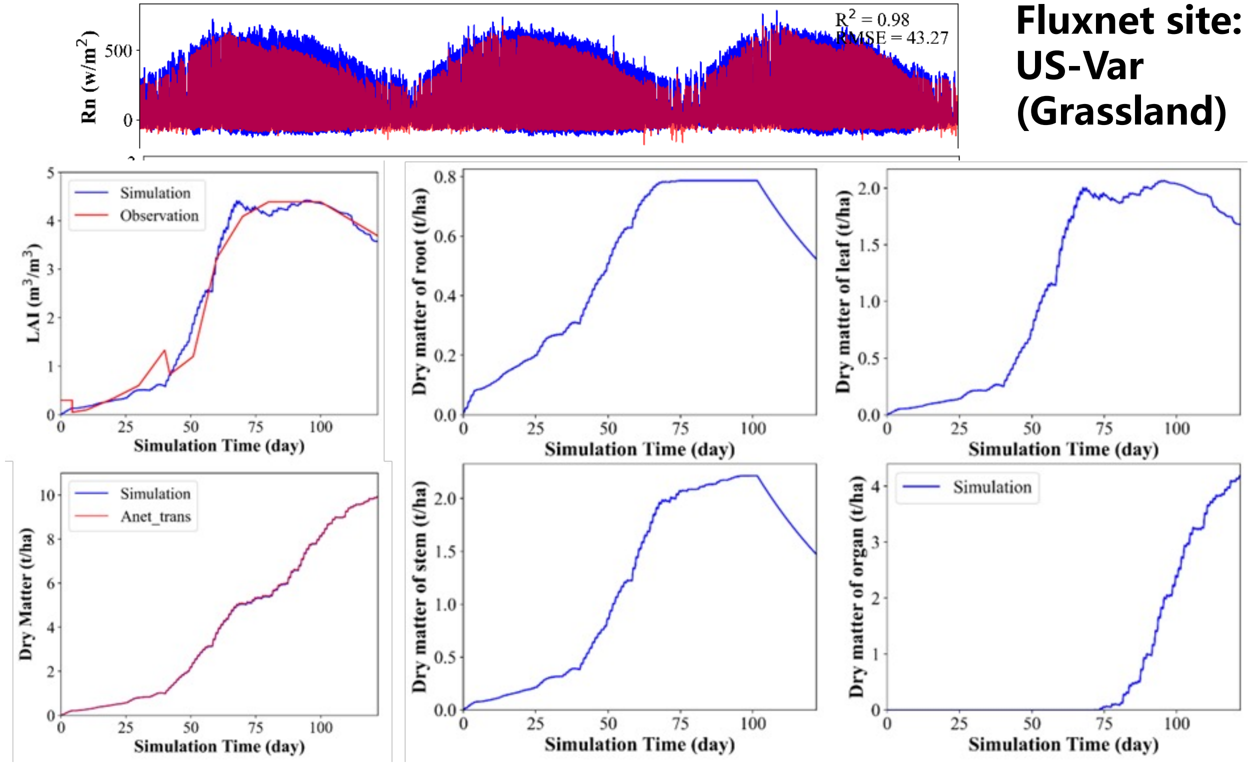
- ***STEMMUS-SCOPE Coupled with Crop Growth Model***

4. STEMMUS-SCOPE Coupled with Crop Growth Model



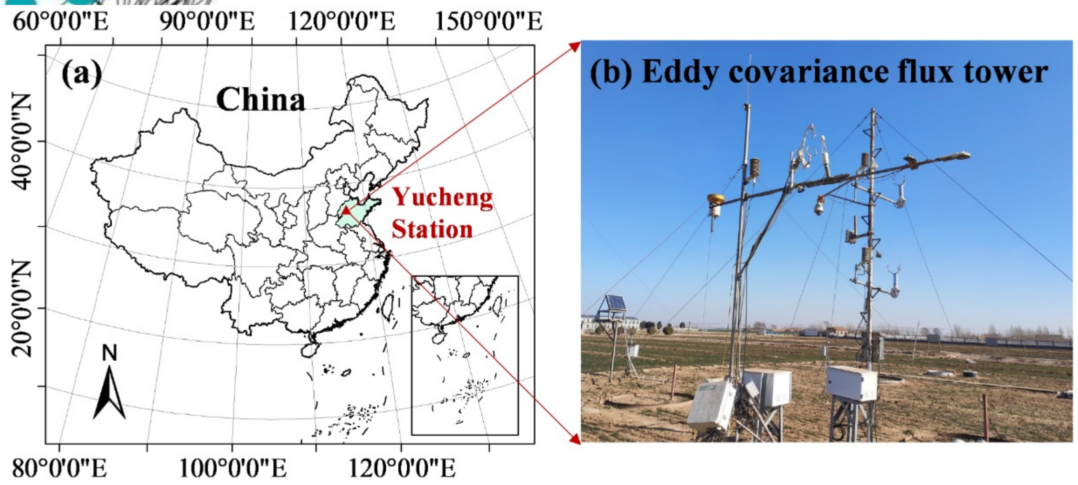
- LAI is currently an input in STEMMUS-SCOPE
- MODIS-LAI tends to have gaps

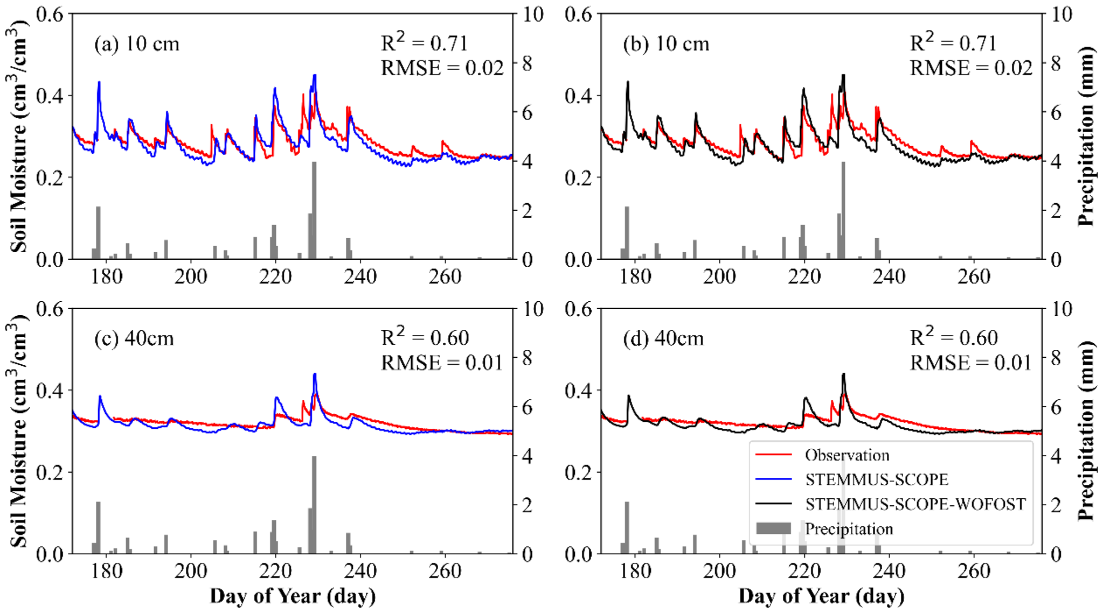


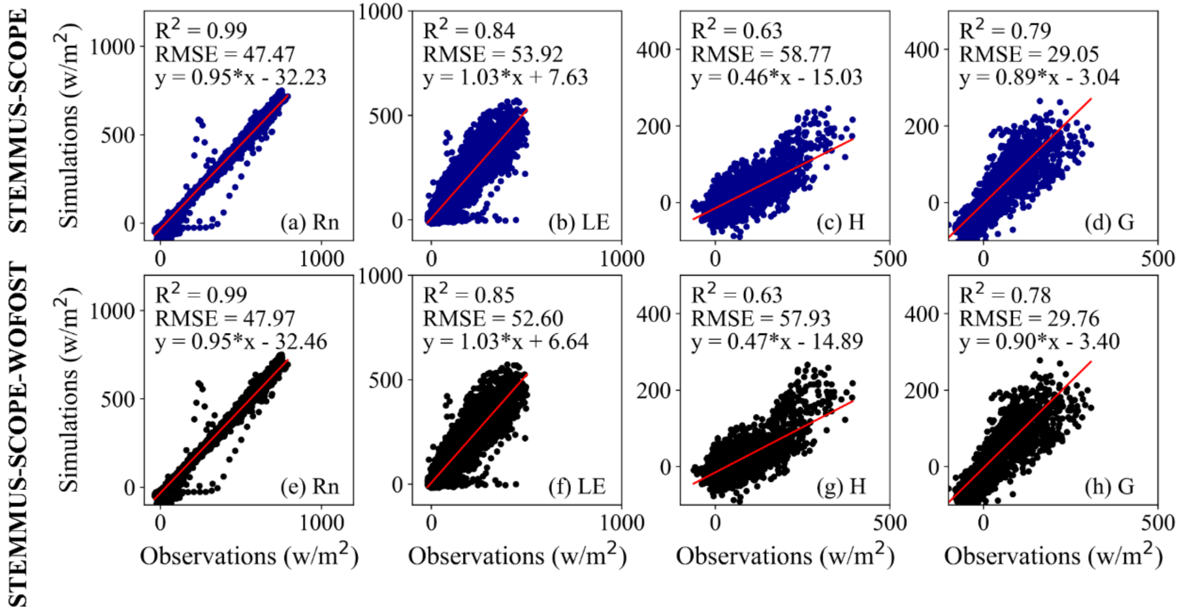
Fluxnet site: US-Var (Grassland)

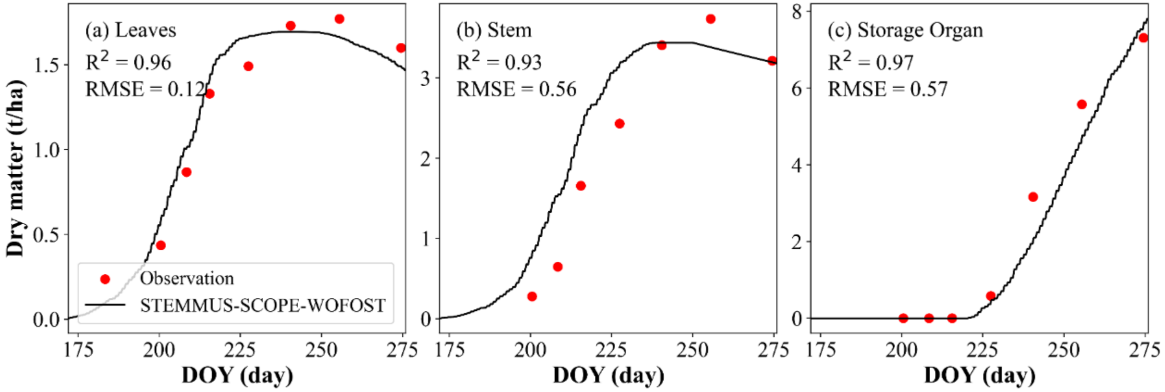
(Yu, et al. 2023, unpublished)

4. STEMMUS-SCOPE Coupled with Crop Growth Model



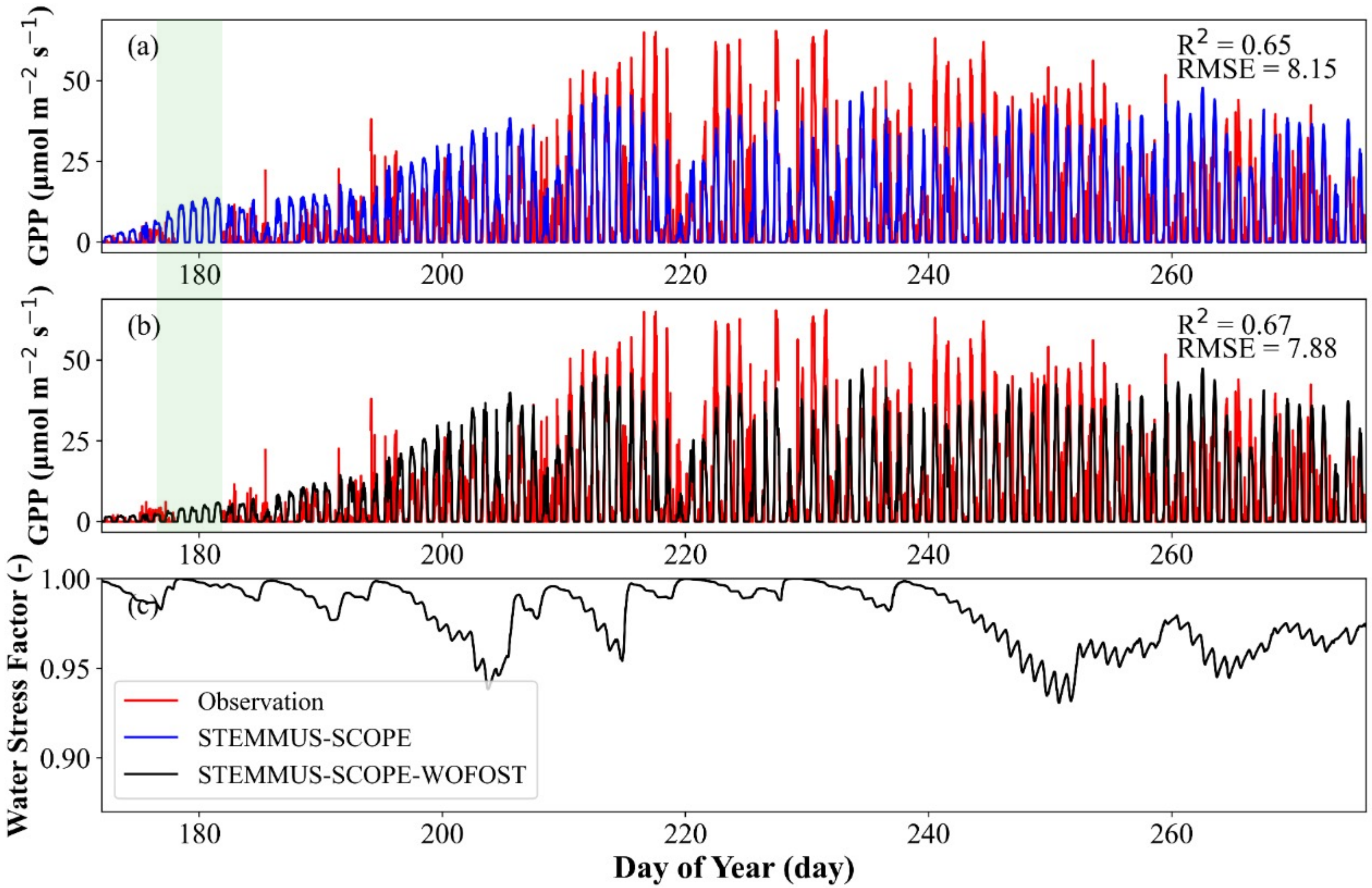


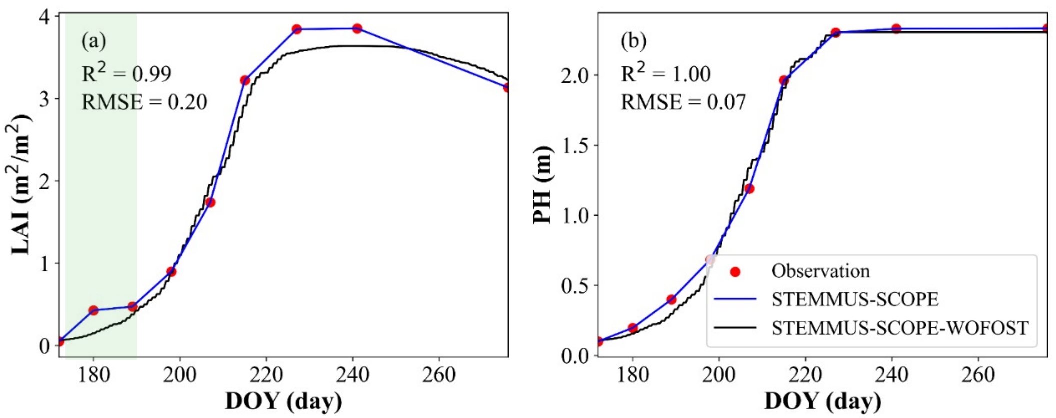




(Yu, et al. 2023, unpublished)

4. STEMMUS-SCOPE Coupled with Crop Growth Model





LAI as the prognostic variable of STEMMUS-SCOPE-WOFOST spare the potential interpolation bias when using sparse observed LAI data.

This helps improve the GPP results.

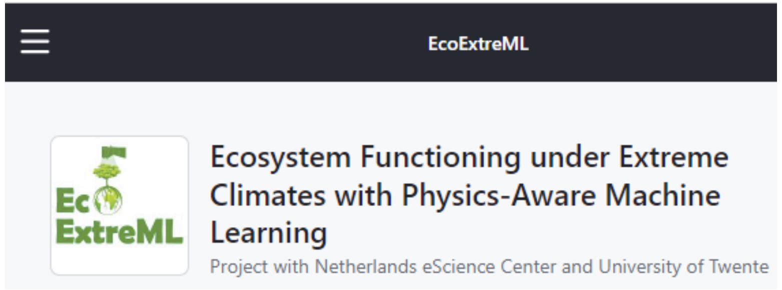
MAIN MESSAGES:

- The Solar Induced Fluorescence (SIF) as an EO observable is a central hub integrating water, energy, and carbon processes.
- The interpretation of SIF requires (and will advance) the full spectrum understanding of Soil-Water-Plant-Energy interactions.
- Plant hydraulics expressed with water potential gradients and hydraulic conductance across the soil-plant-atmosphere continuum is one key step for explaining SIF dynamics.
- Data Assimilation + Radiative Transfer Model (in the domains of visible, infrared, thermal [e.g., STEMMUS-SCOPE] and even the microwave [e.g., STEMMUS-SCOPE-TorVergata]) can help retrieve plant physiological variables/status at ecosystem scales.

EcoExtreML

Accelerating Process Understanding for Ecosystem Functioning under Extreme Climates with Physics-Aware Machine Learning

STEMMUS-SCOPE Open-Source



WUNDER

Water Use and Drought Ecohydrological Responses of Agricultural and Nature Ecosystems in the Netherlands: Towards Climate-Robust Production Systems and Water Management

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