# “Accelerating” Ecosystem Understanding: A Soil-Plant Digital Twin with STEMMUS-SCOPE

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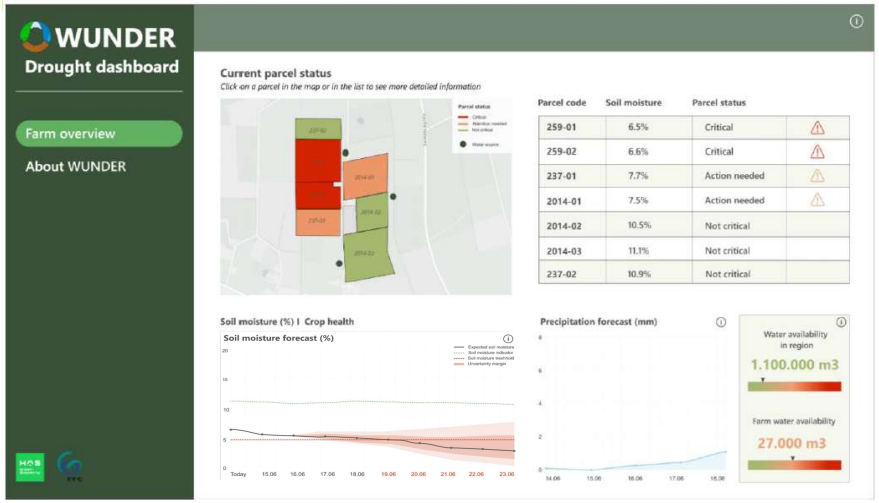
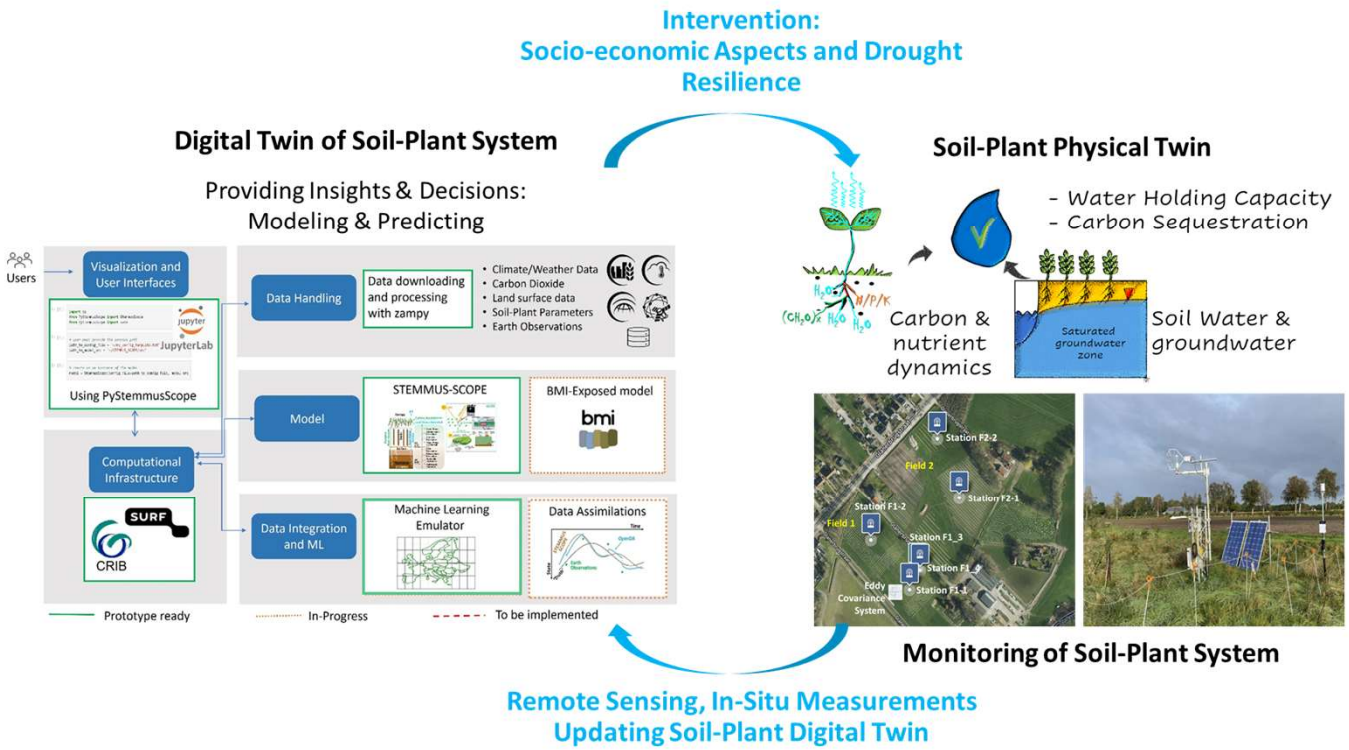
With contributions from:

| | |
|---|---|
| Yunfei Wang | – STEMMUS-SCOPE for 170 Fluxnet Sites in PLUMBER2 |
| Zengjing Song | – STEMMUS-SCOPE & Plant Hydraulics |
| Danyang Yu | – STEMMUS-SCOPE & Plant Growth Model |
| Enting Tang | – STEMMUS-SCOPE & Carbon and Nutrient Dynamics |
| Qianqian Han | – STEMMUS-SCOPE & ML-Based Emulator |
| Prajwal Khanal | – STEMMUS-SCOPE & ML, Satellite Upscaling |
| Lianyu Yu & Mostafa Daoud | – STEMMUS-SCOPE & Groundwater (MODFLOW6) |
| Sarah Alidoost & Bas Retsios | – High Performance Computing |

# A **Soil-Plant Digital Twin**: Facilitating **Food Forest** (Voedselbossen) as a NbS solution for **climate-resilient** production system

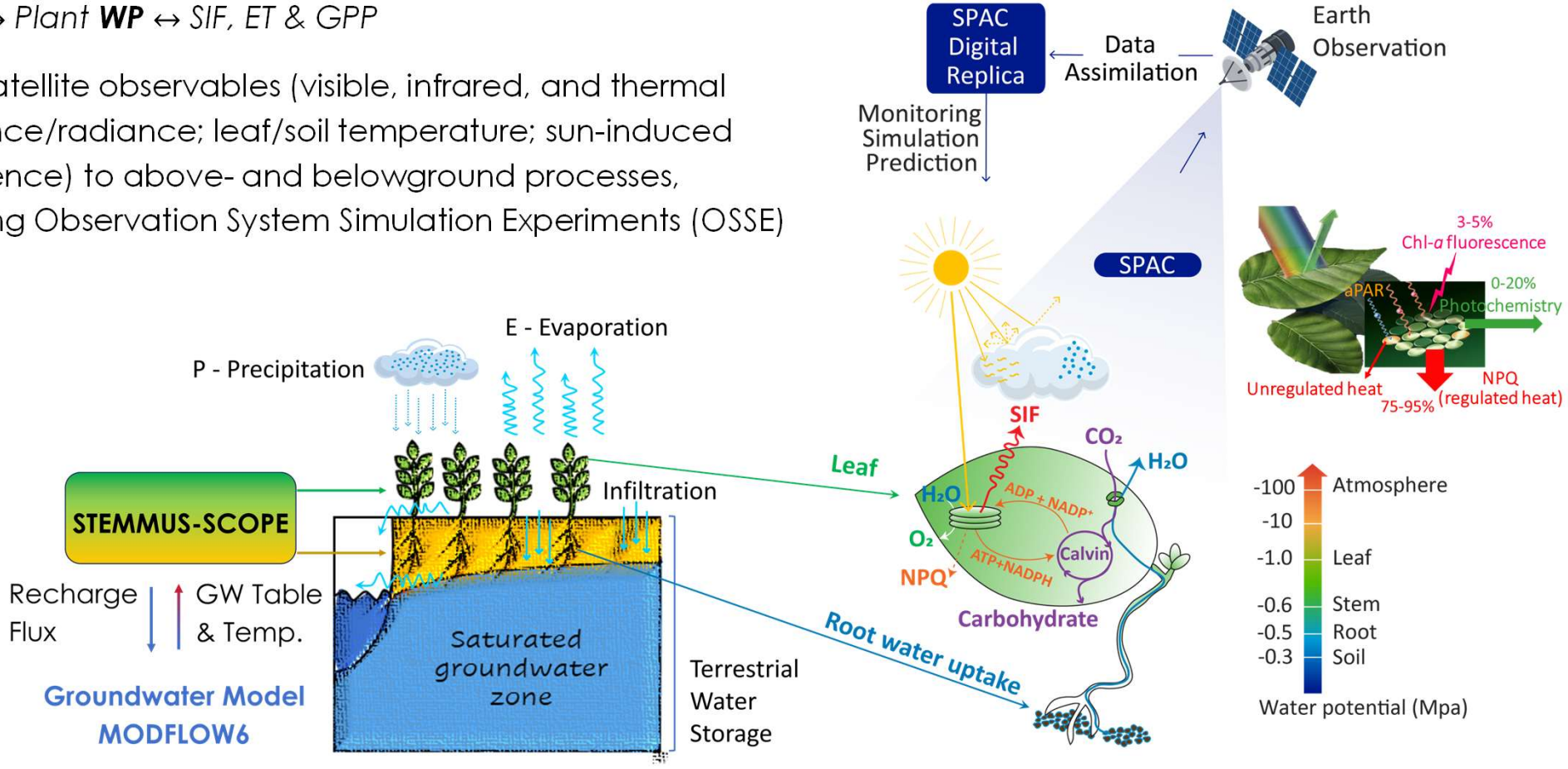

https://voedselbosglanerbeek.nl/wunderbaarlijk-onderzoek


Su & Zeng, 2025, Innova. Geosci.;
Zeng & Su, 2025, RoG;
Zeng & Su, 2025, Comput. Geosci
Zeng & Su, 2024, Frontiers in Sci.

# Photosynthesis and water potential: a central perspective for coupling water, energy, and carbon cycles

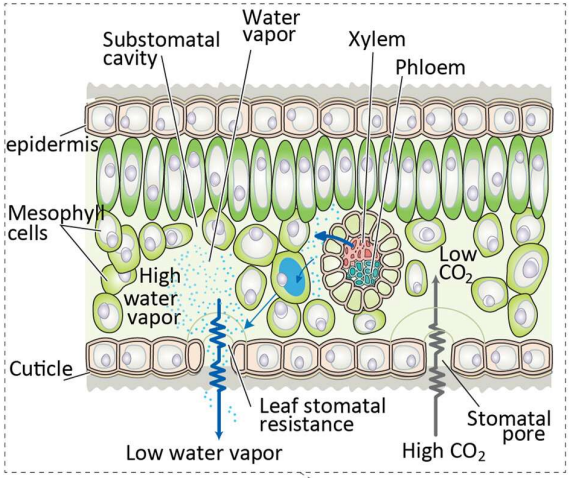
*Soil **WP** ↔ Plant **WP** ↔ SIF, ET & GPP*

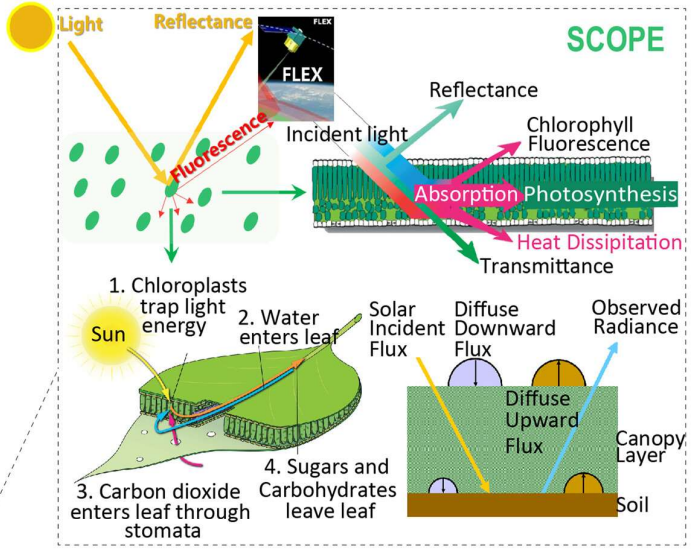
Linking satellite observables (visible, infrared, and thermal reflectance/radiance; leaf/soil temperature; sun-induced fluorescence) to above- and belowground processes, facilitating Observation System Simulation Experiments (OSSE)

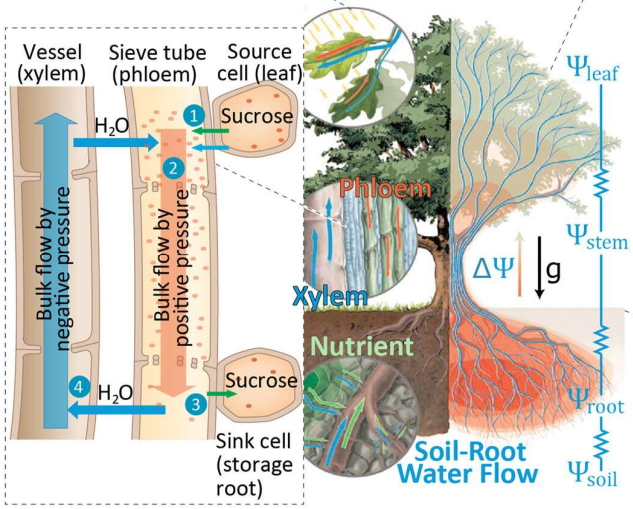


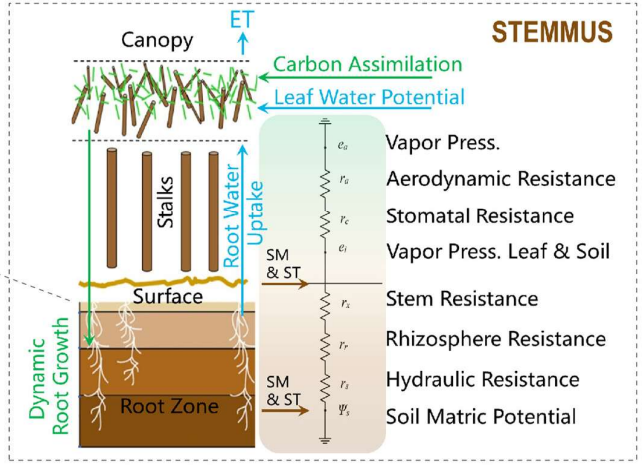

(Su & Zeng, 2025, The Innovation Geoscience)

# A Soil-Plant Digital Twin based on STEMMUS-SCOPE




The rapidly expanding availability of Earth observation (EO) data offers new opportunities but also exposes a key challenge: **how to mechanistically link soil–plant water potential to SIF.**

Meeting this challenge calls for a 'hyper-scaling' representation of soil–plant processes across spatial (molecular to global) and temporal (nanoseconds to years) scales.

(Zeng & Su, 2025, RoG; Zeng & Su, 2025 Comput. Geosci)

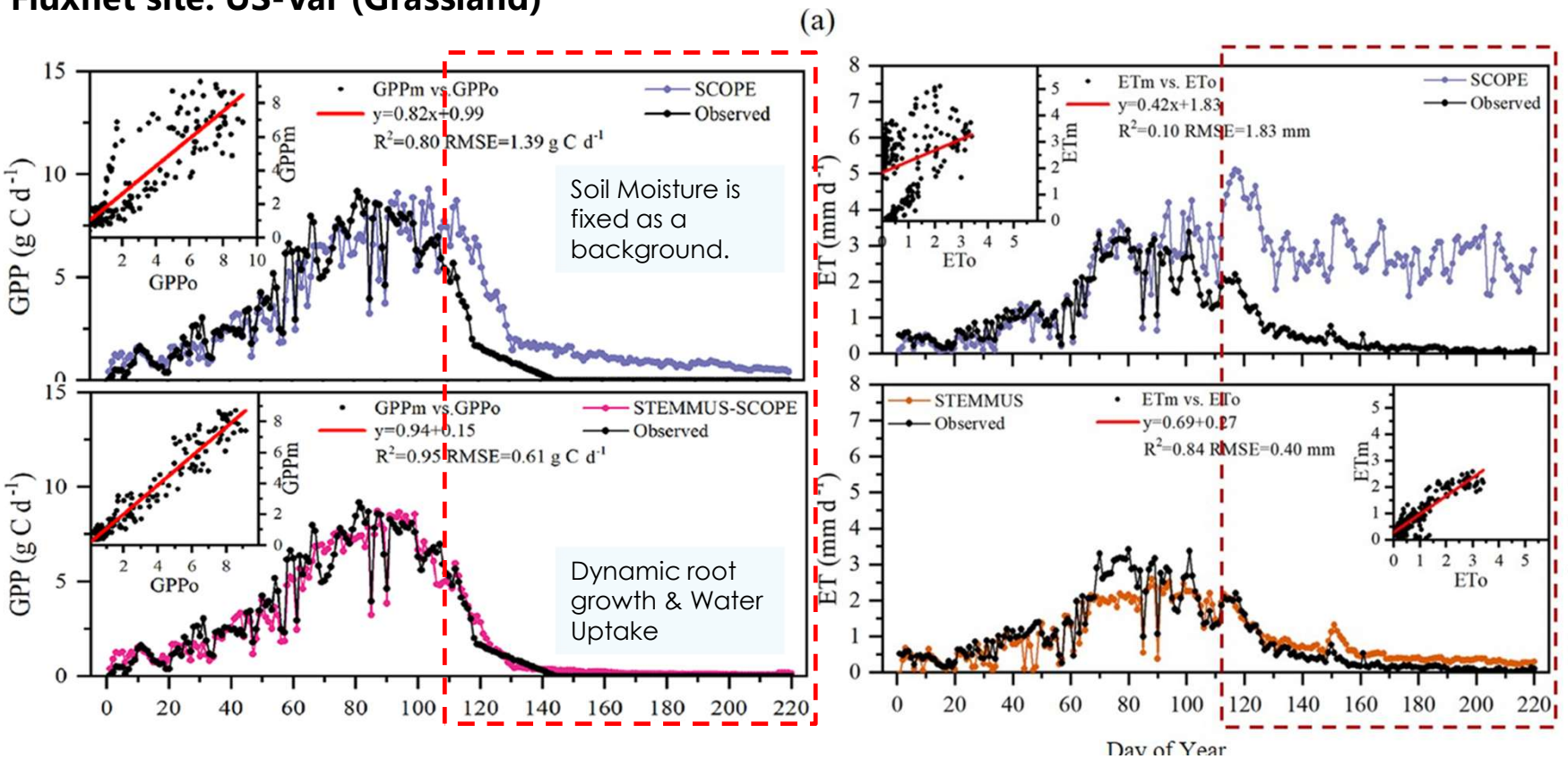
**STEMMUS-SCOPE Open-Source**

# Outline

- ***Understanding Ecosystem Functioning*** *with STEMMUS-SCOPE*
  - Agriculture and Nature Ecosystems
  - SIF vs. GPP, and the role of leaf water potential
- *Challenges and Opportunities*
  - Understanding SIF with Soil-Plant Hydraulics
  - Satellite SIF for evaluating water-energy-carbon fluxes
  - Dynamic vegetation growth and canopy structure
  - STEMMUS-SCOPE emulator for a global Fluxhourly dataset

# 1. STEMMUS-SCOPE for understanding water use efficiency

**Fluxnet site: US-Var (Grassland)**



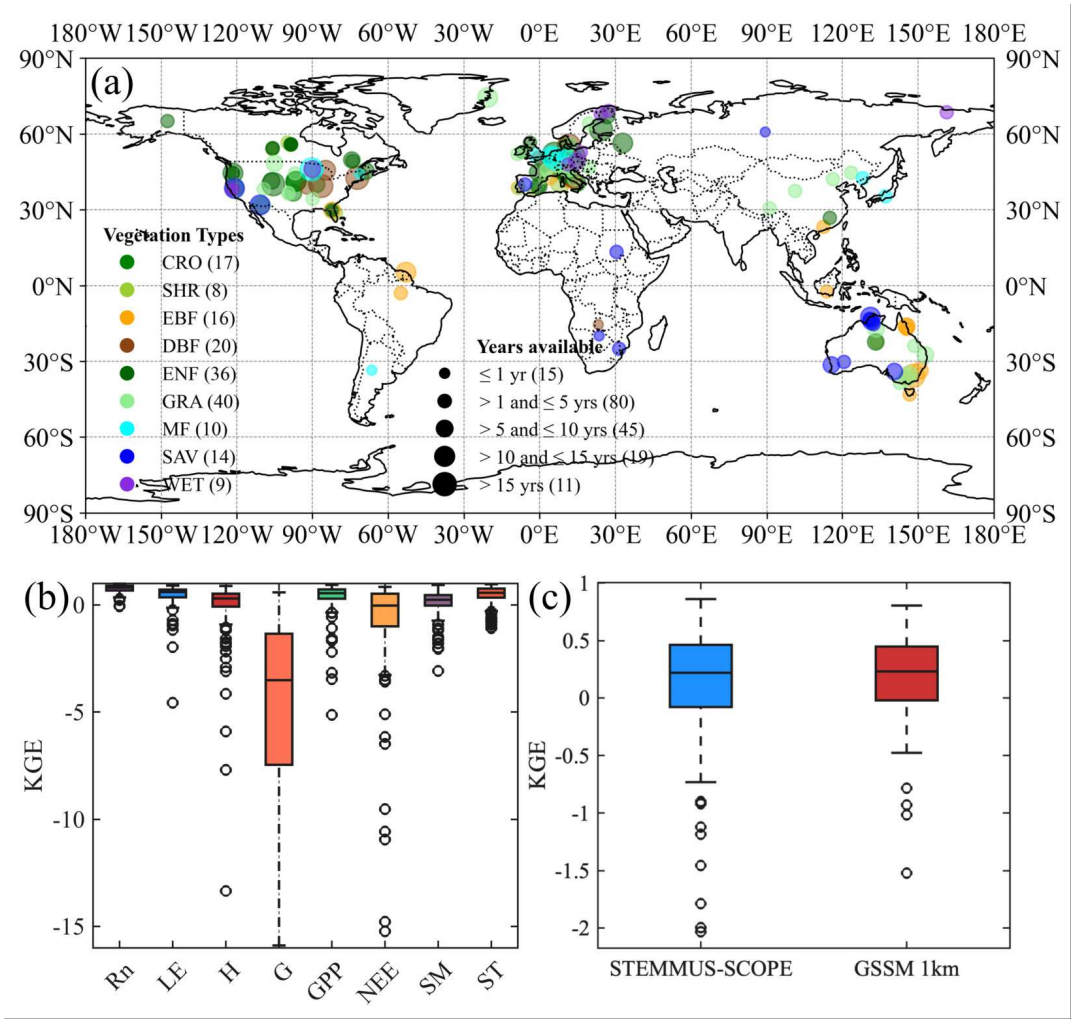

Only Veg.

Coupled

Without considering soil water stress, the water and carbon fluxes are overestimated during dry period;

(Wang, et al. 2021 GMD)

# 1. STEMMUS-SCOPE for GEWEX-PLUMBER2 (general performance)




a) Global distribution of PLUMBER2 sites;

b) Performance (Kling–Gupta efficiency, KGE) of STEMMUS-SCOPE;

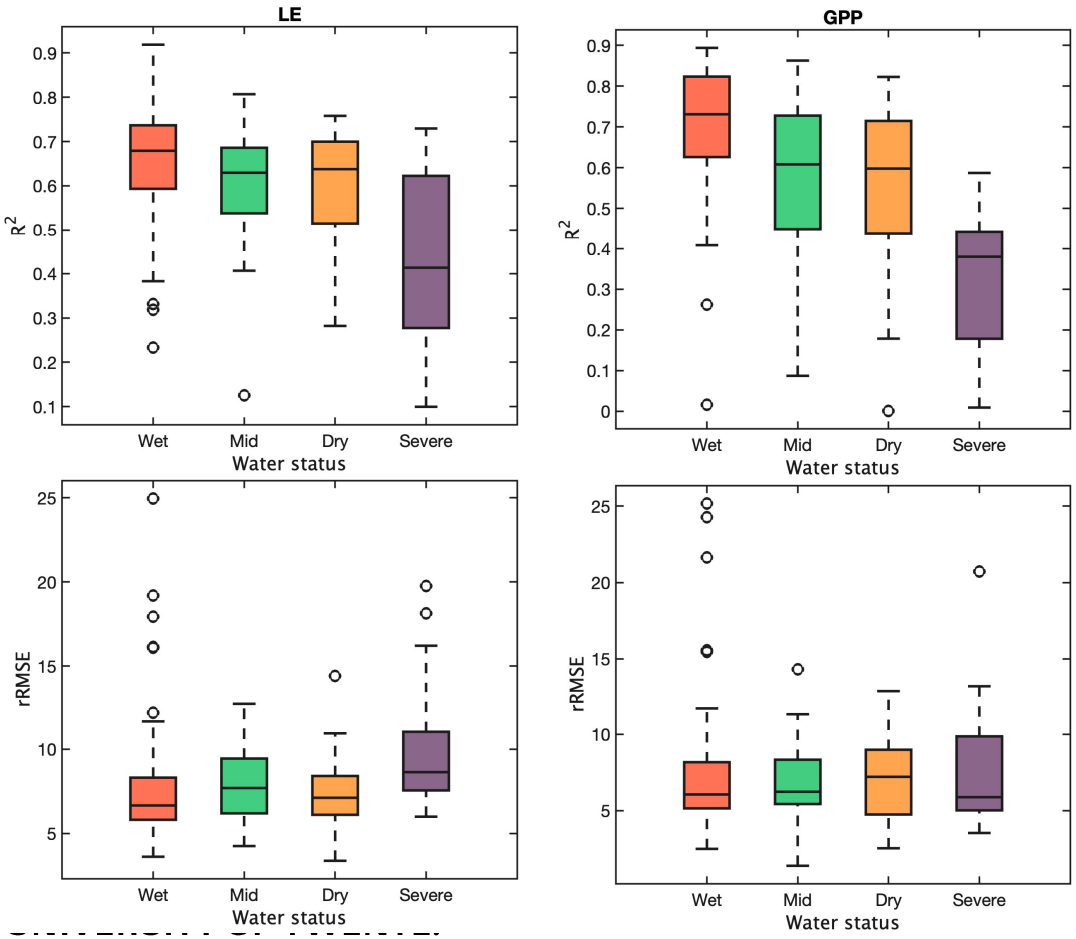
c) KGE of STEMMUS-SCOPE vs. GSSM 1km.

Model Inputs/Driving:
- MODIS LAI
- ERA5 & PLUMBER2
- Soil Hydraulic Parameters (Montzka et al. 2017)
- SoilGrids
- … …

Without tunning … …

(Wang, et al. 2025 Sci. Data)

# 1. Session Summary: agriculture & nature ecosystems




a) Simulated Water-energy-carbon flux dynamics are significantly improved after considering soil water stress with a process-based soil water and heat transport model;

b) STEMMUSE-SCOPE is applied for 170 Fluxnet sites, the general performance is reasonable without model tunning;

c) For severe dry conditions, model performance is still to be improved

(water stress factor, and hydraulic resistance scheme in STEMMUS-SCOPE?)

(Wang, et al. 2025 Sci. Data)

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# 2. SIF vs GPP and Role of Water Potential

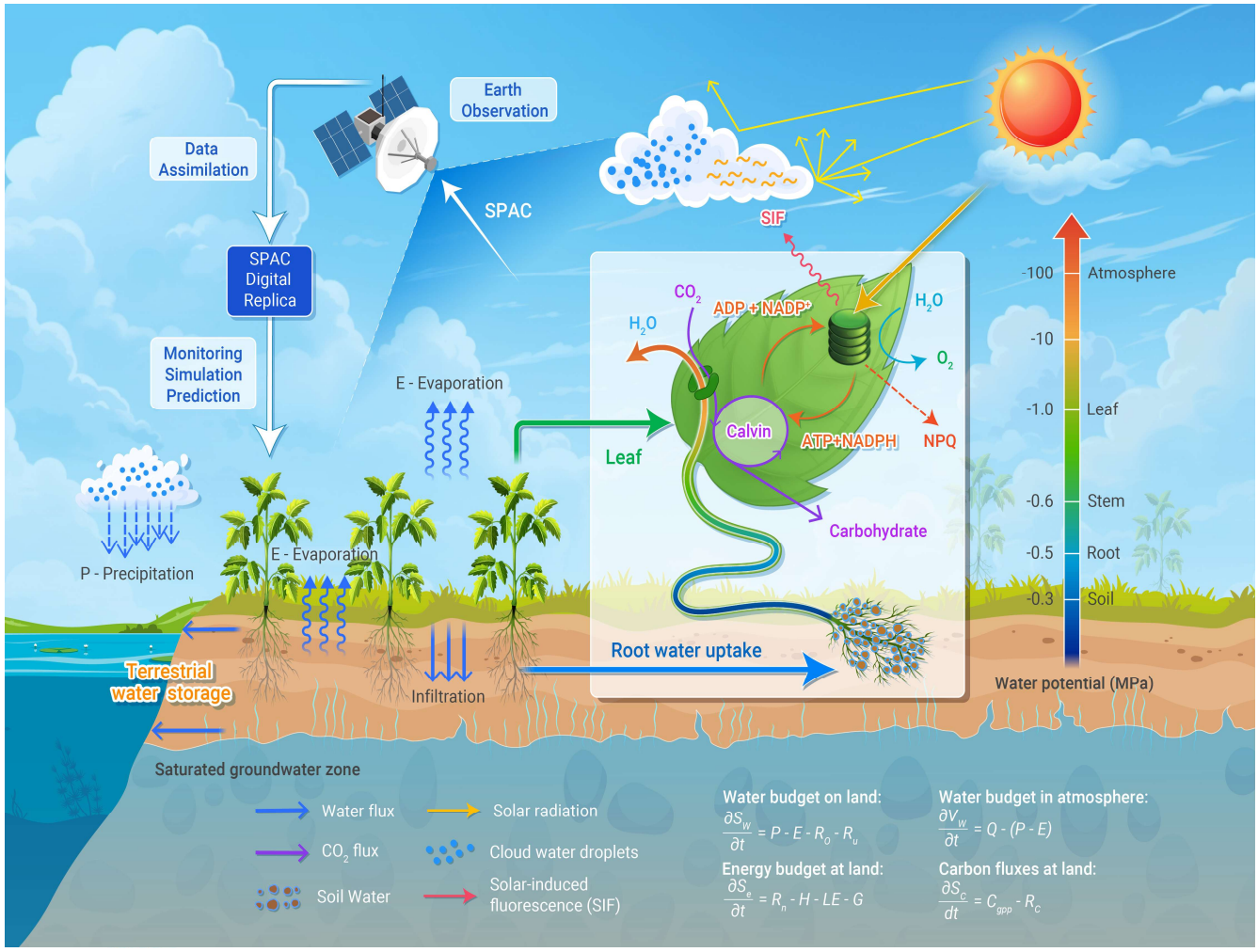
(Su & Zeng, 2025, The Innovation Geoscience)

- Water potential across the SPAC continuum connects the root zone soil to the leaf, impacting the flow of water through xylem.
- This connection also affects the water vapor density in the substomatal intercellular airspace of leaves, which in turn influences gas exchange, photosynthesis, energy balance fluxes, and radiative transfer at leaf and canopy levels

Soil Water Potential — Leaf Water Potential

$$\sum_{i=1}^{n} \frac{\psi_{s,i} - \psi_l}{r_{s,i} + r_{r,i} + r_{x,i}} = \frac{0.622}{P} \frac{\rho_{da}}{\rho_v} \left( \frac{e_l - e_a}{r_c + r_a} \right) = T$$

Soil Hydraulic Resistance — Root Hydraulic Resistance — Plant Axial Xylem Resistance Soil -> Leaf

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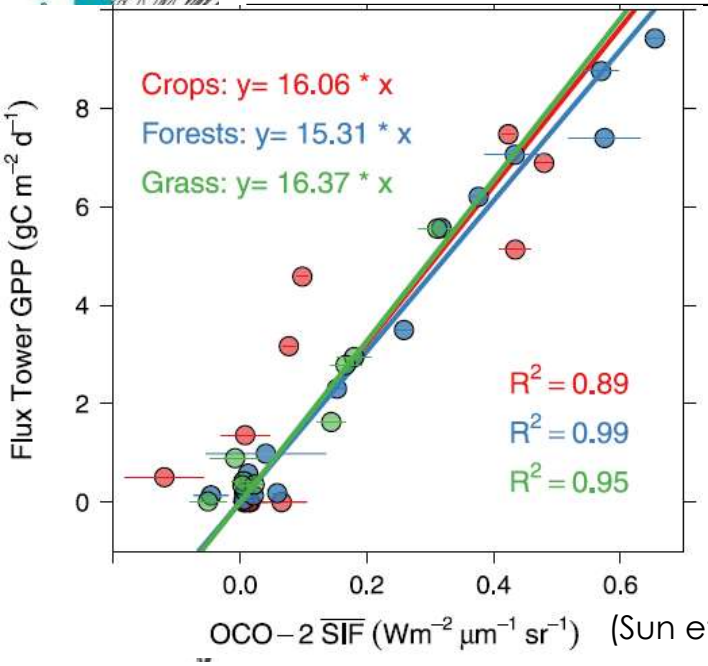
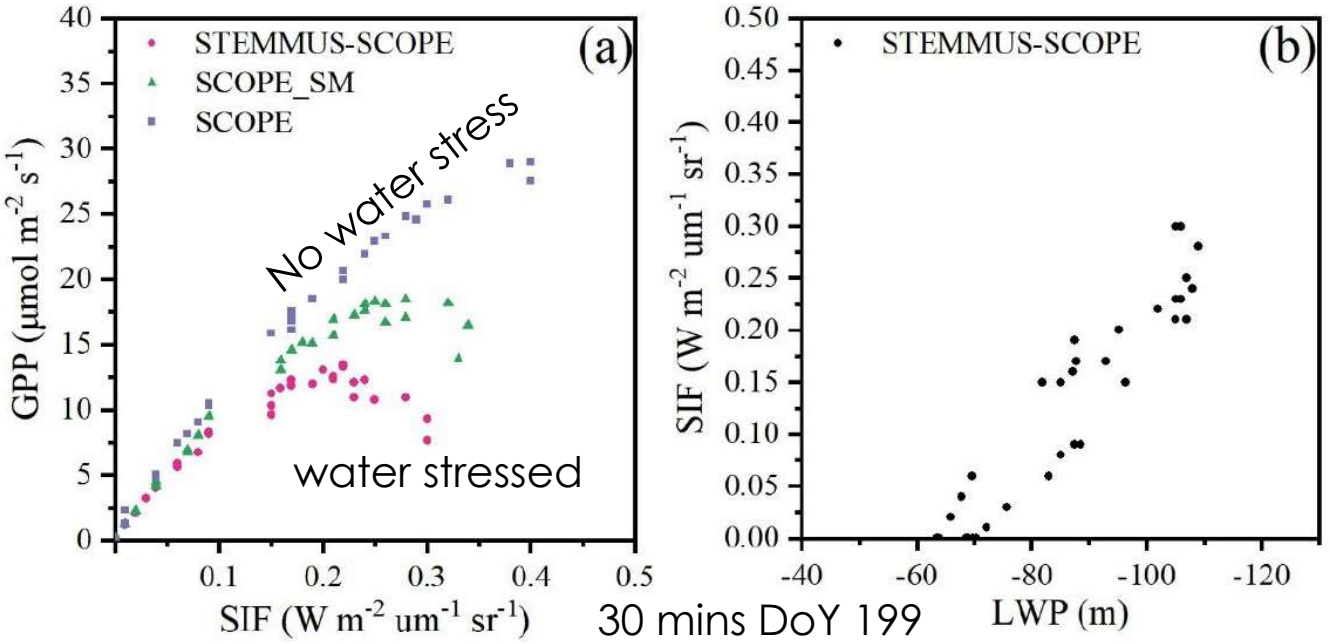
# 2. SIF vs GPP and Role of Water Potential




(Sun et al. 2017)




30 mins DoY 199

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

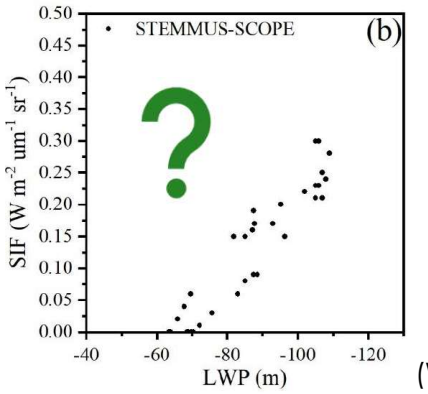
$$SIF = PAR \times fAPAR \times LUE_{Fluorescence}$$

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 Role of Water Potential



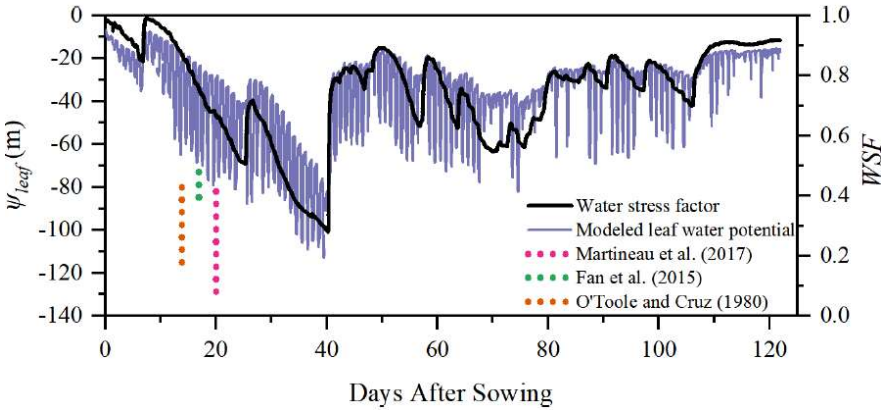

What is the mechanism behind the linear SIF vs. LWP relationship?

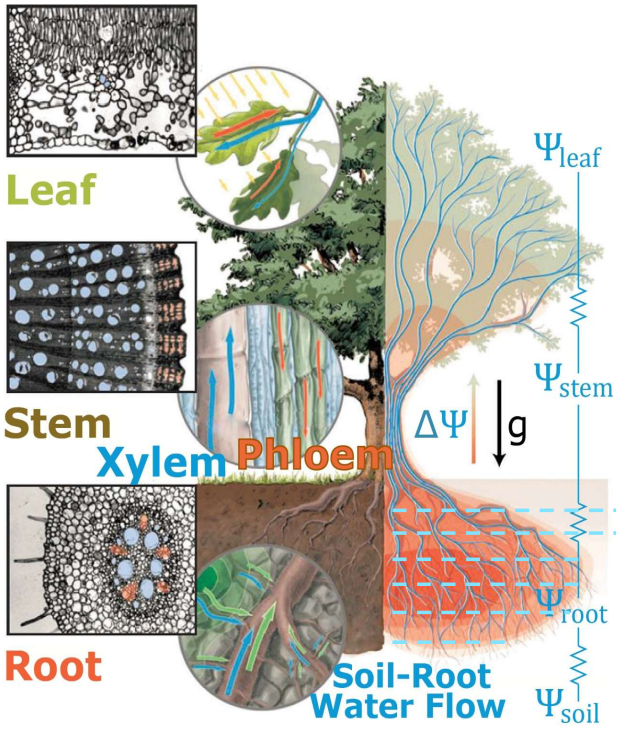
$$WSF = \sum_{i=1}^{n} RF(i) \cdot WSF(i)$$

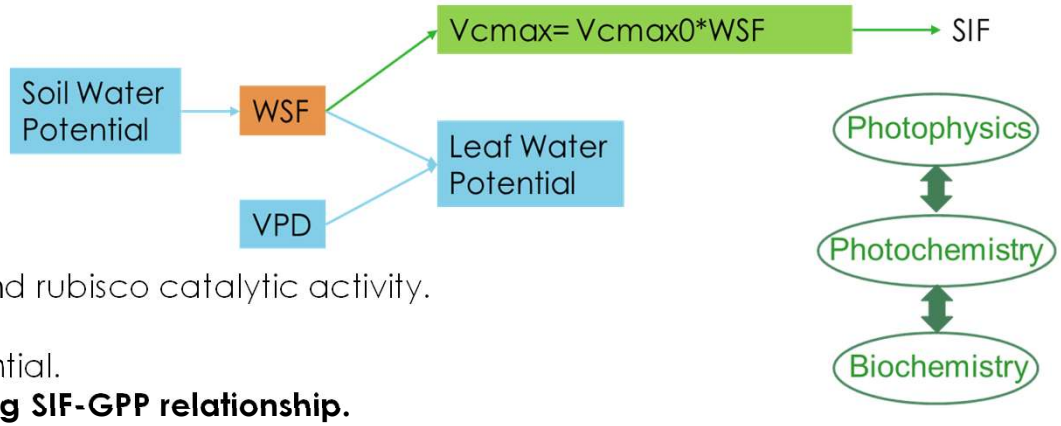
$$WSF(i) = \frac{1}{1 + e^{-100 \cdot \theta_{sat}\left(SM(i) - \frac{\theta_f + \theta_w}{2}\right)}}$$

RF- root length fraction

(Wang, et al. 2021, GMD)



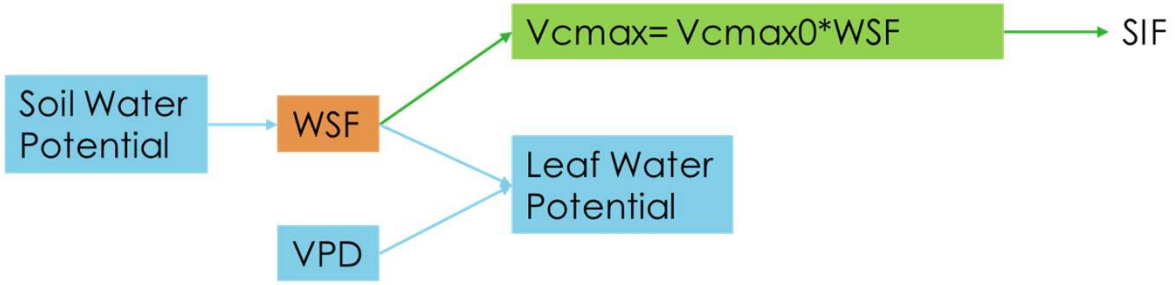




- GPP and SIF are regulated by electron transport rate and rubisco catalytic activity.
- STEMMUS-SCOPE uses Vcmax= Vcmax0*WSF
- Soil water potential & VPD co-regulate leaf water potential.
- **Role of Soil-Plant Hydraulics is critical in better explaining SIF-GPP relationship.**

# 2. Session Summary: SIF vs. GPP and Role of Leaf Water Potential

- 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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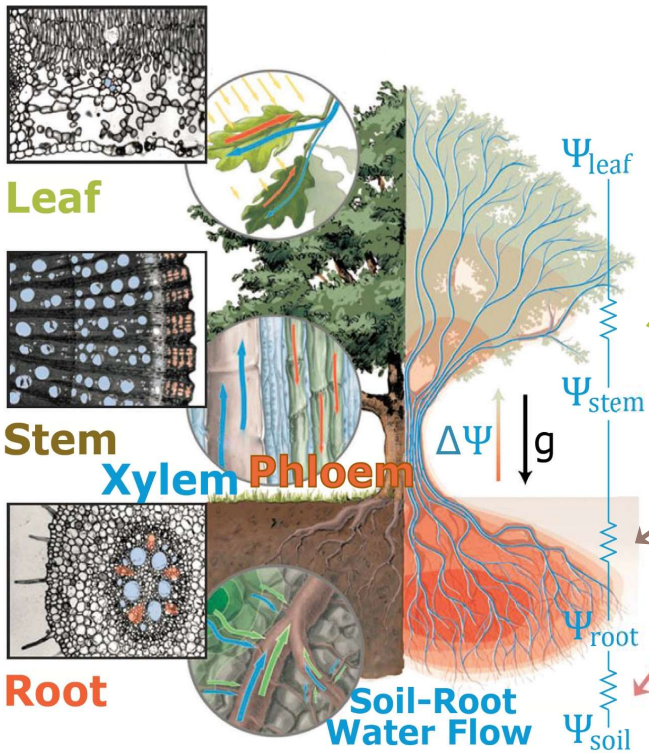
Root Water Uptake in the current STEMMUS-SCOPE is based on soil-plant hydraulic resistance scheme:




$$S_i = \frac{\psi_{s,i} - \psi_l}{r_{s,i} + r_{r,i} + r_{x,i}}$$

$\psi_l$ Leaf water potential

$\psi_{s,i}$ Soil water potential

$r_{s,i}$ Soil - root hydraulic resistance

$r_{r,i}$ Root - stem hydraulic resistance

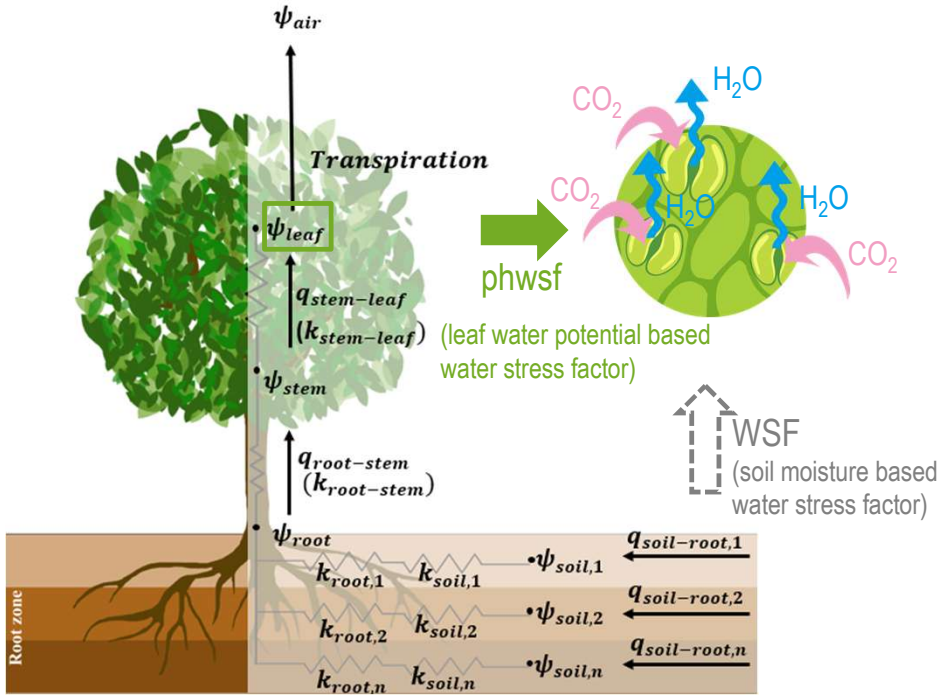
$r_{x,i}$ Stem - leaf hydraulic resistance

Explicit plant hydraulic pathway should be considered.

# 3. Plant hydraulics in STEMMUS-SCOPE

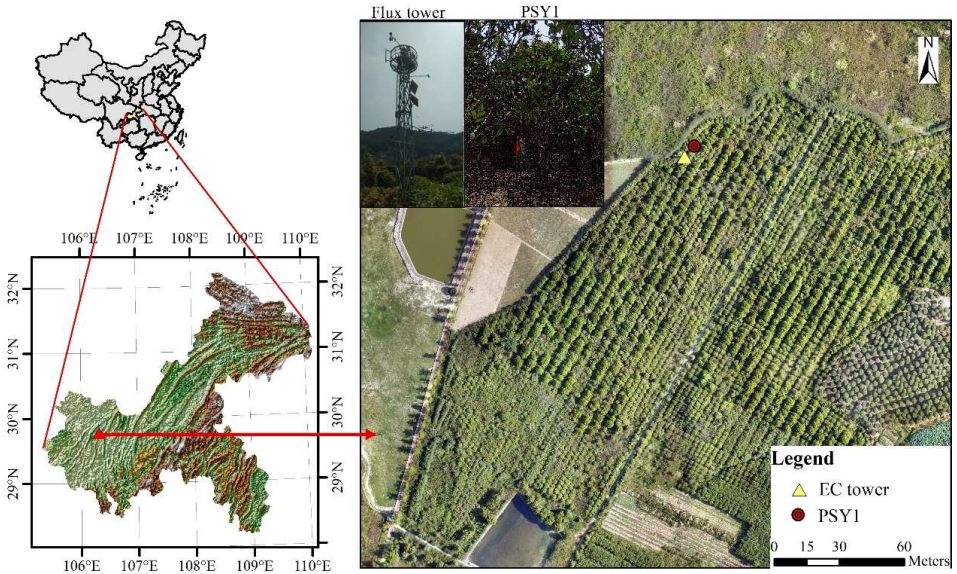
(Song, et al. 2025 unpublished)

- **Plant hydraulics**




The sketch of plant hydraulic pathway in STEMMUS-SCOPE-PHS.

- **Study area**

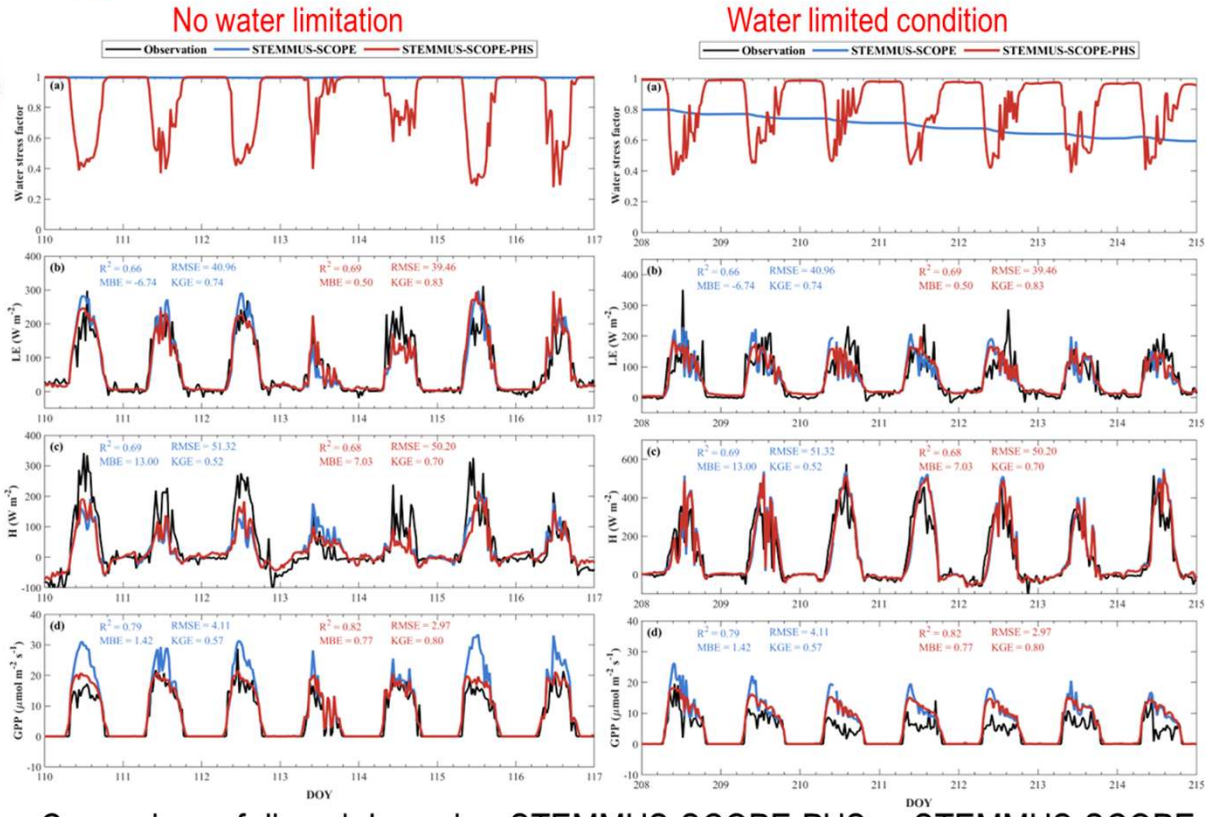



Hutoucun Site

- Location: 106.32°E, 29.75 °N, 473m (Chongqing, China)
- Climate: Subtropical monsoon climate
- Annual temperature: 15 °C
- Annual precipiration: 1240 mm
- Vegetation coverage: Osmanthus tree (evergreen shrubland, C3)

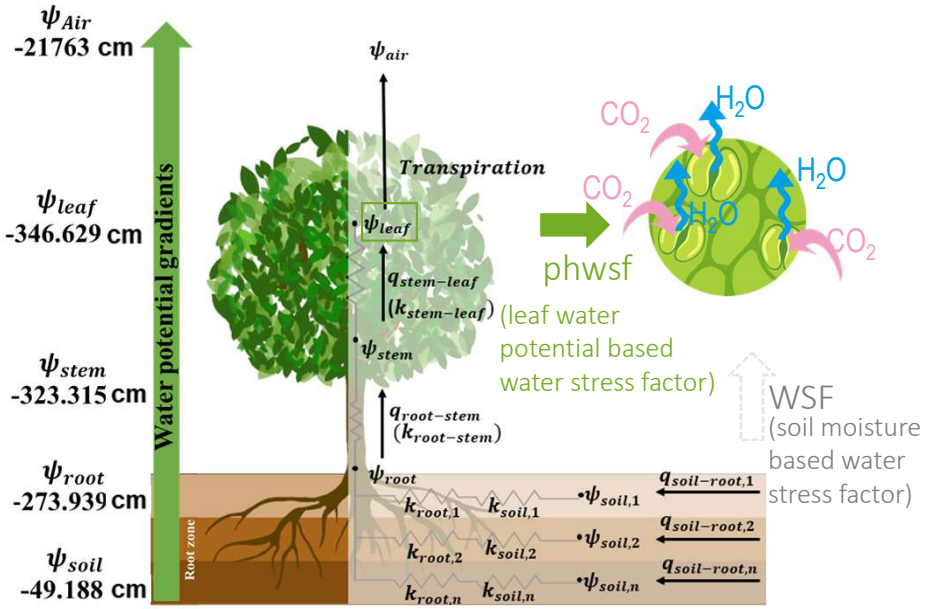
(Song, et al. 2025 unpublished)

# 3. Plant hydraulics in STEMMUS-SCOPE

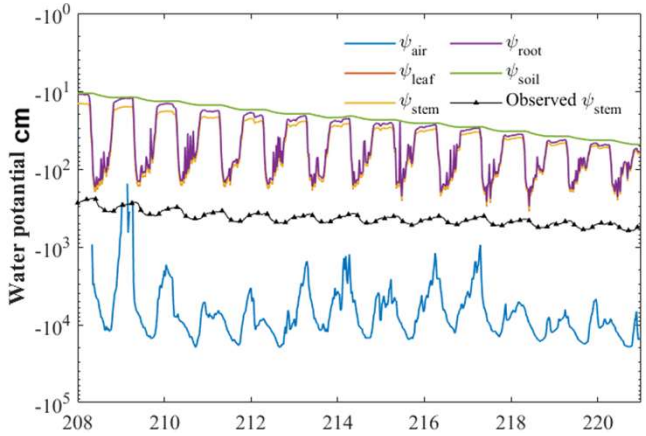



Comparison of diurnal dynamics: STEMMUS-SCOPE-PHS vs STEMMUS-SCOPE.

(Song, et al. 2025, unpublished)




The sketch of plant hydraulic pathway in STEMMUS-SCOPE-PHS.



# 3. Plant hydraulics in STEMMUS-SCOPE

Hydraulic resistances (STEMMUS-SCOPE):

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

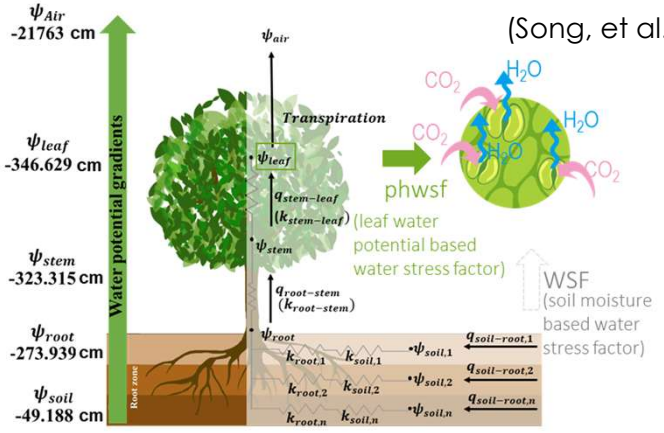
(Wang, et al. 2021)

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

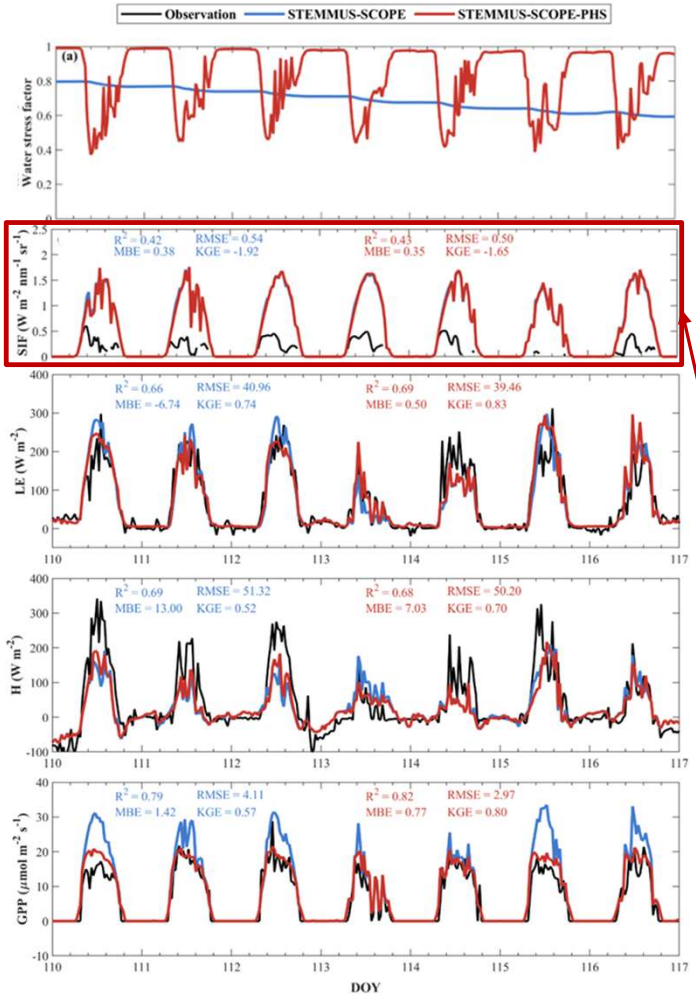
RF- root length fraction

Plant hydraulics (STEMMUS-SCOPE-PH):

(Song, et al. 2025)




The sketch of plant hydraulic pathway in STEMMUS-SCOPE-PHS.

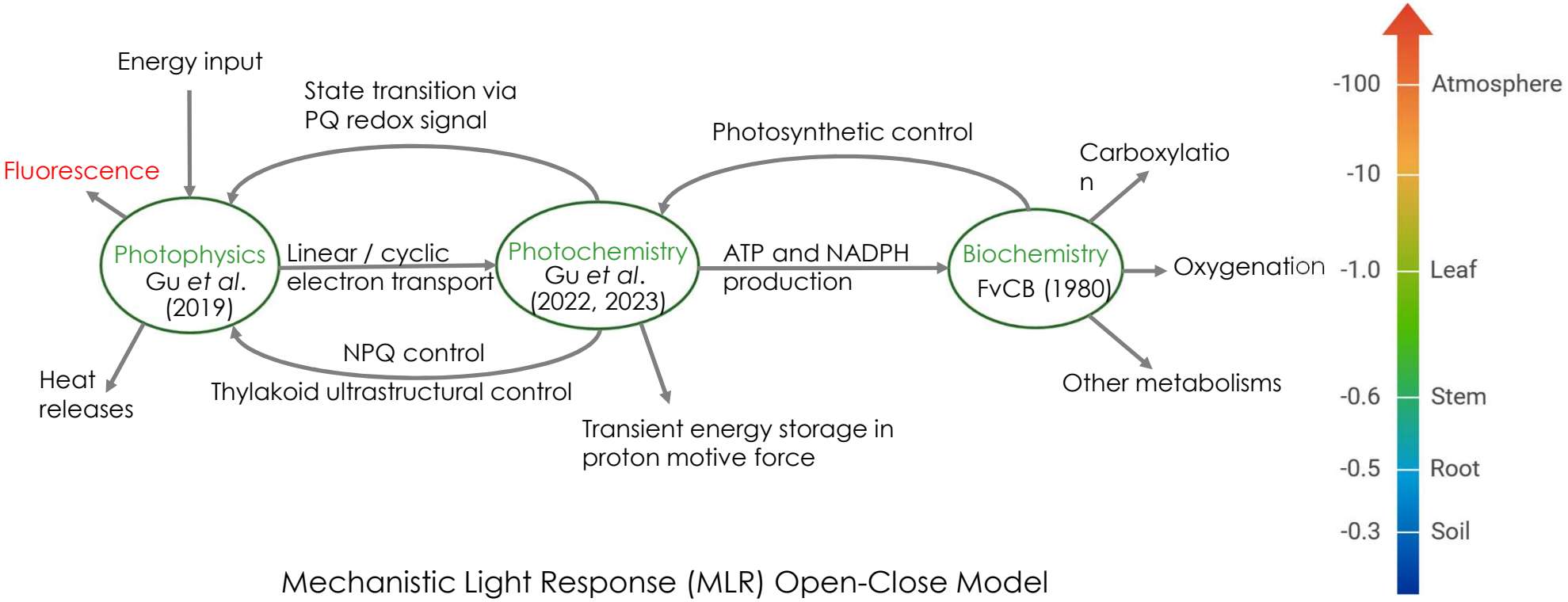



- Water stress considering plant hydraulics (e.g., with leaf water potential) shows more sensitive variation
- With plant hydraulics, STEMMUS-SCOPE-PH reproduce LE, H, and GPP better than the original version
- However, there is still a large overestimation of Solar-Induced Fluorescence …

(GEWEX-GLASS: SIF-MIP)

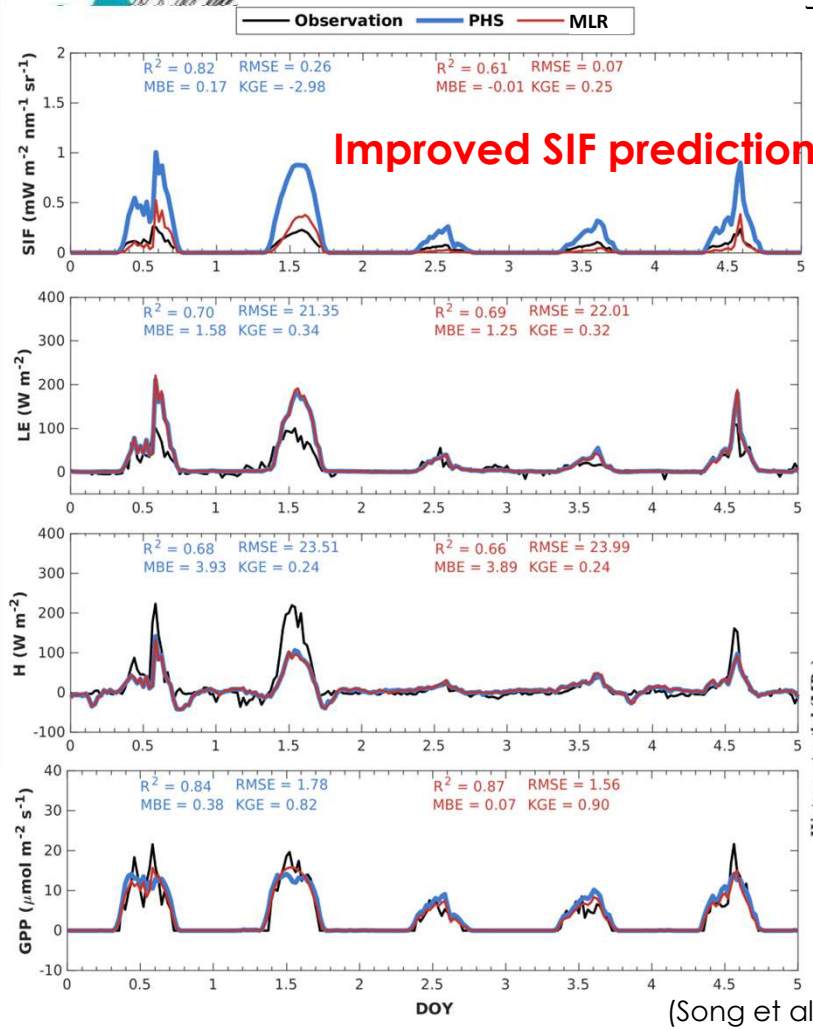
(Song et al. 2025, unpublished)

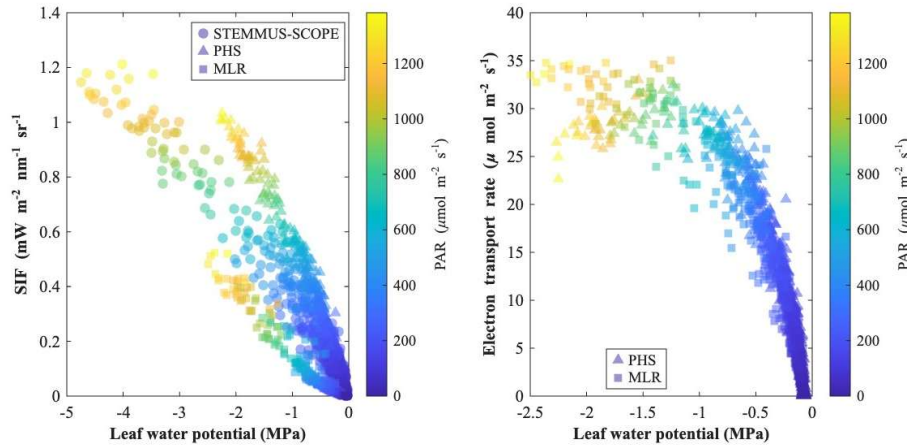
# SIF can only be understood in an *end-to-end* model of photosynthesis

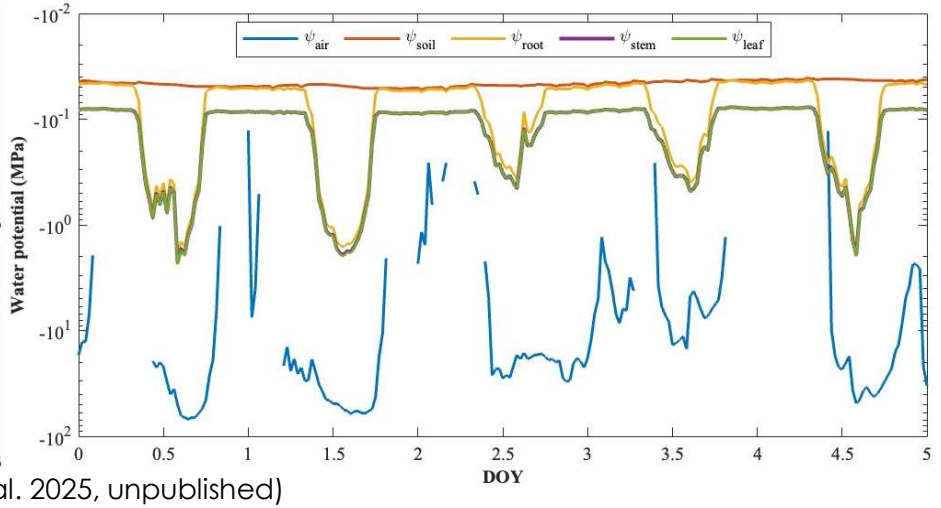



Mechanistic Light Response (MLR) Open-Close Model

# 3. Session Summary: PH + 'end-to-end' photosynthesis model




(Song et al. 2025, unpublished)

- Incorporating Mechanistic Light Response (MLR) model into STEMMUS-SCOPE plant hydraulics model improve the SIF prediction
- The plant-hydraulics model shows a more robust (e.g., less scattered) SIF-LWP relationship
- Electron transport rate has a negative relationship with LWP
- The simulated water potential gradient across the soil-root-stem-leaf are meaningful

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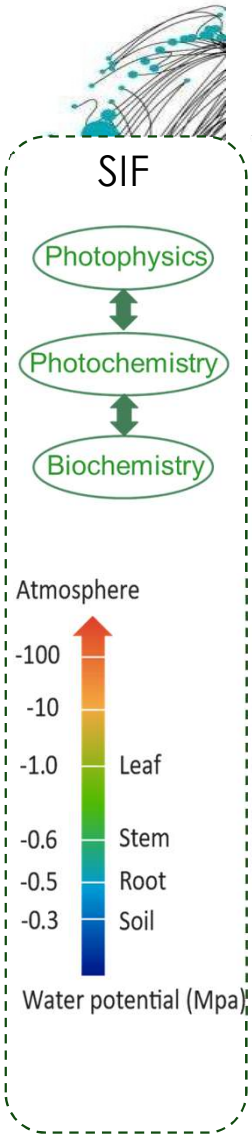
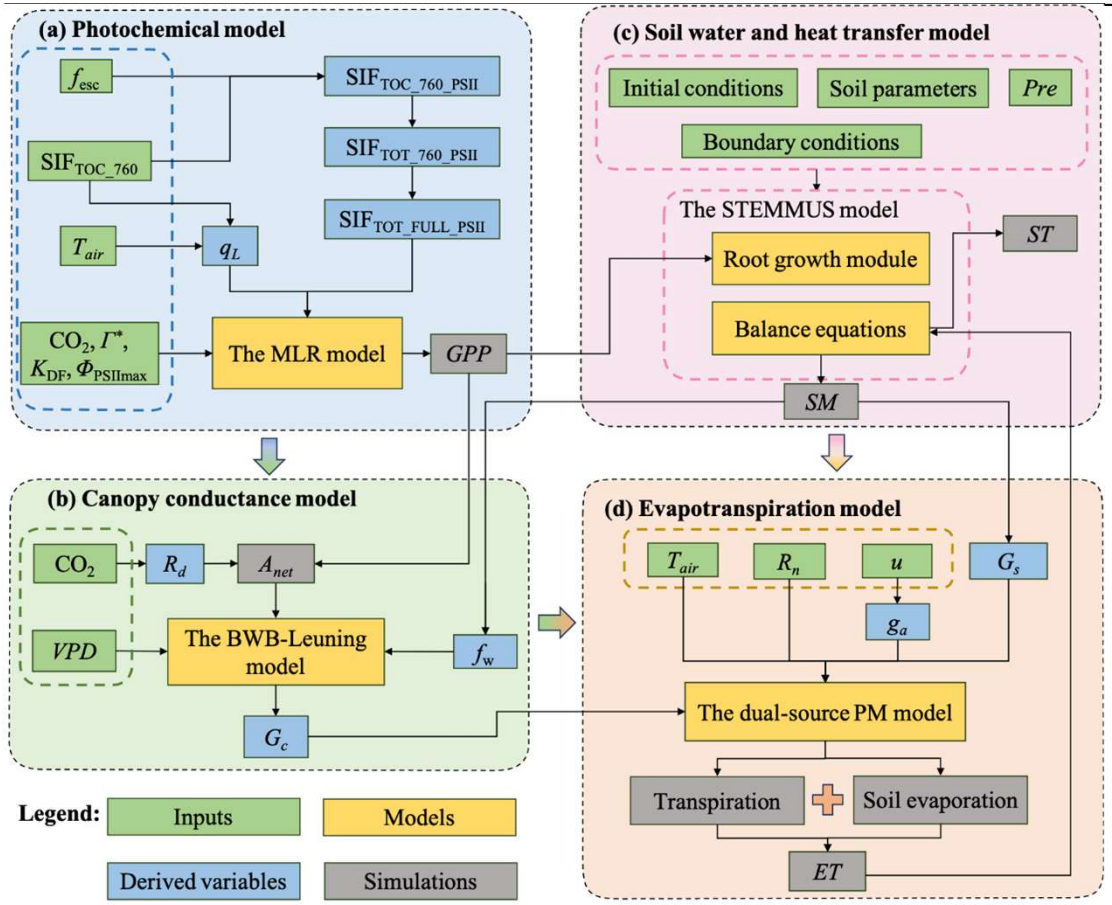
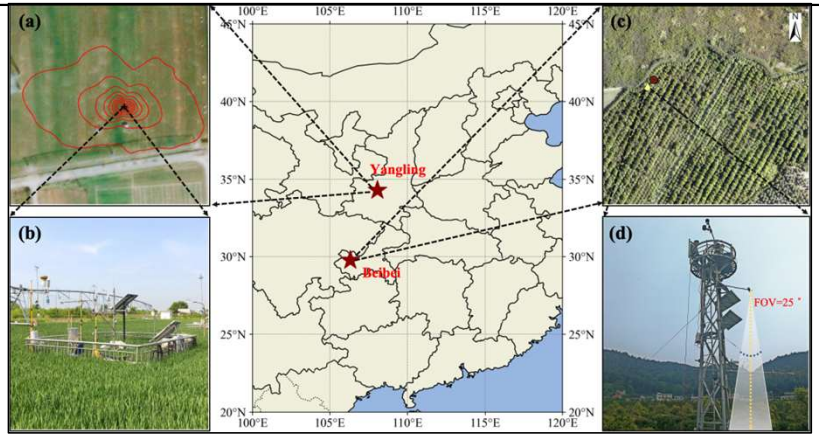
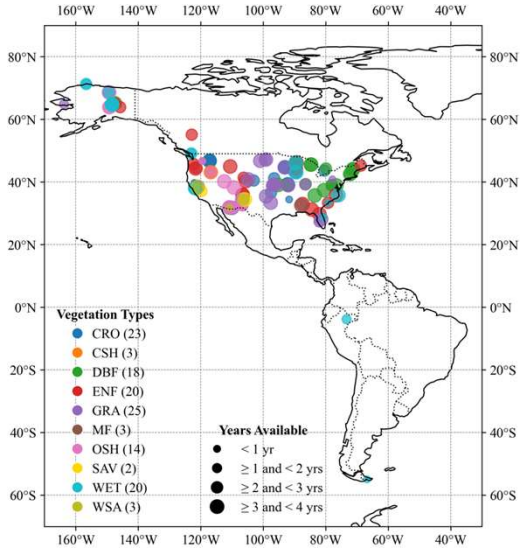
# 4. Satellite SIF for evaluating water-energy-carbon fluxes



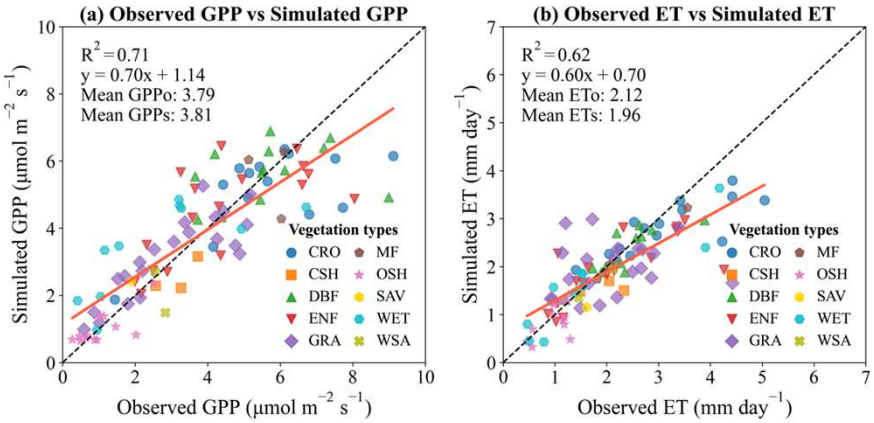

STEMMUS-MLR model (Wang et al. 2026, under revision)



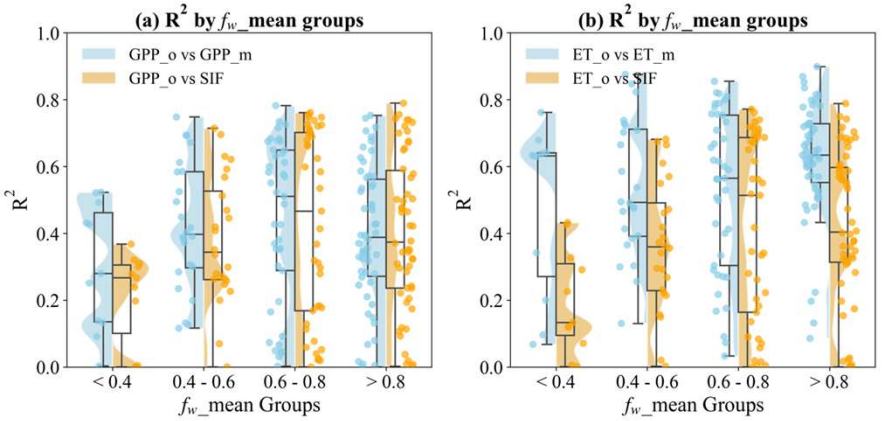



# 4. Session Summary: Satellite SIF

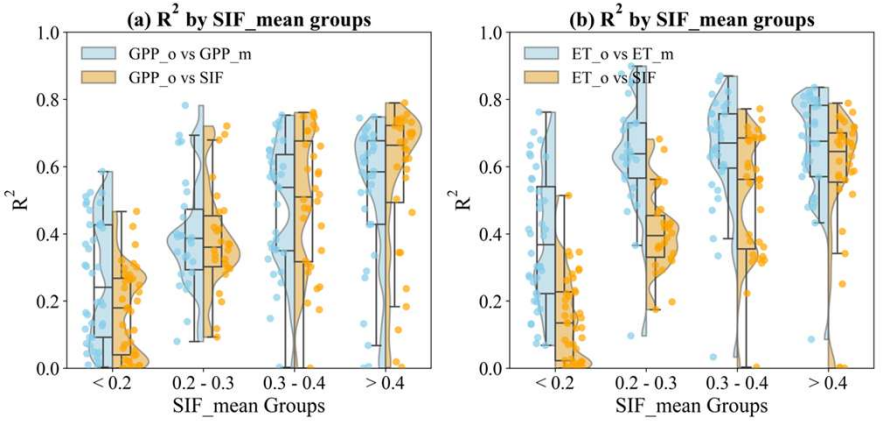
(Wang et al. 2026, under revision)




- A process-based model (STEMMUS-MLR) is developed to inversely estimate GPP and ET by mechanistically coupling Solar-Induced Fluorescence (SIF) with root-zone soil moisture
- Over arid regions, low signal-to-noise ratio of SIF deteriorates the model performance




Model GPP/ET and Sat SIF vs. observations, fw – Stress Level




Model GPP/ET and Sat SIF vs. observations, grouped by $SIF_{mean}$

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  - **Dynamic vegetation growth and canopy structure**
  - STEMMUS-SCOPE emulator for a global Fluxhourly dataset

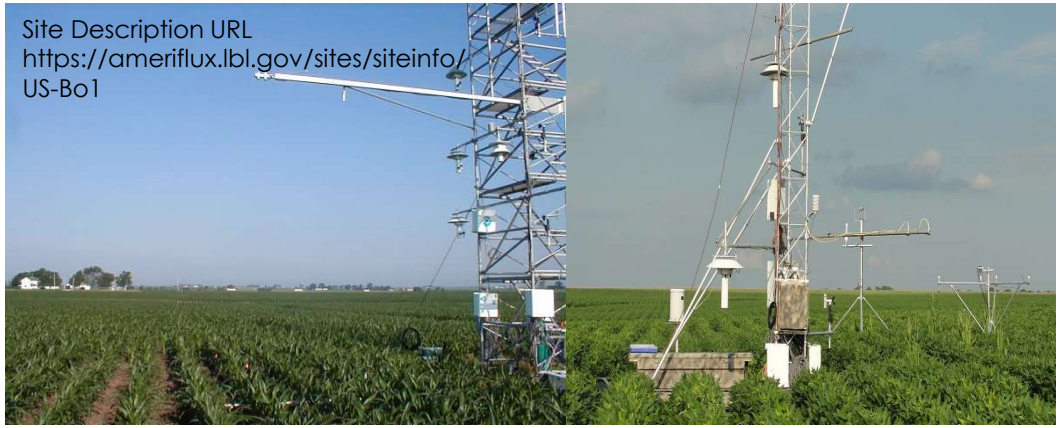
# 5. Dynamic vegetation growth, canopy structure

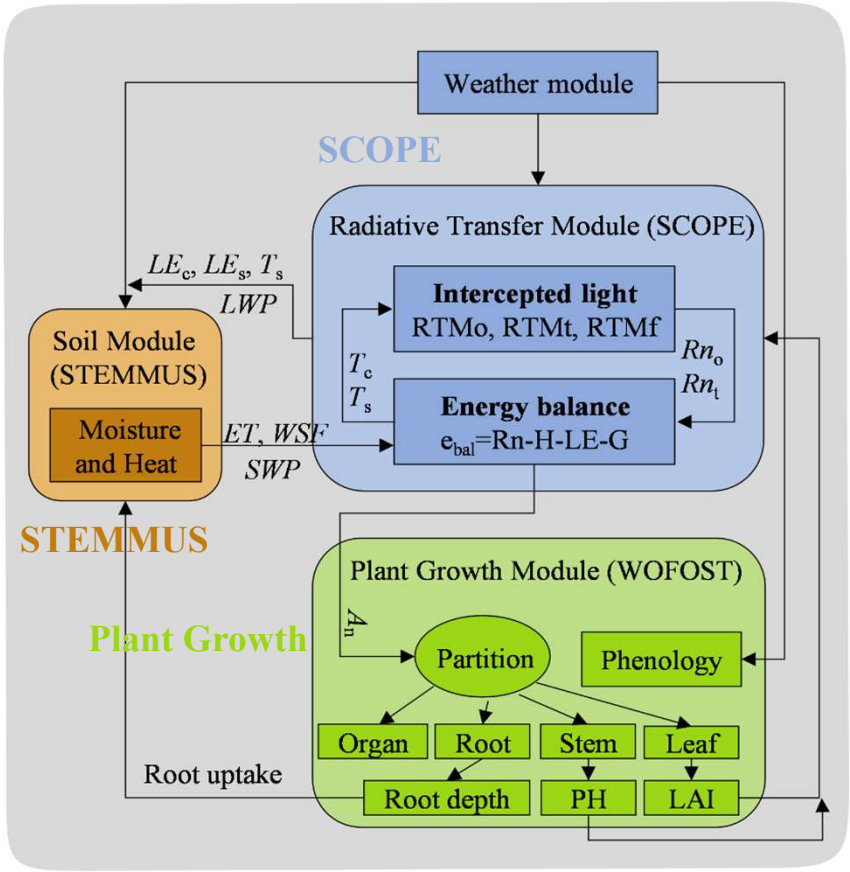
- LAI is currently an input in STEMMUS-SCOPE
- MODIS-LAI tends to have gaps

(Yu, et al. 2025 under review)

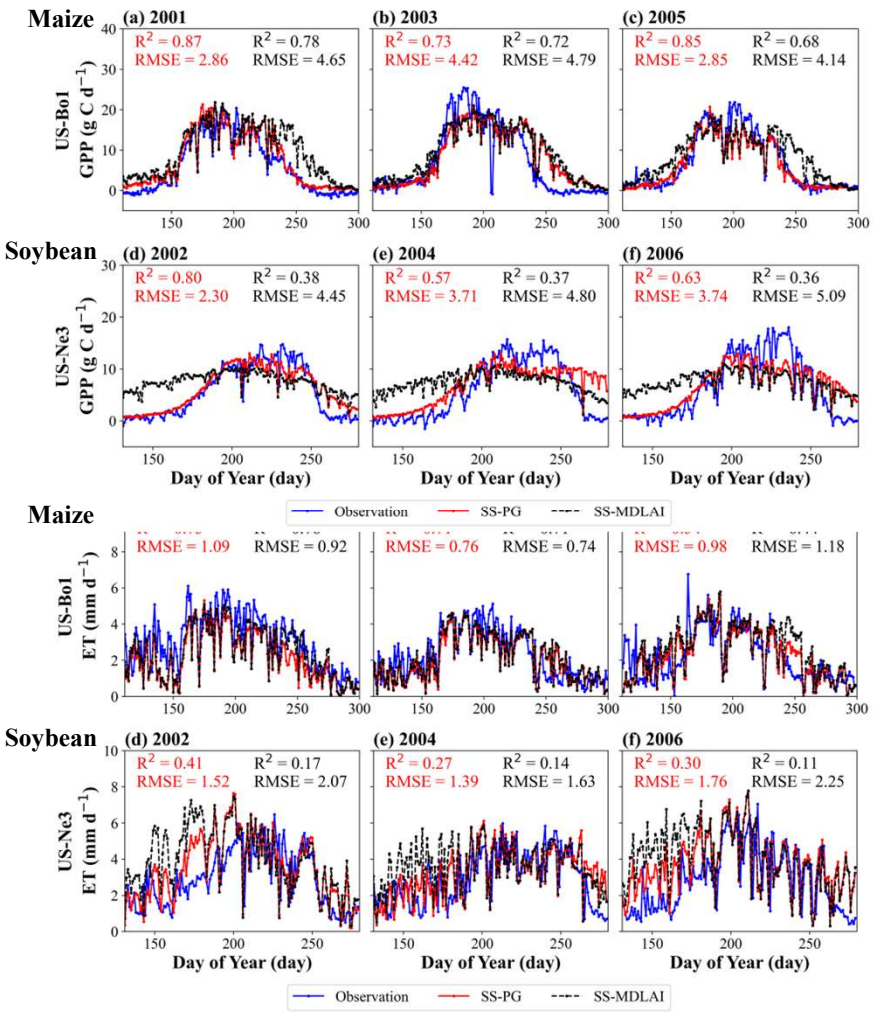
Fluxnet sites: US-Bo1, Illinois

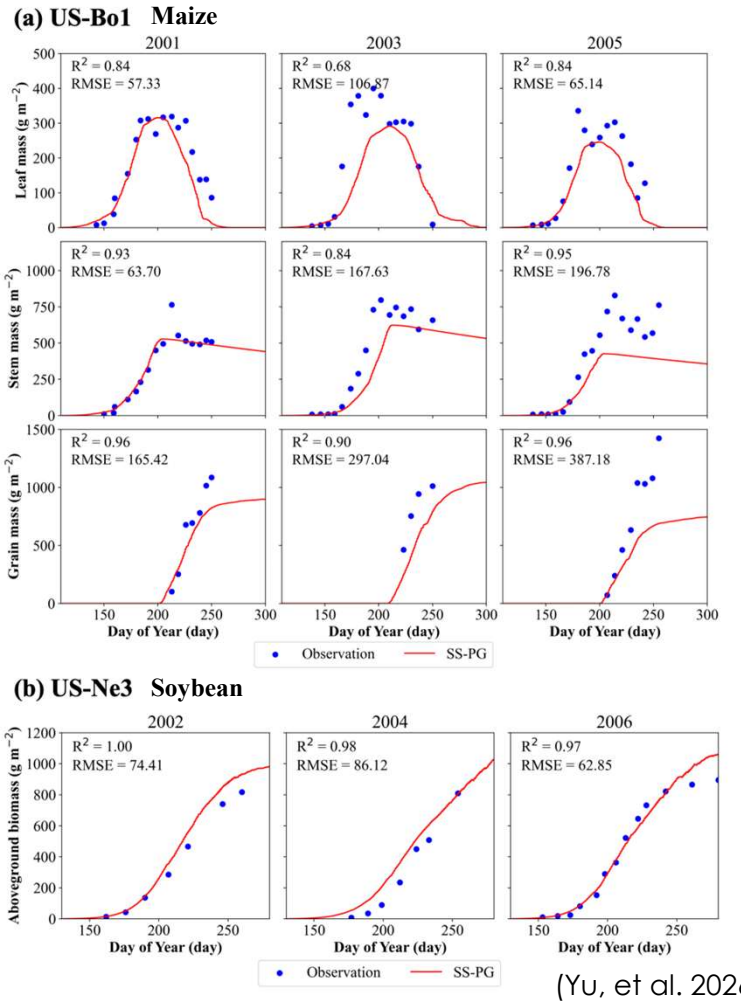
Agriculture, continuous no-till since 1986, Annual rotation between corn (C4) and soybeans (C3).



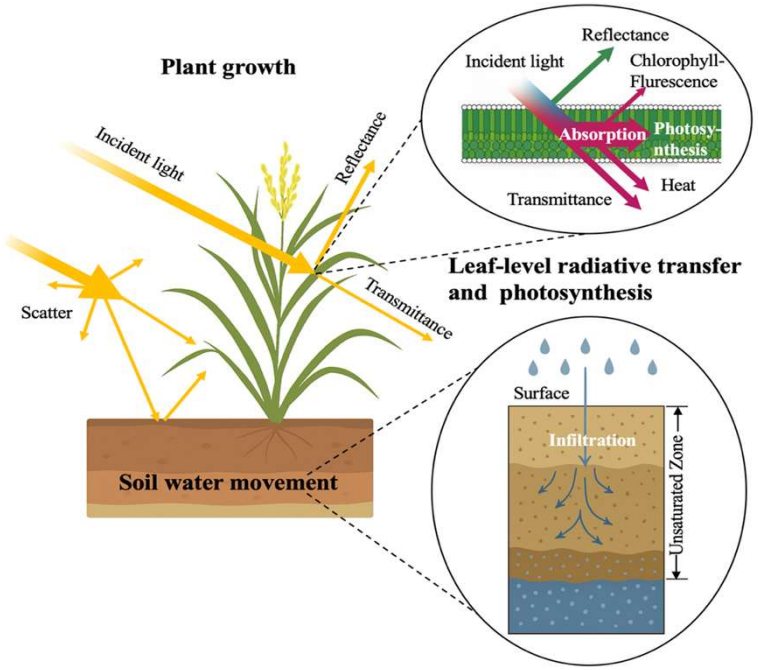
# 5. Dynamic vegetation growth, canopy structure

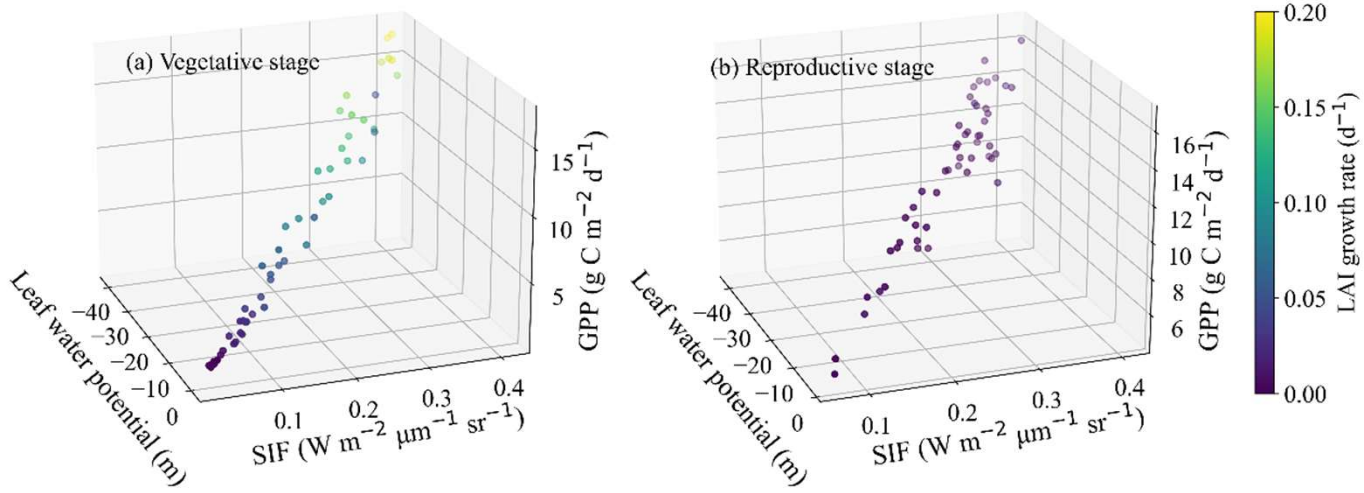



(Yu, et al. 2026 under revision)

# 5. Dynamic vegetation growth, canopy structure



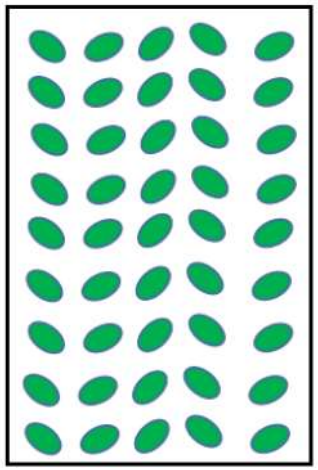




The STEMMUS-SCOPE-DVG model links the satellite observation (e.g., SIF) to plant biomass, land surface fluxes, and root zone soil moisture, in a physiologically consistent manner.

(Yu, et al. 2025 under review)

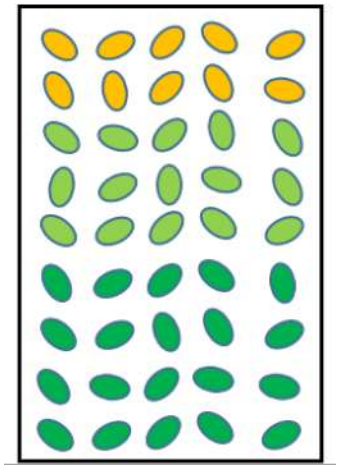
# 5. Dynamic vegetation growth, **Canopy Structure**

Model assumption



**SAIL and SCOPE 1.0: Homogeneous canopy layers and leaf properties**

(Verhoef et al., 1998, 2007)



**SCOPE 2.0: Homogeneous canopy layers with heterogeneous leaf properties**

(Yang et al., 2017)

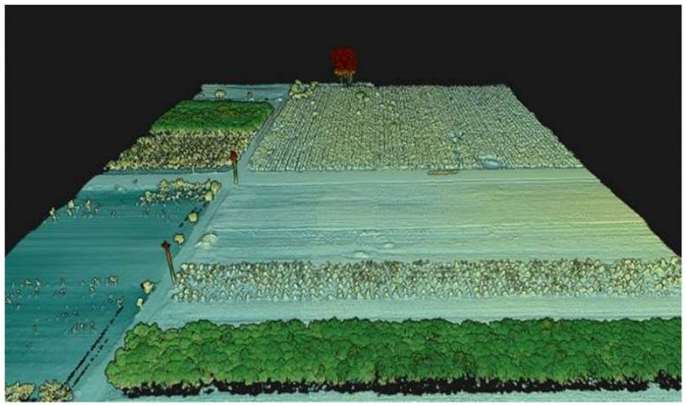
Reality

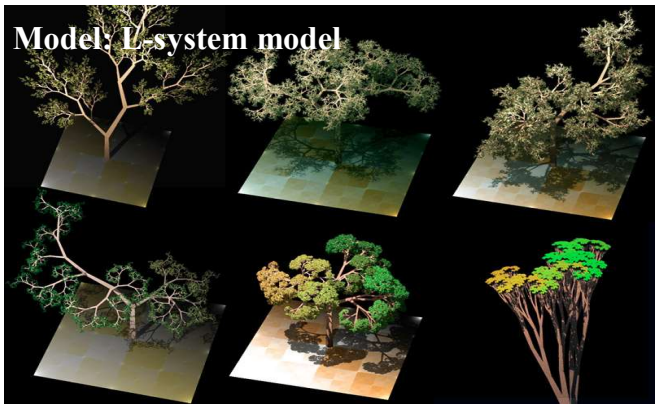
**Heterogeneous vertical canopy layers with heterogeneous leaf properties**

(Photographed at ITC) (Yu et al. 2025, unpublished)

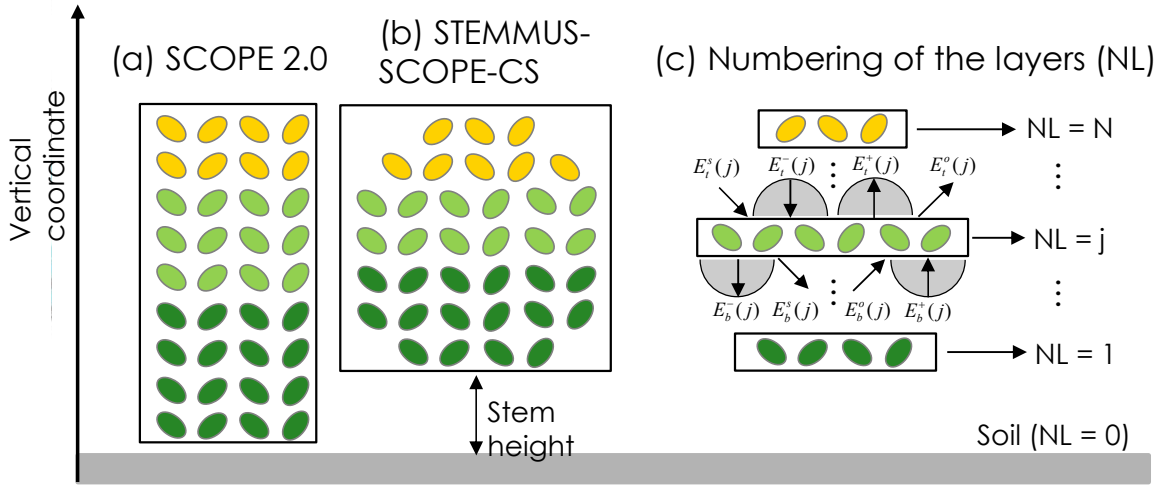
How to characterize the canopy structure in the STEMMUS-SCOPE?

# 5. Dynamic vegetation growth, **Canopy Structure**



# 5. Dynamic vegetation growth, **Canopy Structure**




An Example for Evergreen Broadleaf (ID-Pag)

four-stream canopy/layer interaction matrix

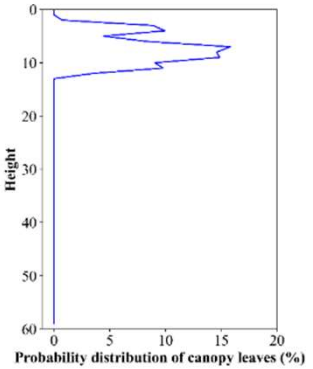
$$\begin{bmatrix} E_b^s(j) \\ E_b^-(j) \\ E_t^+(j) \\ E_t^o(j) \end{bmatrix} = \begin{bmatrix} \tau_{ss}(j) & & & \\ \tau_{sd}(j) & \tau_{dd}(j) & \rho_{dd}(j) & \\ \rho_{sd}(j) & \rho_{dd}(j) & \tau_{dd}(j) & \\ \rho_{so}(j) & \rho_{do}(j) & \tau_{do}(j) & \tau_{oo}(j) \end{bmatrix} \begin{bmatrix} E_t^s(j) \\ E_t^-(j) \\ E_b^+(j) \\ E_b^o(j) \end{bmatrix} + \begin{bmatrix} \gamma_d H_v(j) \\ \gamma_d H_v(j) \\ \gamma_o H_v(j) \end{bmatrix}$$

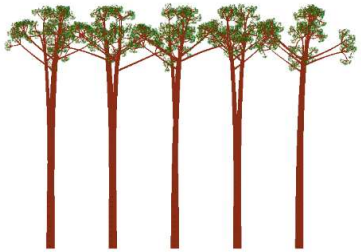
Reflectance and transmittance coefficients for each layer

$$\begin{bmatrix} 1-\tau_{ss}(j) \\ 1-\tau_{dd}(j) \\ \tau_{sd}(j) \\ \rho_{sd}(j) \\ \rho_{dd}(j) \end{bmatrix} = \begin{bmatrix} k(j) \\ a(j) \\ s'(j) \\ s(j) \\ \sigma(j) \end{bmatrix} LAI(j)$$

$$\begin{cases} LAI_{sum}(j) = \sum_{NL=N}^{j} LAI(NL) \\ P_s(j) = e^{k*LAI_{sum}(j)} \end{cases}$$

**Distribution probability of sunlight**

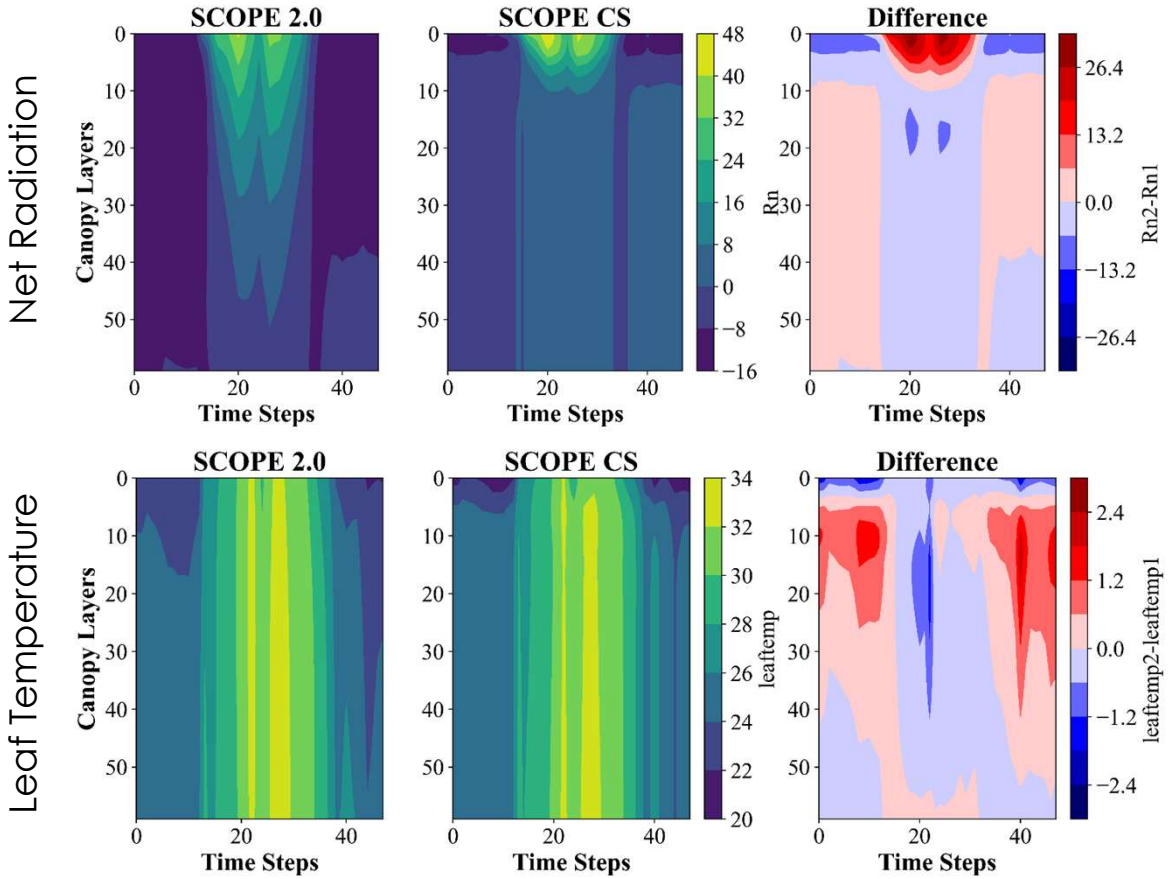


L-system

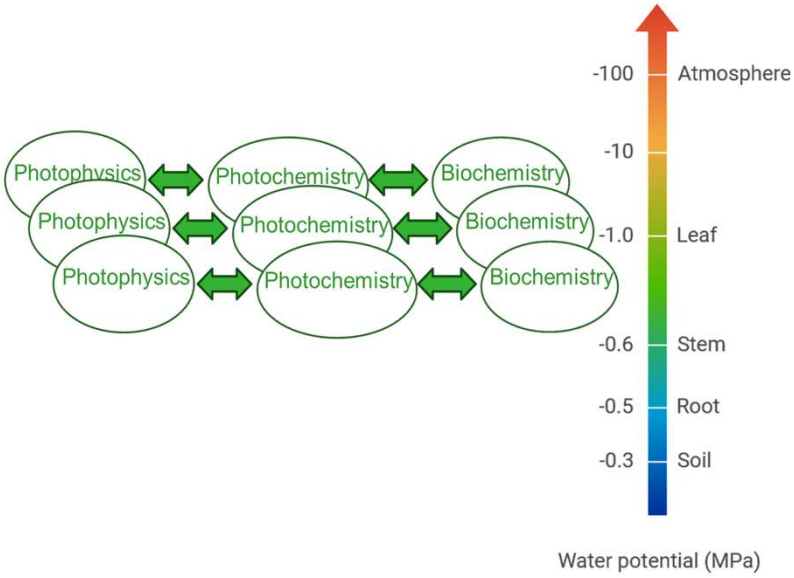
(Yu et al. 2025, unpublished)

# 5. Session Summary: Vegetation Growth and canopy structure




(Yu et al. 2025, unpublished)

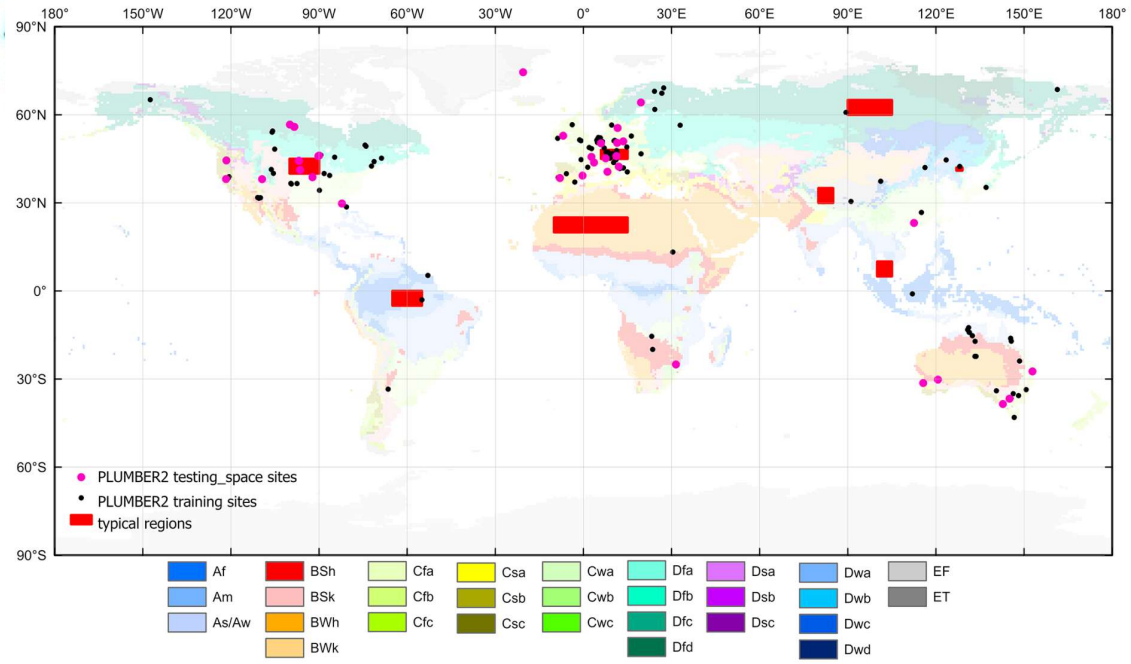
- The SCOPE-CS model can simulate more reasonable energy distributions over the vertical canopy profile.
- This will then lead to a better quantification of productivity and water use efficiency.

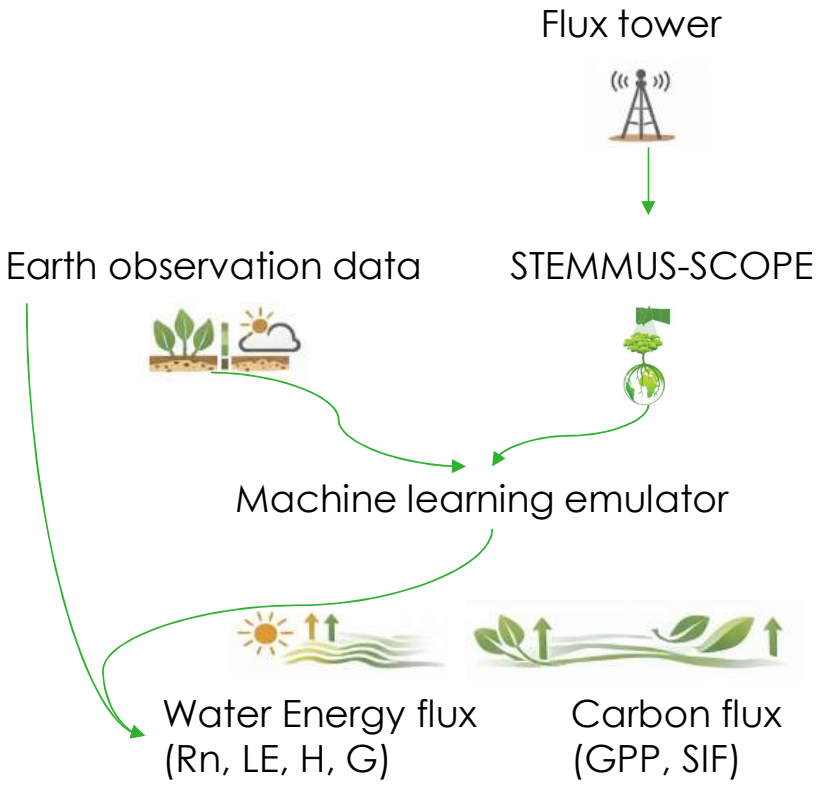


# Outline

- *Understanding Ecosystem Functioning with STEMMUS-SCOPE*
  - Agriculture and Nature Ecosystems
  - SIF vs. GPP, and the role of leaf water potential
- *Challenges and Opportunities*
  - Understanding SIF with Plant Hydraulics
  - Satellite SIF for evaluating water-energy-carbon fluxes
  - Dynamic vegetation growth and canopy structure
  - **STEMMUS-SCOPE emulator for a global Fluxhourly dataset**

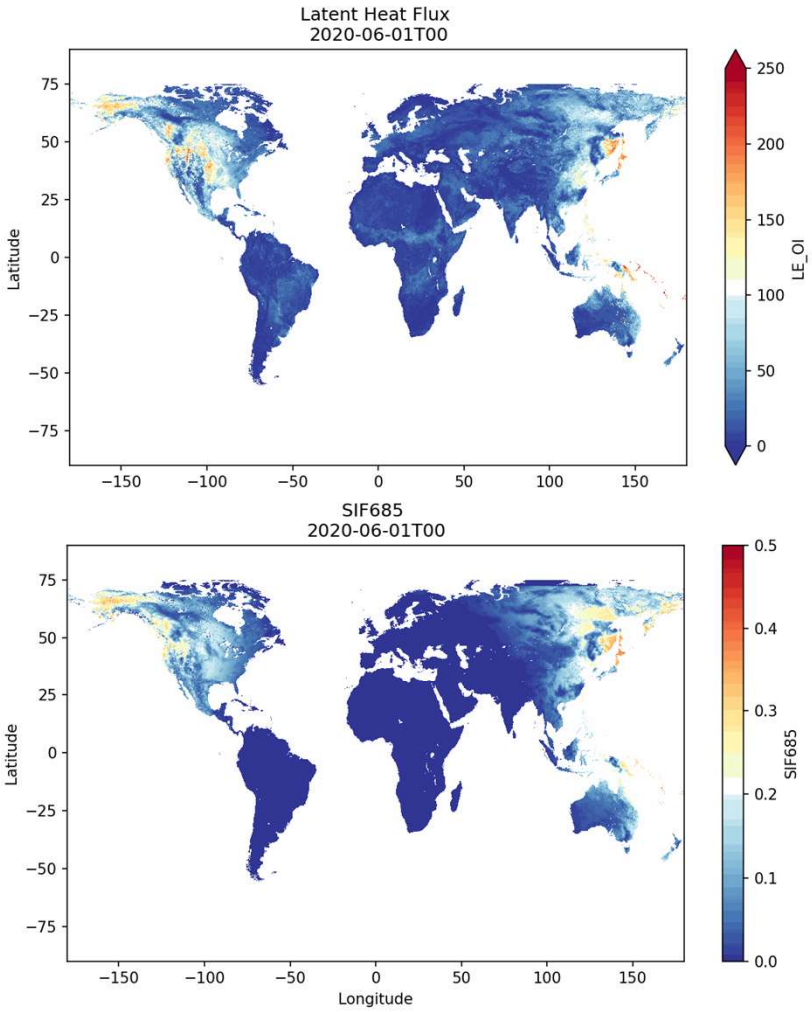
# 6. FluxHourly: a 9km-hourly, water-energy-carbon, SIF datasets



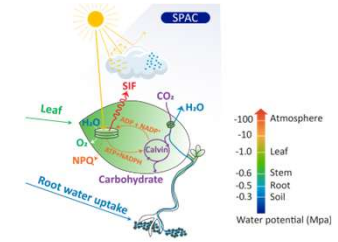



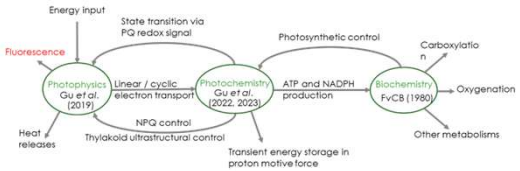

Hybrid framework combining process-based modeling, in-situ data, and machine learning

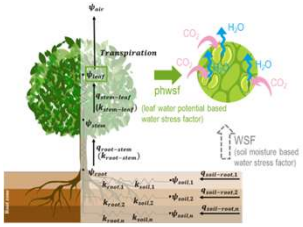
# 6. FluxHourly: a 9km-hourly, water-energy-carbon, SIF datasets



# Overall 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 end-to-end photosynthetic processes and soil-plant hydraulics.
- Soil-Plant hydraulics creates a mechanistic link between SIF and soil-plant water potentials.
- Linking soil water potential to foliar SIF also requires the representation of dynamic vegetation growth and canopy structure.
- With the enhanced soil-plant process understanding, a simple ML-emulating model can ‘accelerate’ ecosystem understanding.

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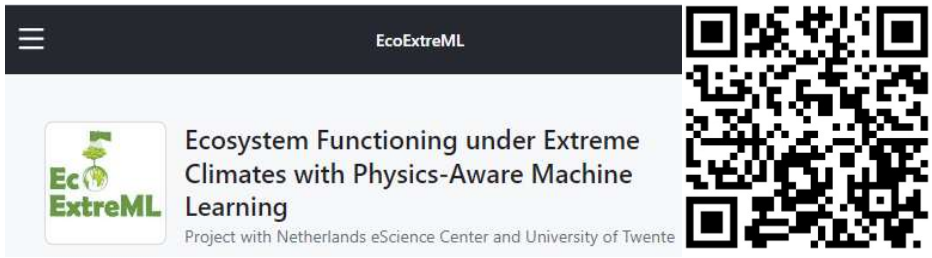
EcoExtreML

Accelerating Process Understanding for **Eco**system Functioning under **Extre**me Climates with Physics-Aware **M**achine **L**earning

## 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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netherlands eScience center

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