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Land Model and Biogeochemistry Working Group Meeting 2026

Multi-site calibrations of CLM6 for water and carbon fluxes – emergence of parameter coherence

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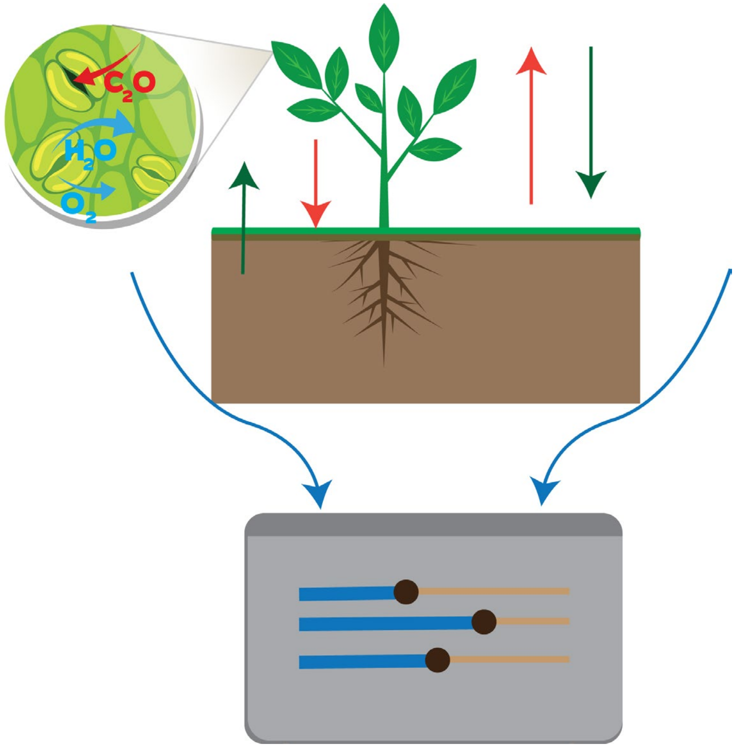
Motivation

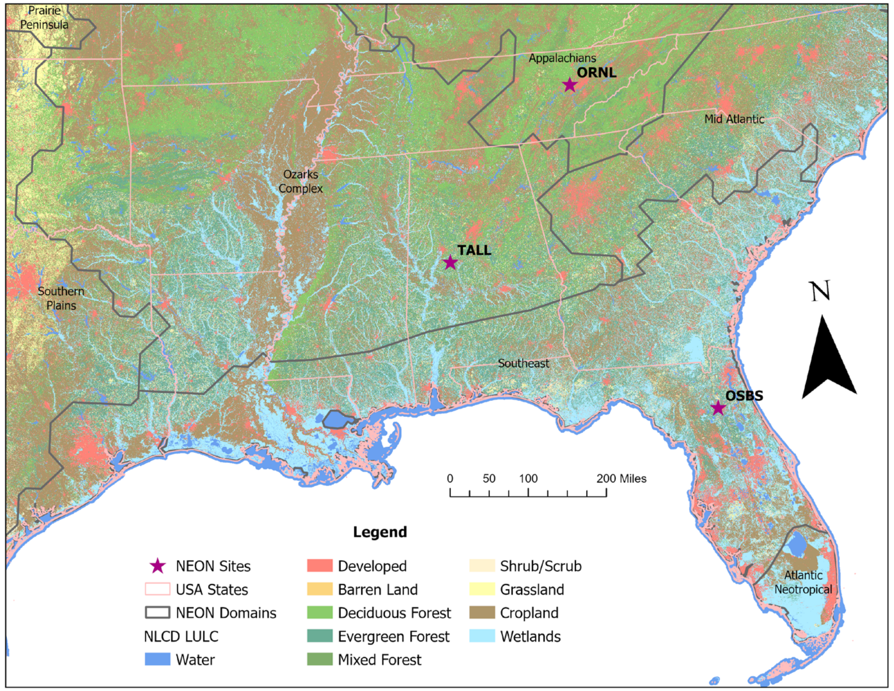
- Many key model parameters controlling photosynthesis, stomatal conductance, and soil-plant hydraulics are poorly constrained at ecosystem scale.
- Large within-PFT variation: e.g., Vcmax varies 2–3× even for the same PFT (Kattge et al., 2009).
- These uncertainties propagate to ecosystem productivity and carbon–water flux estimates (Bonan et al., 2011; Butler et al., 2022).
- Much of this variability is driven by climate, soils, and species, factors not captured by global default values (Kattge et al., 2009; Rogers, 2014).
- Fixed PFT structures impose rigid behavior, limiting representation of physiological diversity and altering water–carbon coupling (Rogers, 2014).

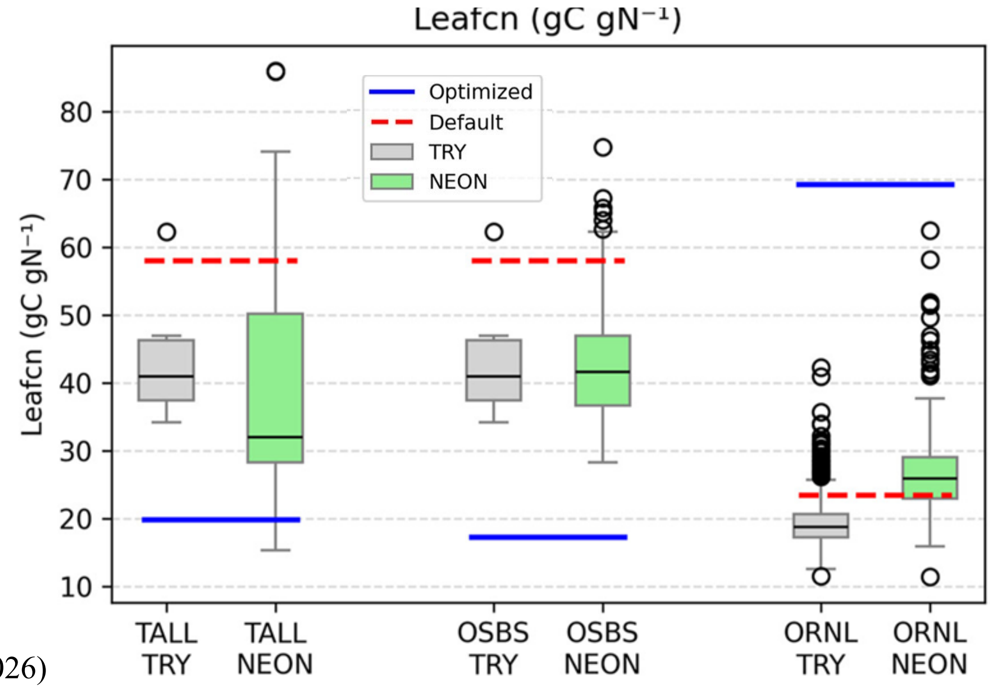


Ecosystem processes parameterization

Challenges and Opportunity

- **Calibration** relies on global or site-specific defaults, rarely capturing trait distributions
- **Single objective optimization** (e.g. GPP) forces tradeoffs, improving one flux often degrades another (e.g. ET) – compensatory effects (Kavoo et al. 2026)
- **Parameter equifinality** obscures physically plausible combinations
- **Identifiability issues**: multiple parameter sets fits one site but fail across scales.

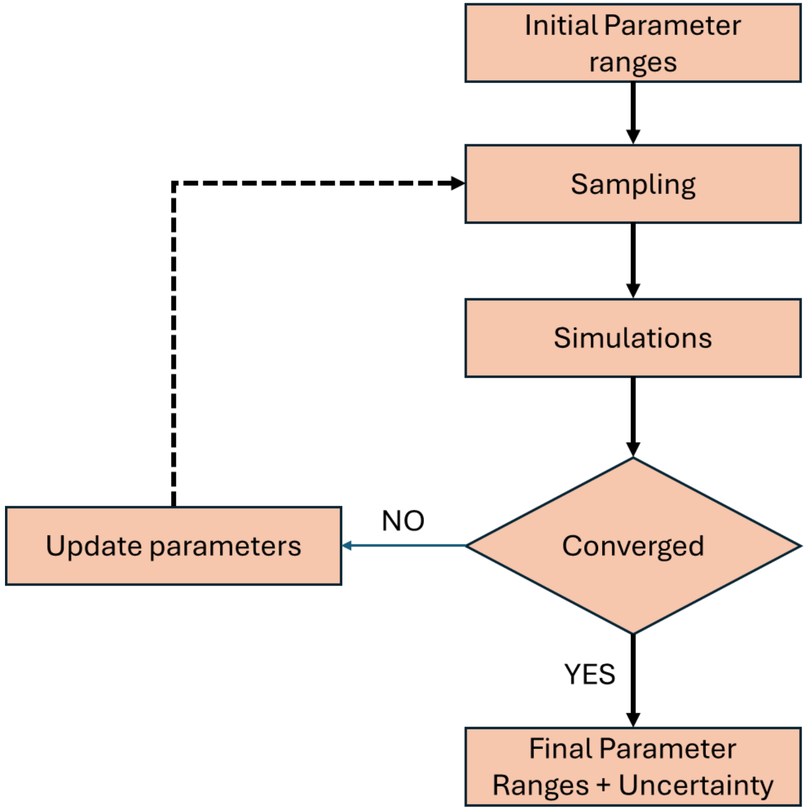




Source; Kavoo et al. (2026)

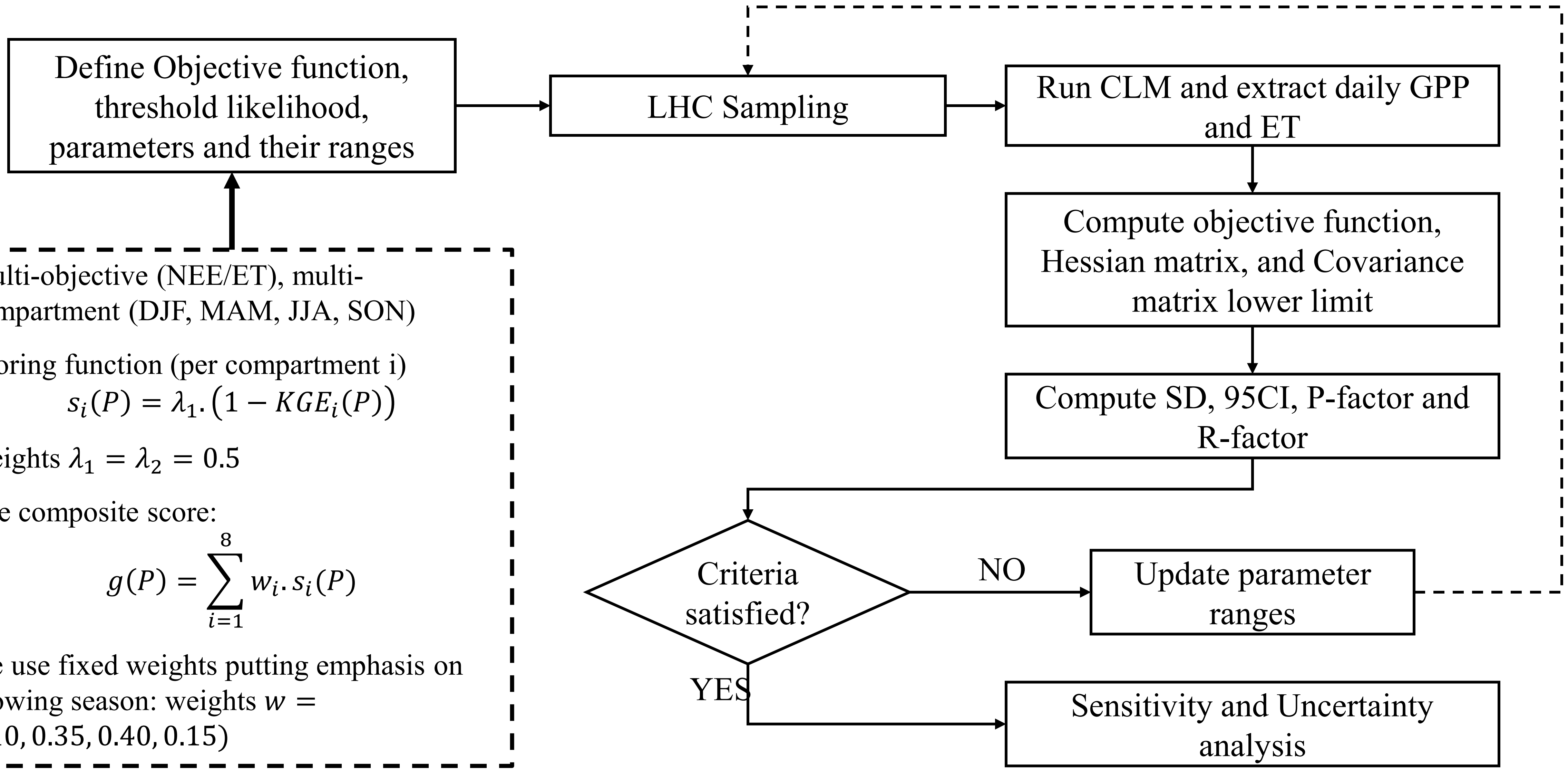
Sequential Uncertainty Fitting(SUFI) Algorithm

- **Wide applications in hydrology** – calibration and uncertainty analysis (Abbaspour et al. 2007)
- **Iteratively constrains parameter ranges** based on model data mismatch using key performance indicators (Abbaspour et al. 2007):
  - Proportion of observation data points that fall within 95% prediction uncertainty band.
  - Average thickness of the 95% prediction uncertainty band divided by SD of observations.
- **Computationally efficient in high-dimensional space**: enabling exploration of many interacting parameters without prohibitive computation cost



SUFI workflow schematic

SUFI Implementation Workflow for CLM-NEON



Multi-objective (NEE/ET), multi-compartment (DJF, MAM, JJA, SON)

Scoring function (per compartment i)

$$s_i(P) = \lambda_1.\left(1 - KGE_i(P)\right)$$

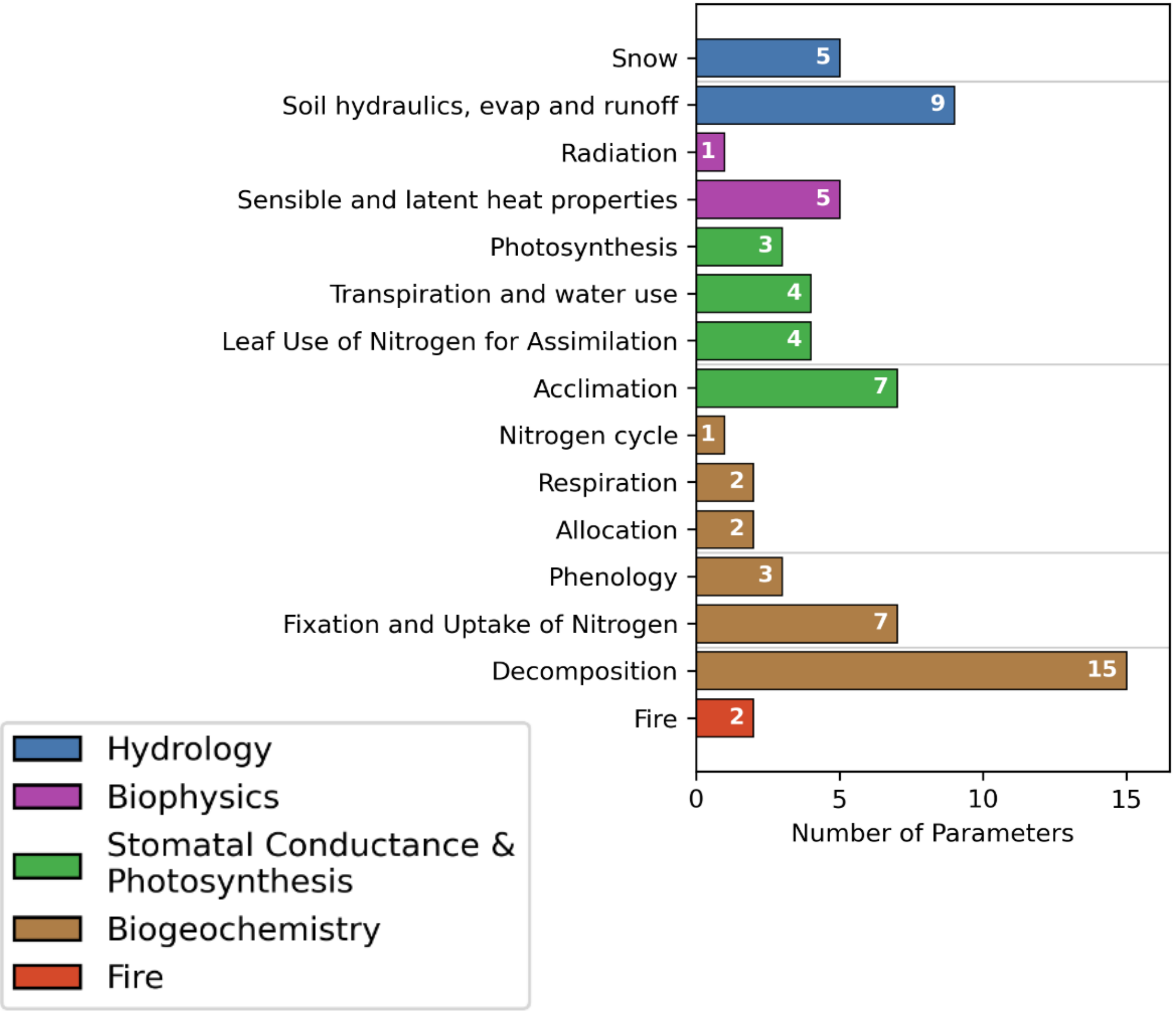
Weights $\lambda_1 = \lambda_2 = 0.5$

The composite score:

$$g(P) = \sum_{i=1}^{8} w_i . s_i(P)$$

We use fixed weights putting emphasis on growing season: weights $w = 0.10, 0.35, 0.40, 0.15$)

Multi-Site PPE Setup



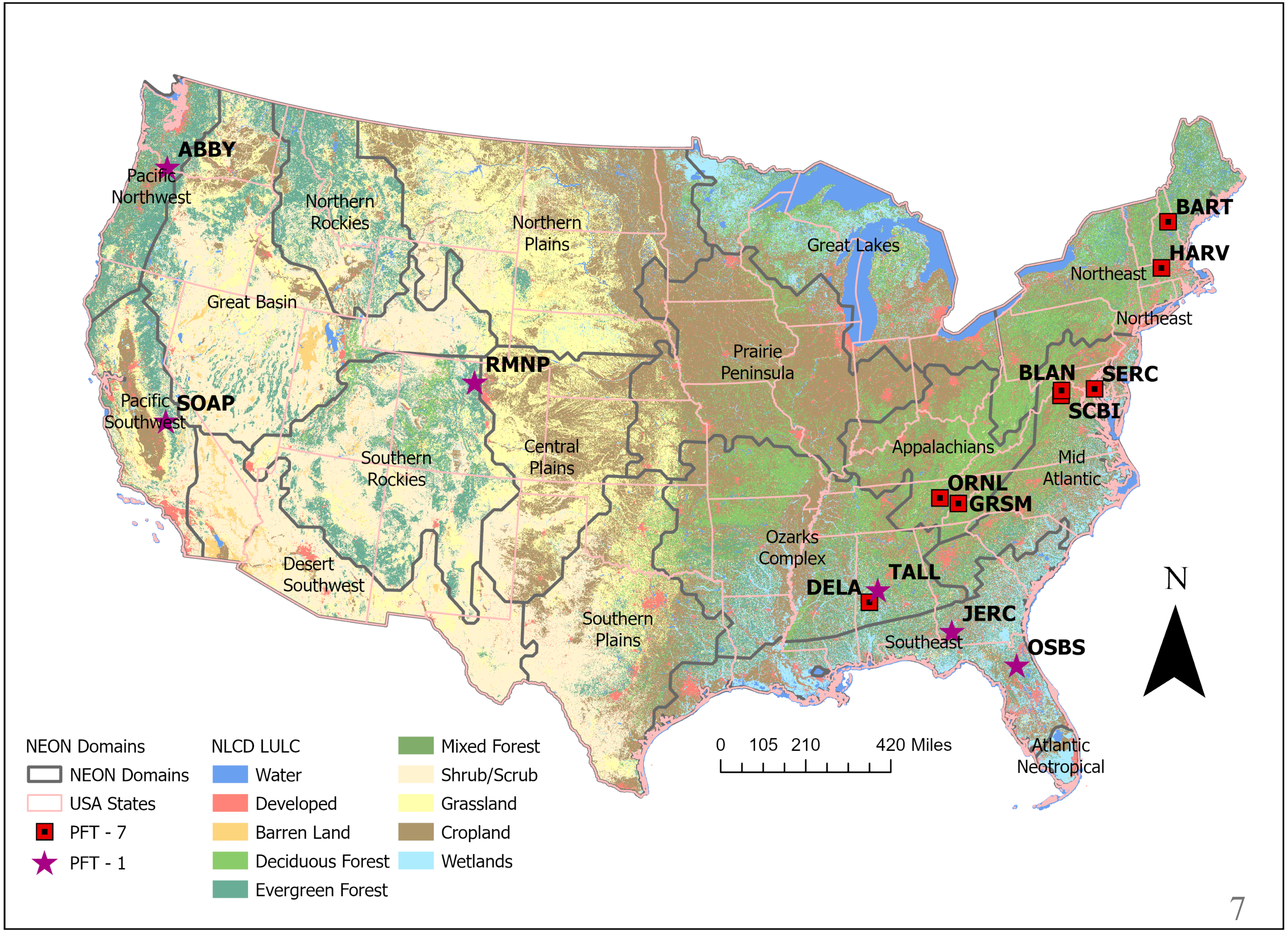
Multi-objective calibration:

- Via Perturbed Parameter Ensemble (PPE)
- 14 sites (Needleleaf - 6, broadleaf 8)
- 1000 simulations: Sampled using (LHC)
- 56 parameter groups (reduced from 70)

Setup

- Spin-up: PLUMBER2 protocol (pre-industrial CO2, Ndep)
- Transient run: 1850 – 2018
- Production run: 2018 - 2024

Study Area



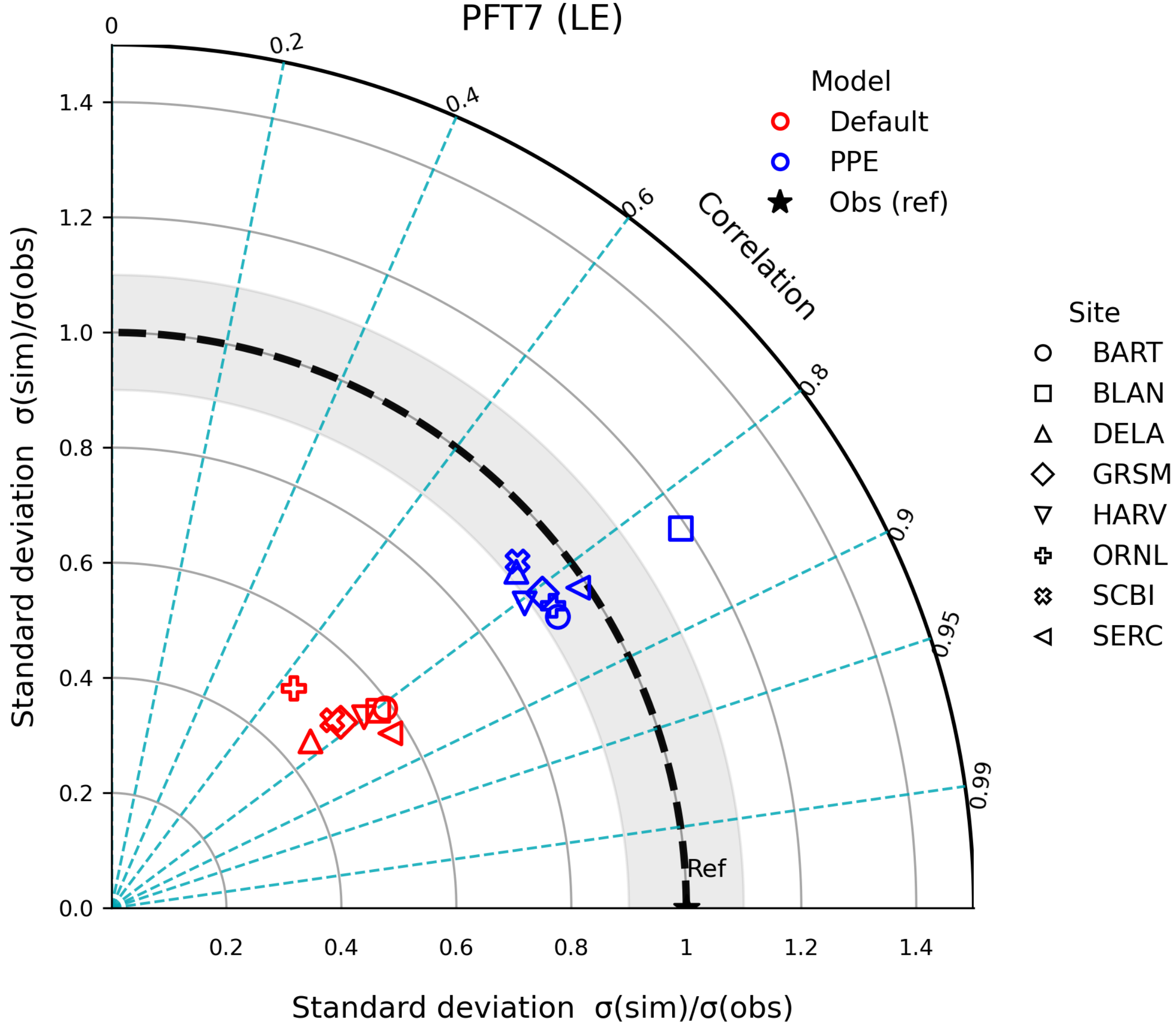
ABBY
Pacific Northwest
Northern Rockies
Northern Plains
Great Lakes
BART
HARV
Northeast
Northeast
Great Basin
RMNP
Prairie Peninsula
BLAN
SERC
SCBI
Pacific Southwest
SOAP
Southern Rockies
Central Plains
Appalachians
Mid Atlantic
ORNL
GRSM
Ozarks Complex
Desert Southwest
TALL
DELA
JERC
Southern Plains
Southeast
OSBS
N
Atlantic Neotropical
0 105 210 420 Miles
NEON Domains
NEON Domains
USA States
PFT - 7
PFT - 1
NLCD LULC
Water
Developed
Barren Land
Deciduous Forest
Evergreen Forest
Mixed Forest
Shrub/Scrub
Grassland
Cropland
Wetlands

Results: Performance (PFT 7 - BDT)

Improvements 13% overall

<u>Latent Heat Flux (8/8 sites)</u>

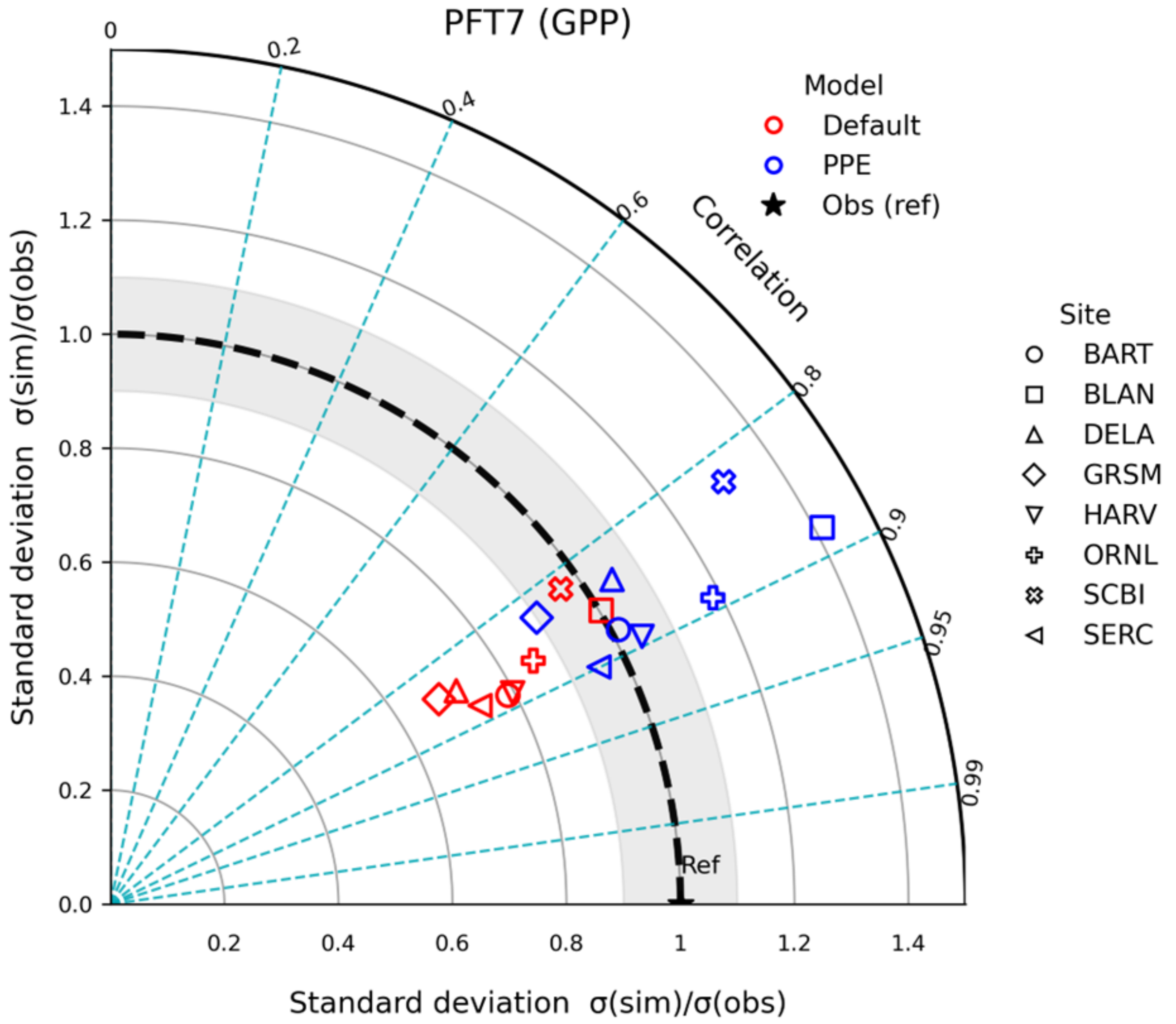
- Default means: Corr=0.788,σ ratio =0.532, CRMSD_norm =0.667
- PPE means: Corr=0.816,σ ratio =0.928, CRMSD_norm =0.600
- **Overall Δ (PPE − Default)**
  - ΔCorr =0.028
  - Δσ Ratio =0.396
  - ΔCRMSD_norm =-0.066



Results: Performance (PFT 7 - BDT)

<u>**Gross Primary Productivity (5/8 sites)**</u>

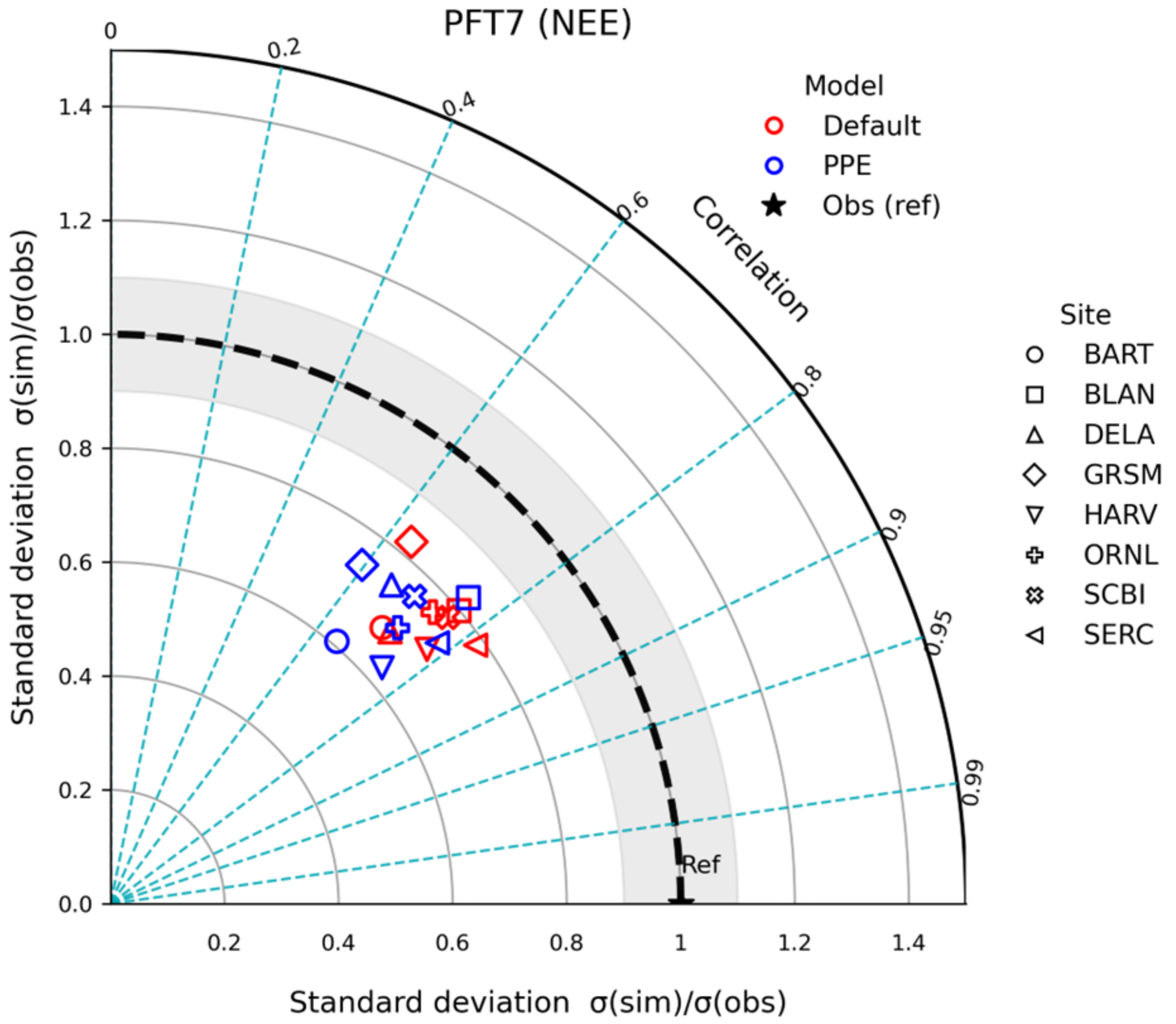
- Default medians: Corr=0.862,σ ratio =0.792, CRMSD_norm =0.516
- PPE medians: Corr=0.882,σ ratio =1.046, CRMSD_norm =0.552
- **Overall Δ (PPE − Default)**
  - ΔCorr =0.020
  - Δσ Ratio =0.254
  - ΔCRMSD_norm =0.035



Results: Performance (PFT 7 - BDT)

Net Ecosystem Exchange (5/8 sites)

- Default means: Corr=0.751,σ ratio =0.770, CRMSD_norm =0.660
- PPE means: Corr=0.712,σ ratio =0.737, CRMSD_norm =0.704
- **Overall Δ (PPE − Default)**
  - ΔCorr =-0.040
  - Δσ Ratio =-0.032
  - ΔCRMSD_norm =0.044

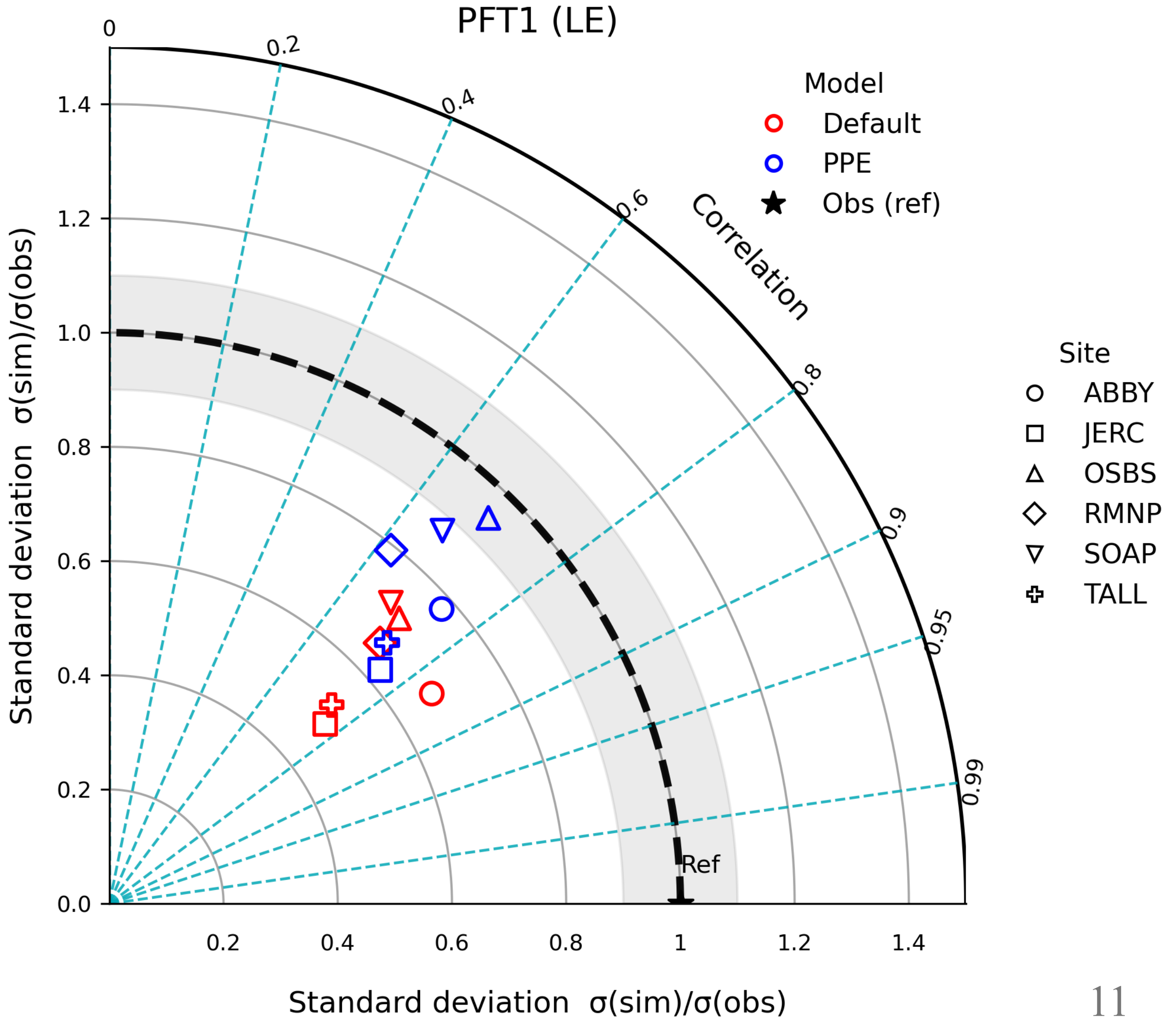


Results: Performance: PFT 1 (NET)

Improvements 5% overall

<u>Latent Heat Flux 6/6 sites)</u>

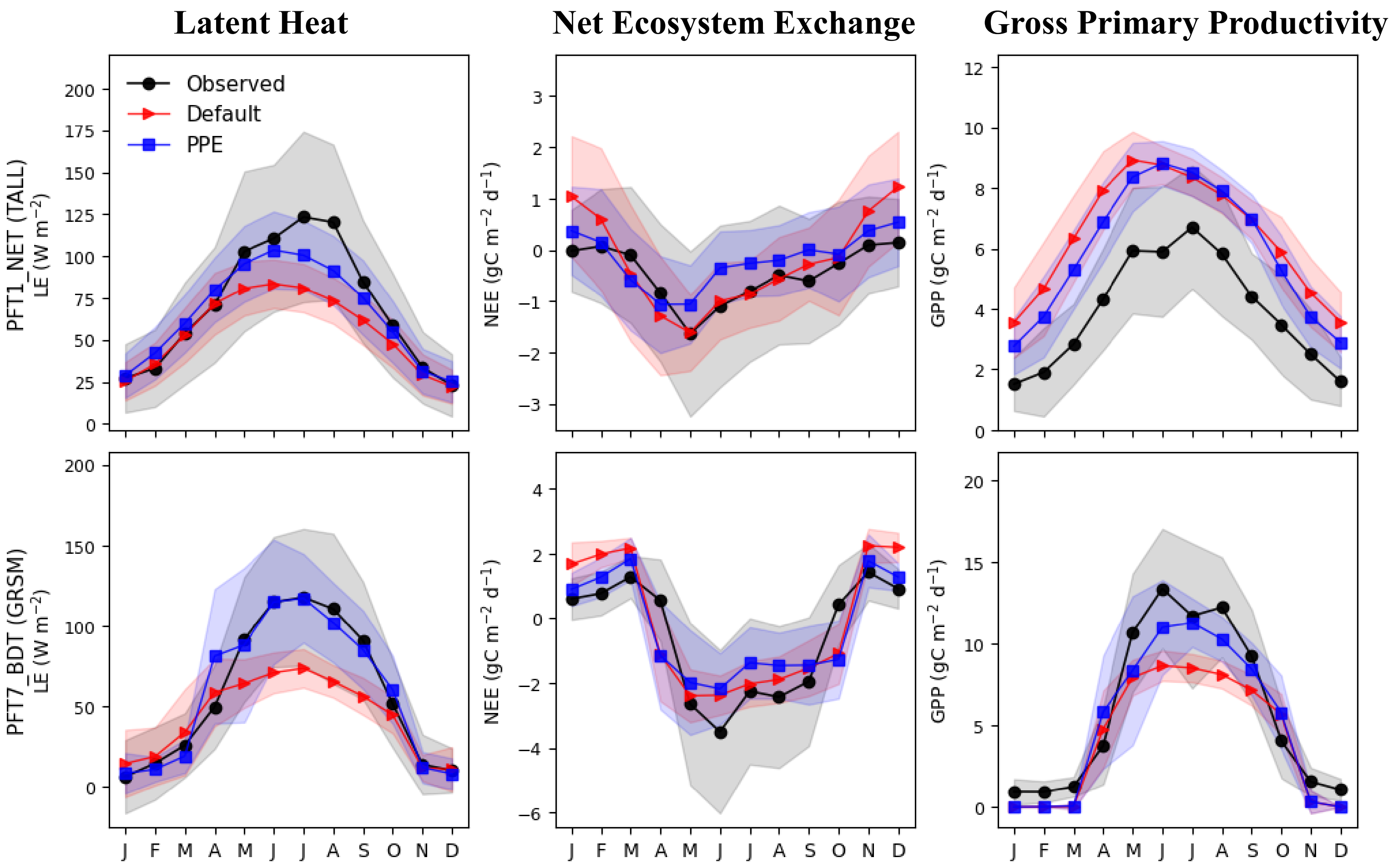
- Default medians: Corr=0.733,σ ratio =0.666, CRMSD_norm =0.699
- PPE medians: Corr=0.715,σ ratio =0.785, CRMSD_norm =0.721
- **Overall Δ (PPE − Default)**
  - ΔCorr =-0.018
  - Δσ Ratio =0.119
  - ΔCRMSD_norm =0.022



Seasonal Fluxes and Skill score

<u>Model data alignment:</u> PPE matches summer GPP & LE better.

<u>Large error reductions (PFT 7):</u> RMSE drops by 8–11 W m^{-2} (LE) and 0.5 - 0.6 g C m^{-2} d^{-1} (GPP).



Impact of PPE on Simulated LE: PFT 7 (BDT)

Hexbin Meaning:

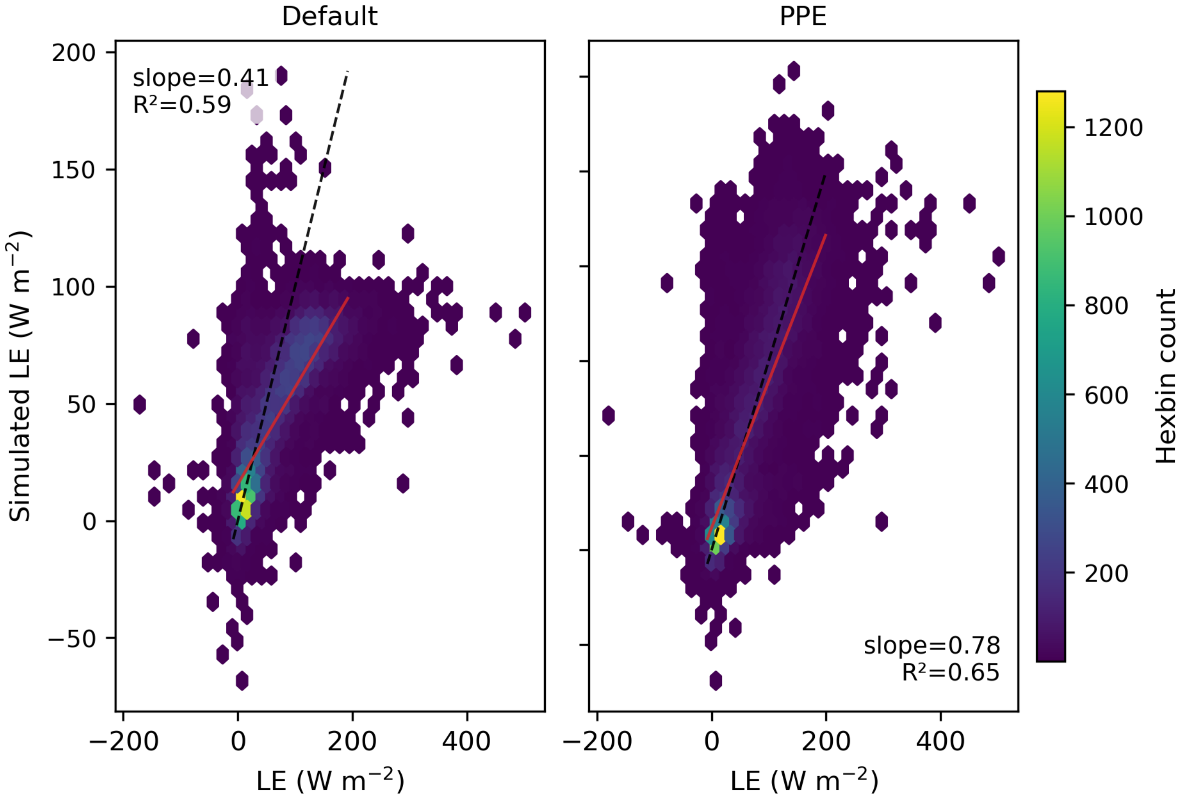
- Color indicates how many points fall in that area.
- Overall distribution of daily model–observation pairs

Reference Lines:

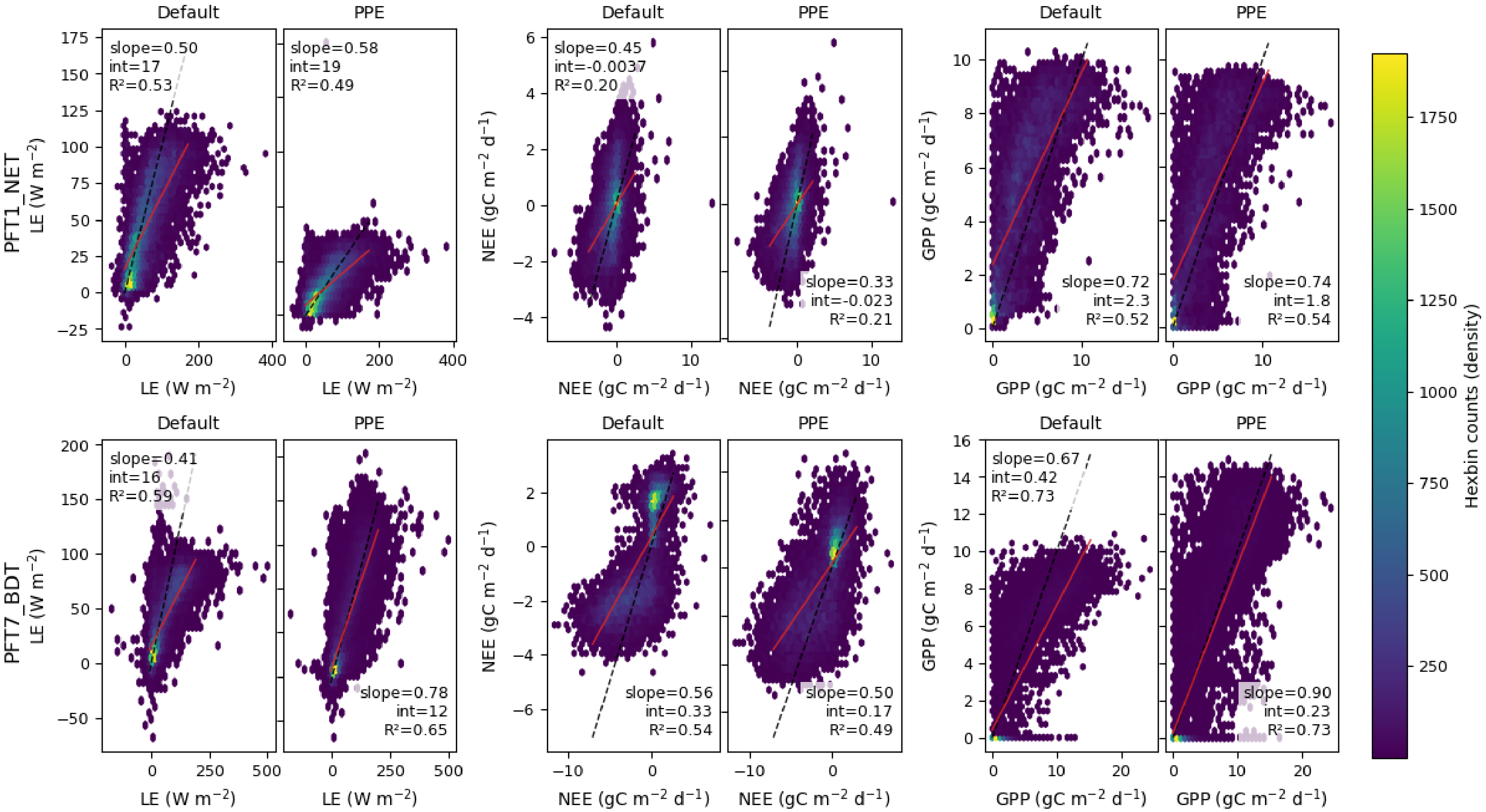
- 1:1 line: perfect agreement.
- Red line: regression fit (model behavior)

Example Latent Heat:

- Default: slope ≈ 0.41: CLM6 underestimates high LE values
- PPE: slope ≈ 0.78: Simulated LE closer to 1:1 line.

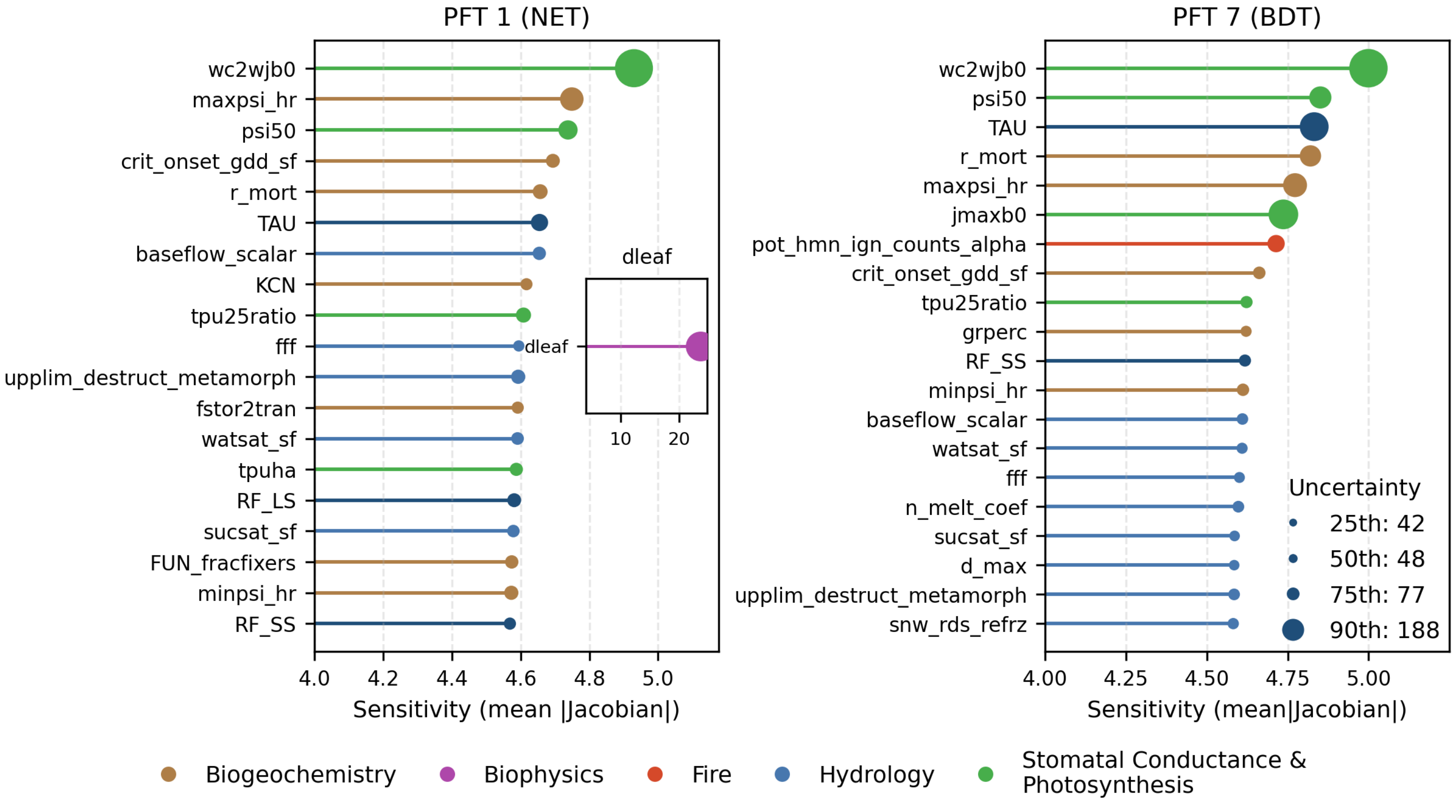


Impact of PPE on Water – Carbon Fluxes



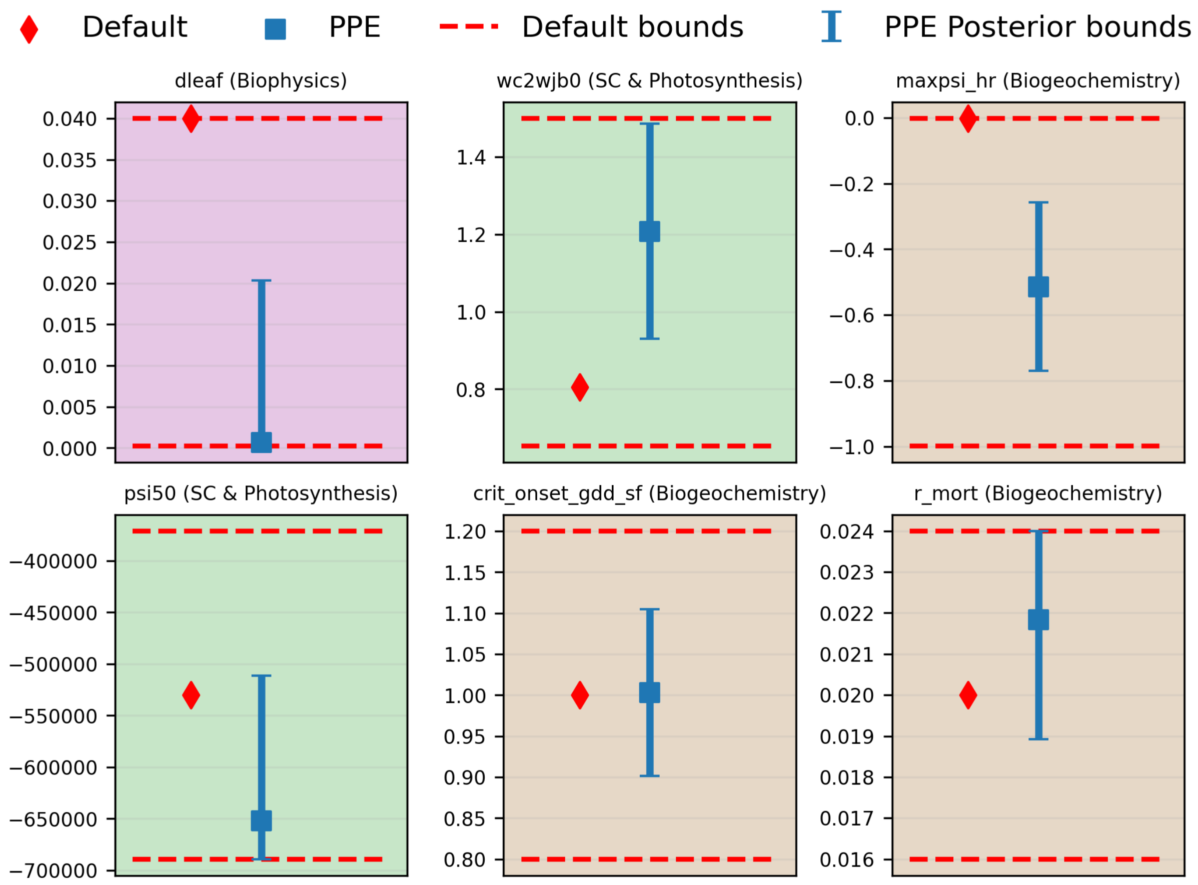
Parameter Sensitivity

- A small subset of parameters (***e.g., wc2wjb0, maxpsi_hr, psi50, r_mort***) show consistently high sensitivity.
- The wide uncertainty ranges (colored dots) highlight that not all influential parameters are equally stable.



A revised parameter Range – A key outcome of this study

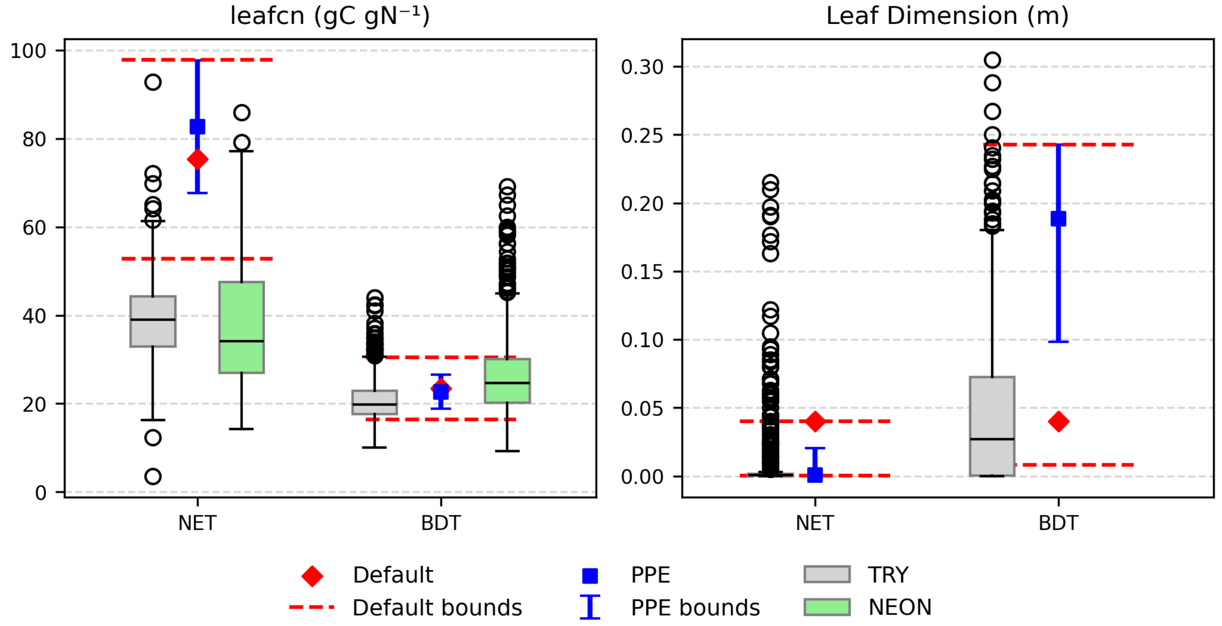
Several parameters (***e.g., dleaf, wc2wjb0, maxpsi_hr***) show posterior values that shift substantially from the Default and lie within much narrower posterior bounds, indicating strong identifiability.



Observed Traits and Parameter Constraints

Leaf C:N (*leafcn*): A less sensitive parameter but the default value and bounds sit well above observed TRY/NEON range, limiting how far the posterior could move.

Leaf dimension (*dleaf*): highly sensitive parameter especially in PFT 1. The posterior shifts from the default and aligns closely with the median observed trait.



What I found doing multi-site optimization?

- A revised posterior parameter range
- Non-compensation optimized parameter value
- Getting close to solving long-standing biases in CLM, e.g. ET underestimation
- Does it work on regional / global scale – remain to be tested.

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