LEMONTREE

Land Ecosystem Models based On New Theory, obseRvations and ExperimEnts

Implementation of an eco-evolutionary approach to photosynthesis and acclimation in the JULES land surface model

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Plant responses to environment happen at different timescales

Instantaneous response

Seconds to hours

Stomatal opening/closing, light reactions, enzyme kinetics respond immediately to changes in light, temperature, and CO_2

Acclimation

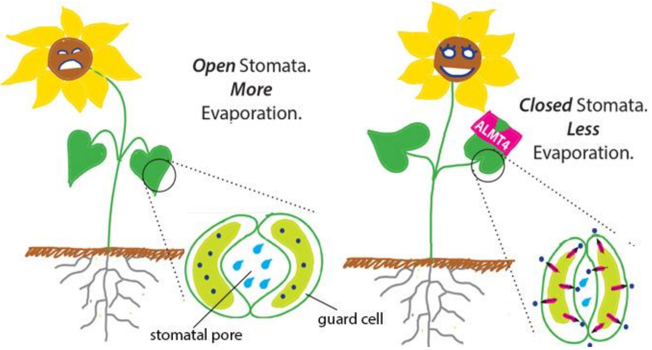
Days, weeks to months

Physiological and structural adjustments: changes in Vcmax, Jmax, stomatal sensitivity ξ, and leaf nitrogen allocation

Adaptation

Years and centuries

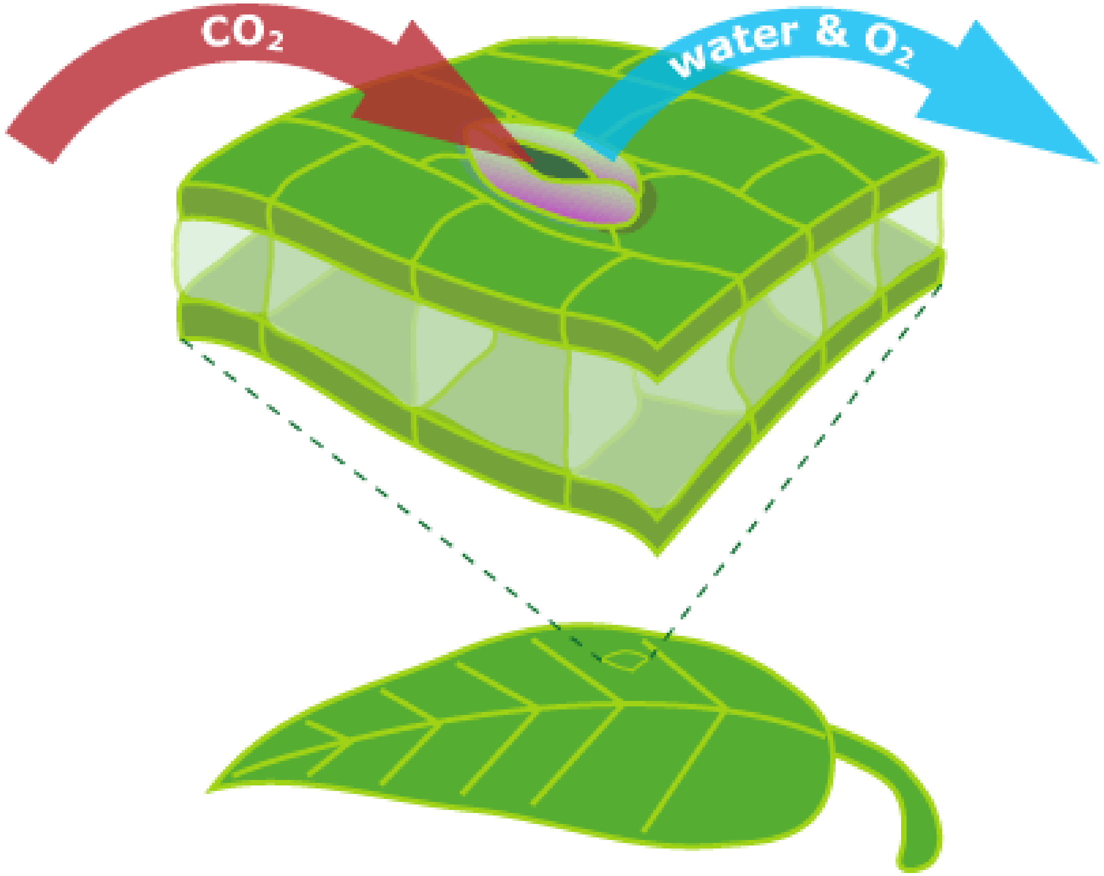
Evolutionary changes through competition, migration, and natural selection on trait distributions across populations



Unifying framework - Eco-evolutionary optimality

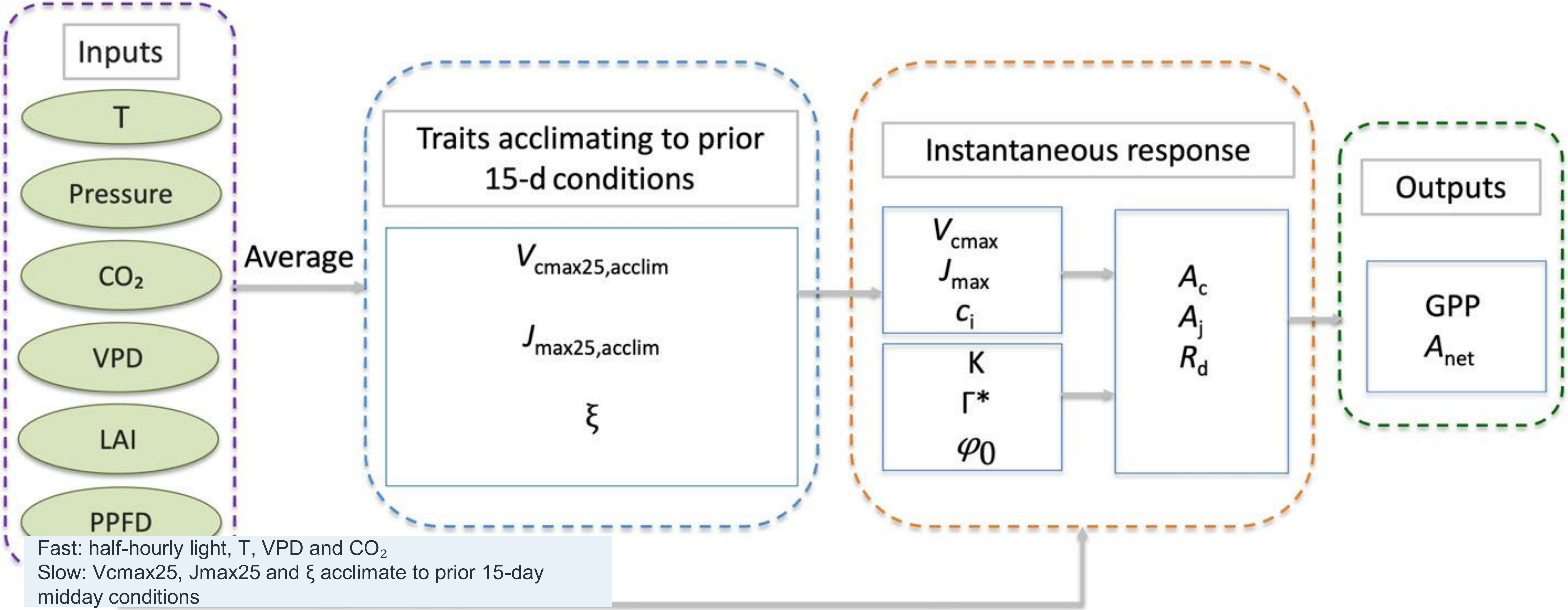
Key idea: carbon gain is optimized against two costs

- water loss through stomata → optimal χ and ξ
- maintenance of carboxylation capacity → optimal Vcmax and Jmax



CO_2 enters while O_2 and water exits leaf through leaf stomata

The sub-daily P model separates slow acclimation from fast instantaneous response



Fast: half-hourly light, T, VPD and CO_2
Slow: Vcmax25, Jmax25 and ξ acclimate to prior 15-day midday conditions

Three changes: $\Gamma^* \rightarrow 0$ · $\beta \rightarrow \beta_{C_4}$ · $m_j \rightarrow 1$

Mengoli et al. (2022), J. Adv. Model. Earth Syst.

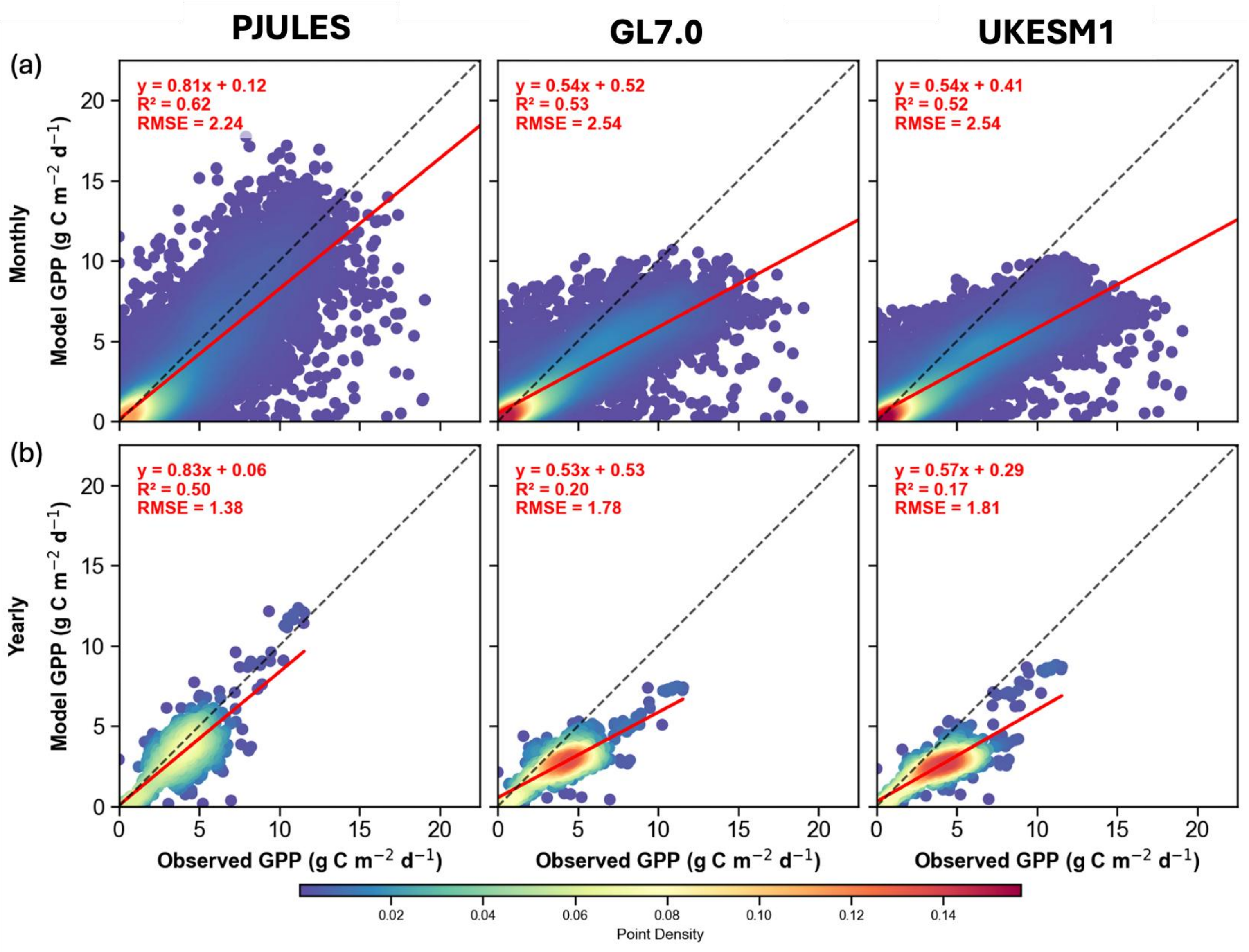
PJULES replaces PFT-dependent empirical parameters with environment-driven predictions

Feature	JULES-GL7.0	JULES-UKESM1	PJULES
Plant types	5 PFTs	13 PFTs	**C_3 / C_4 only**
Photosynthesis	Collatz et al. (1991)	Collatz et al. (1991)	**P-model**
Stomatal cond.	Jacobs scheme	Jacobs scheme	**Least-cost (ξ)**
Vcmax / Jmax	PFT-specific fixed	PFT-specific fixed	**Env.-predicted**
Acclimation	None	None	**15-day memory**
Canopy scheme	Multi-layer (10)	Multi-layer (10)	**Big-leaf**

LEAF SCHEME • 6 Collatz biochemical parameters; +2 Jacobs stomatal parameters; +fd respiration; +glmin conductance

CANOPY & STRESS • PAR/optics (kpar, kext, omega, alpar, orient, can_struct_a) • N profile (kn or knl) • soil-moisture pathway (fsmc / ψ thresholds) → exact set is configuration-dependent

PJULES outperforms standard JULES at monthly and yearly timescales



Monthly GPP

PJULES: R^2 = 0.62, RMSE = 2.24

GL7.0: R^2 = 0.53, RMSE = 2.54

UKESM1: R^2 = 0.53, RMSE = 2.49

Yearly GPP

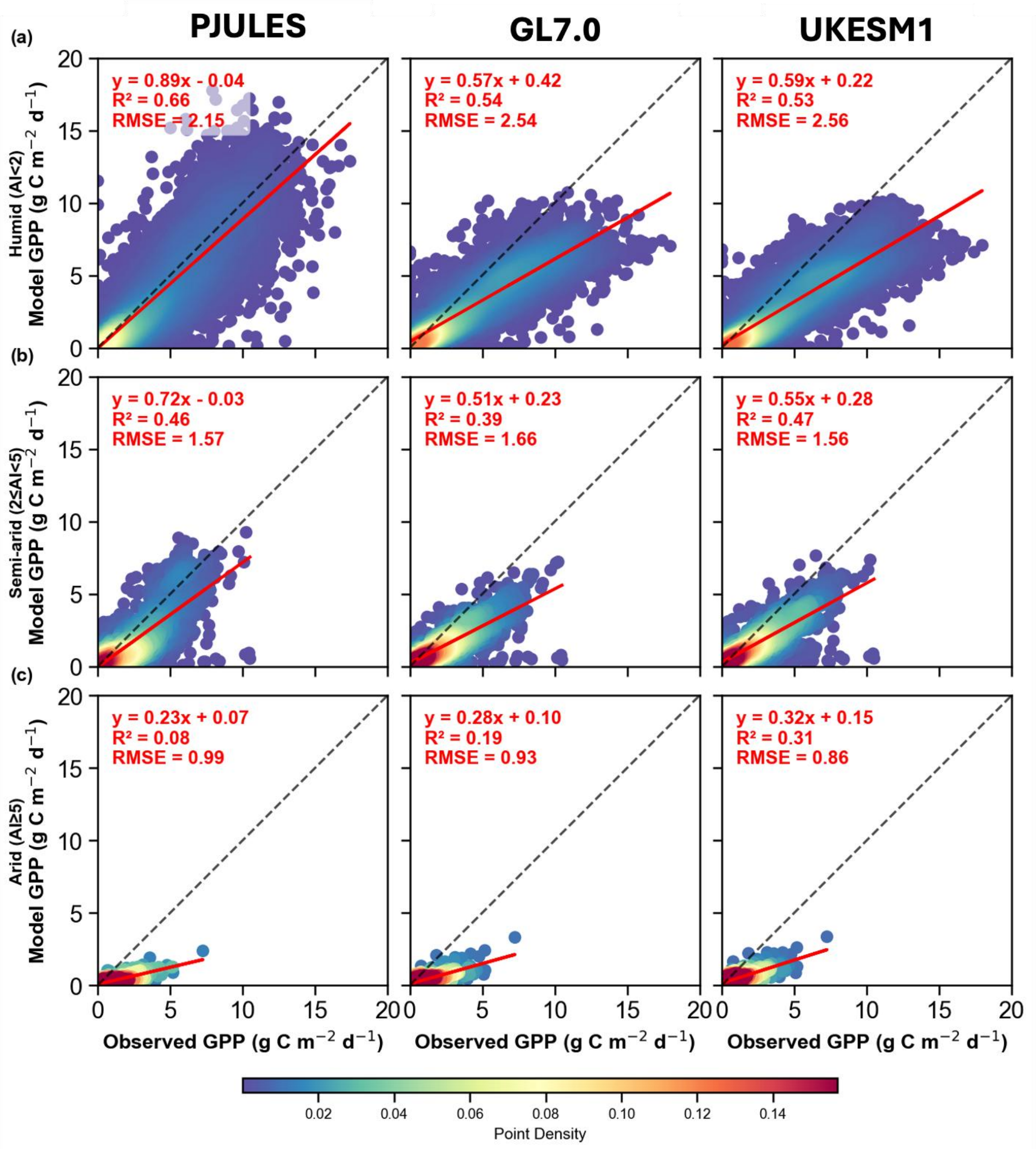
PJULES: R^2 = 0.46, RMSE = 1.69

GL7.0: R^2 = 0.32, RMSE = 2.00

UKESM1: R^2 = 0.26, RMSE = 1.95

Panel labels: P-model = PJULES, Multi-layer = GL7.0, Multi-layer 13 = UKESM1.

Performance advantage is strongest at humid sites all models degrade with aridity



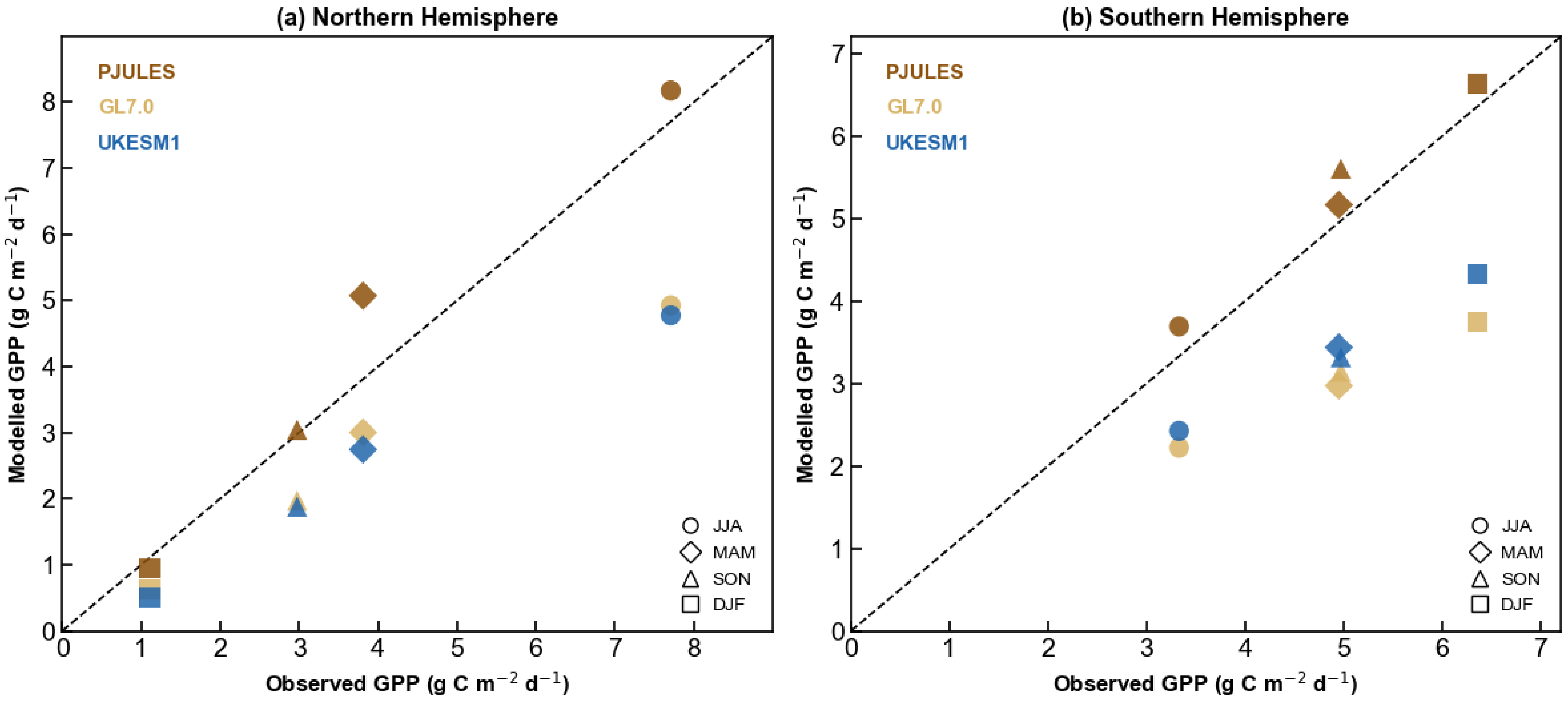
- PJULES performs best at humid sites (R^2 = 0.66, RMSE = 2.15)

All three models underestimate GPP with increasing aridity

Current soil moisture stress function (β) is likely too aggressive

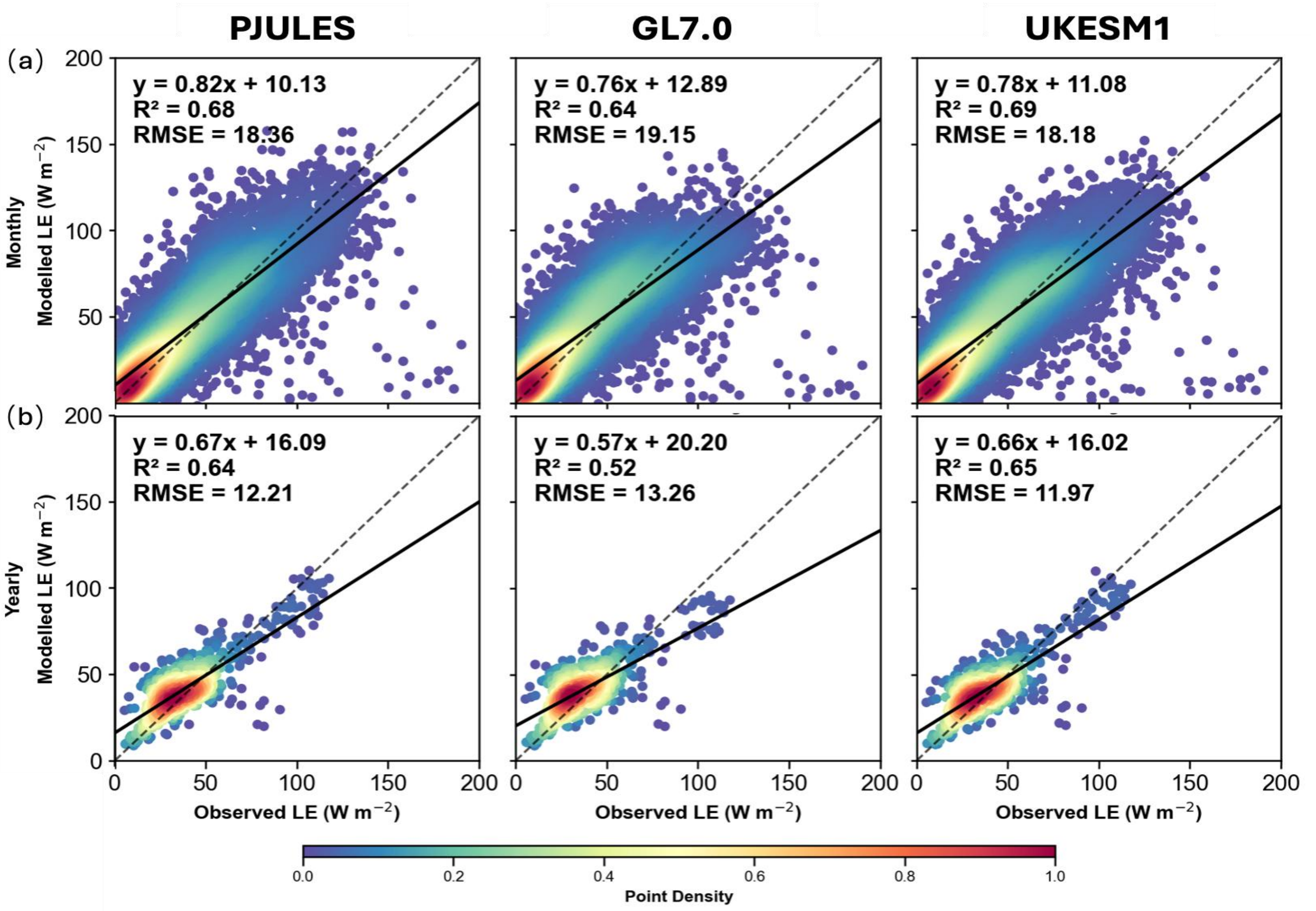
An aridity-adapted β scheme (Mengoli et al., 2025) is a clear next step

PJULES captures seasonal GPP cycles better than multi-layer configurations



- **Summer (JJA):** PJULES overestimates by only 6% vs 26–34% underestimation in GL7.0 and UKESM1
- **Spring (MAM):** PJULES overestimates by 33% — early green-up bias linked to phenology

Improved GPP simulation is not accompanied by degradation in latent heat flux



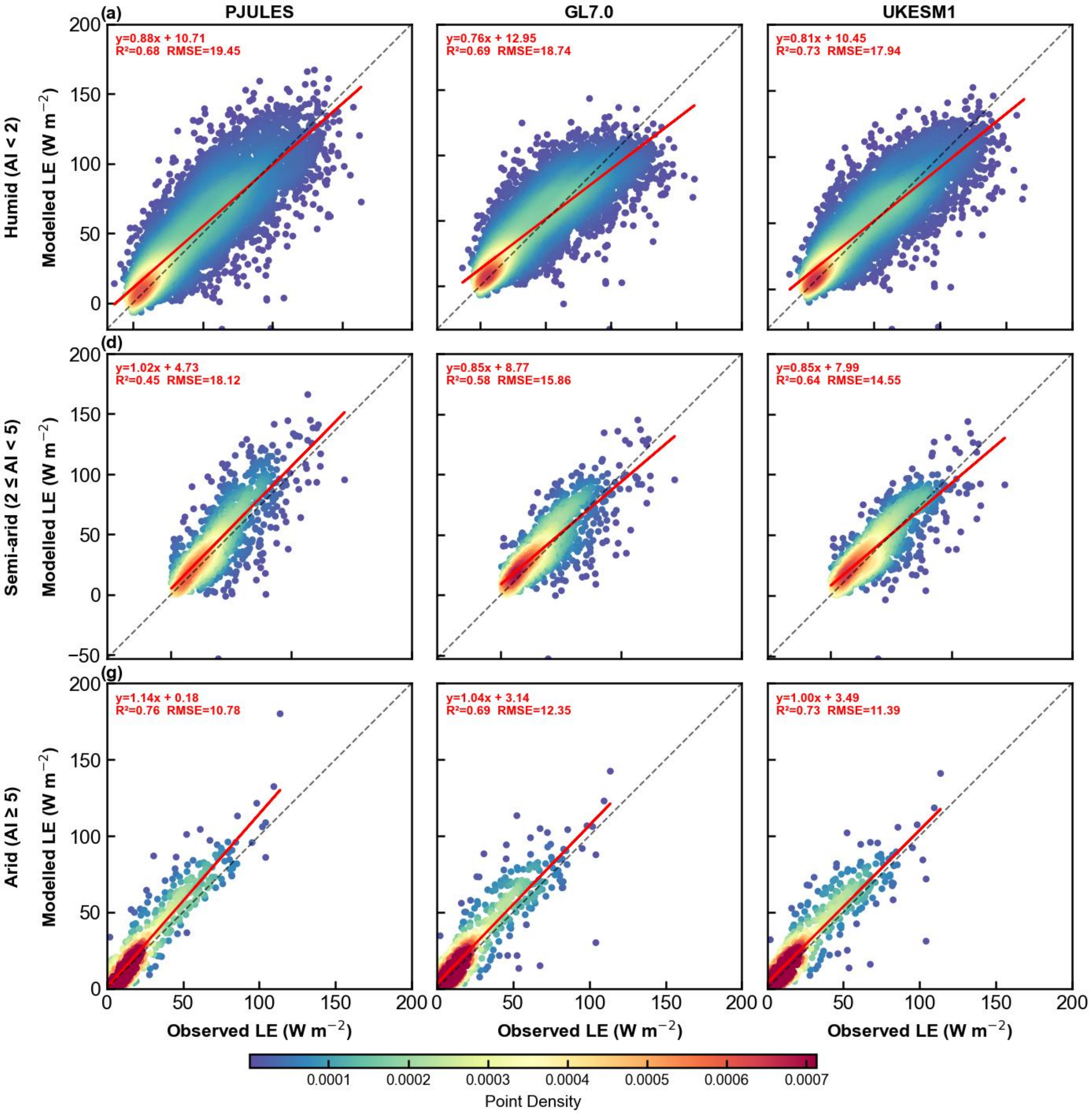
Implication

- PJULES produces a more physically consistent representation of carbon and water fluxes

GPP and LE improvements are not in tension — unlike empirical tuning approaches

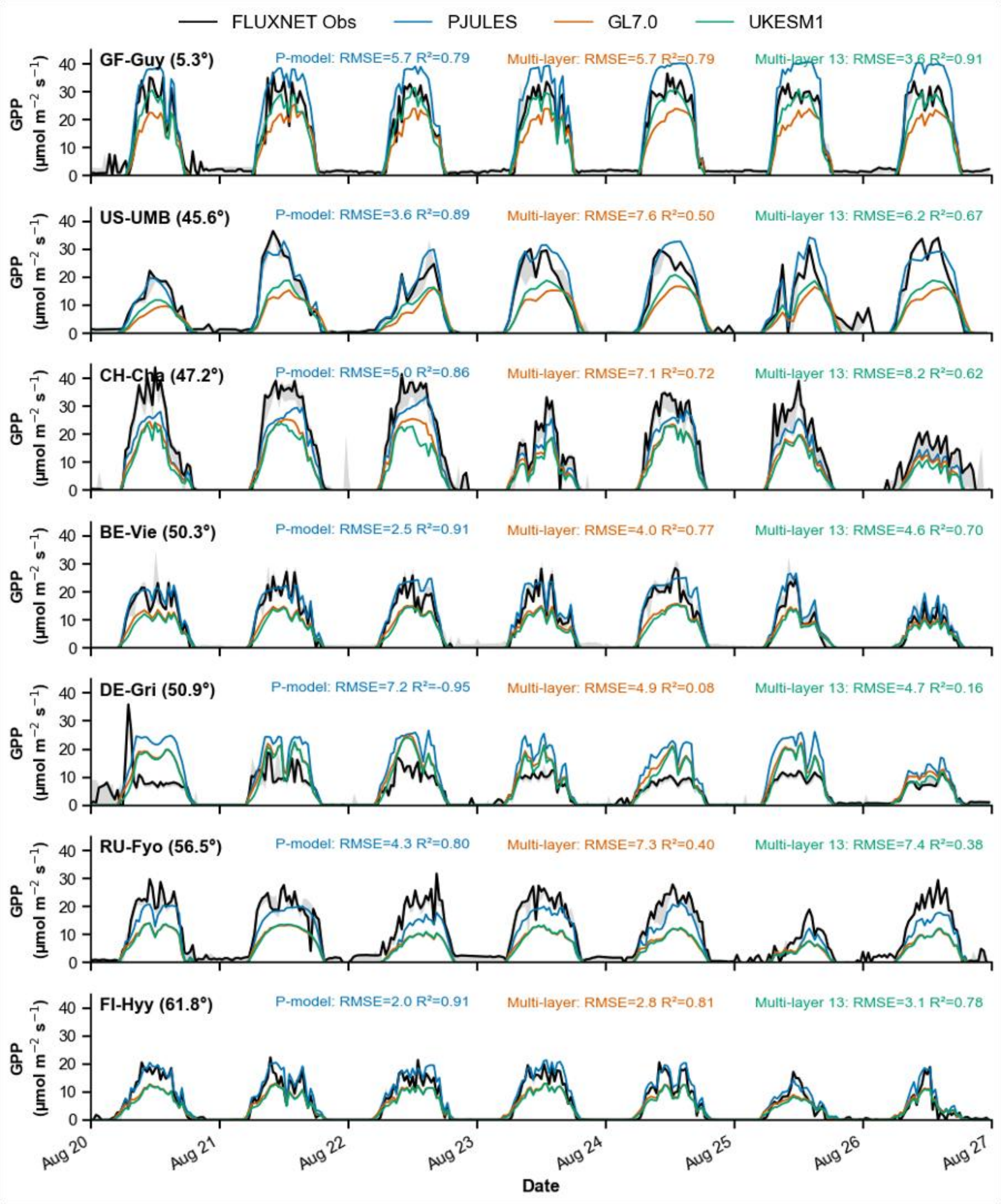
The optimality-based approach couples carbon and water at the mechanistic level through ξ

Latent heat flux is well simulated across aridity gradients; Better than carbon flux



- PJULES slope closest to 1:1 at humid (0.88) and semi-arid (1.02) sites
- R^2 values are comparable across models: differences in LE skill are much smaller than the GPP improvements seen with PJULES.

At arid sites, all three configurations perform similarly (R^2 = 0.69–0.76) — LE is less sensitive to photosynthesis scheme choice where soil evaporation dominates.

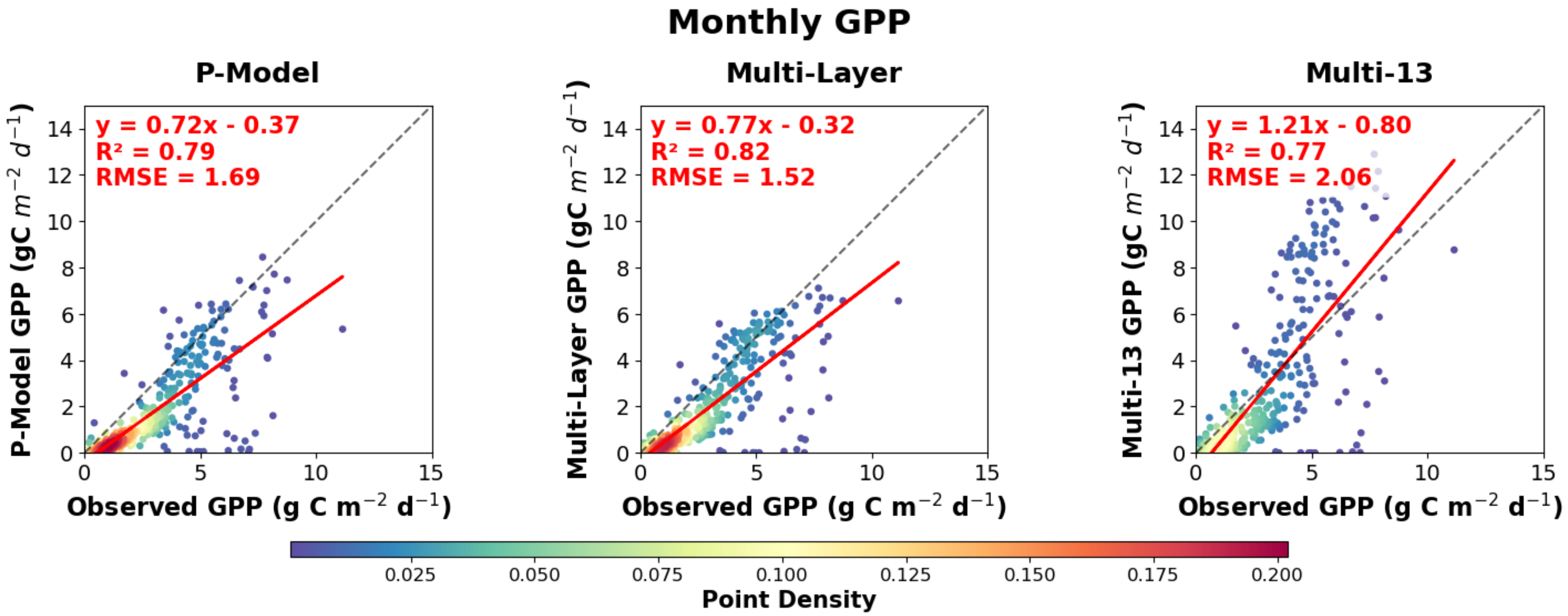


PJULES tracks the diurnal cycle better than multi-layer schemes

Half-hourly GPP over one week (20–27 Aug), seven sites ordered by latitude (5°N to 62°N).

- **Temperate & boreal forests:** PJULES best captures the timing and amplitude of the midday peak, with the highest R^2 and lowest RMSE at five of seven sites (FI-Hyy R^2=0.91, RMSE=2.0; BE-Vie R^2=0.91; US-UMB R^2=0.89).
- **Multi-layer schemes:** GL7.0 and UKESM1 underestimate midday GPP at most forest sites, flattening the daytime peak.
- **Tropical evergreen (GF-Guy):** PJULES overshoots the midday peak; the 13-PFT UKESM1 fits best here (R^2=0.91 vs 0.79)

C_4 performance is competitive without PFT-specific photosynthetic tuning

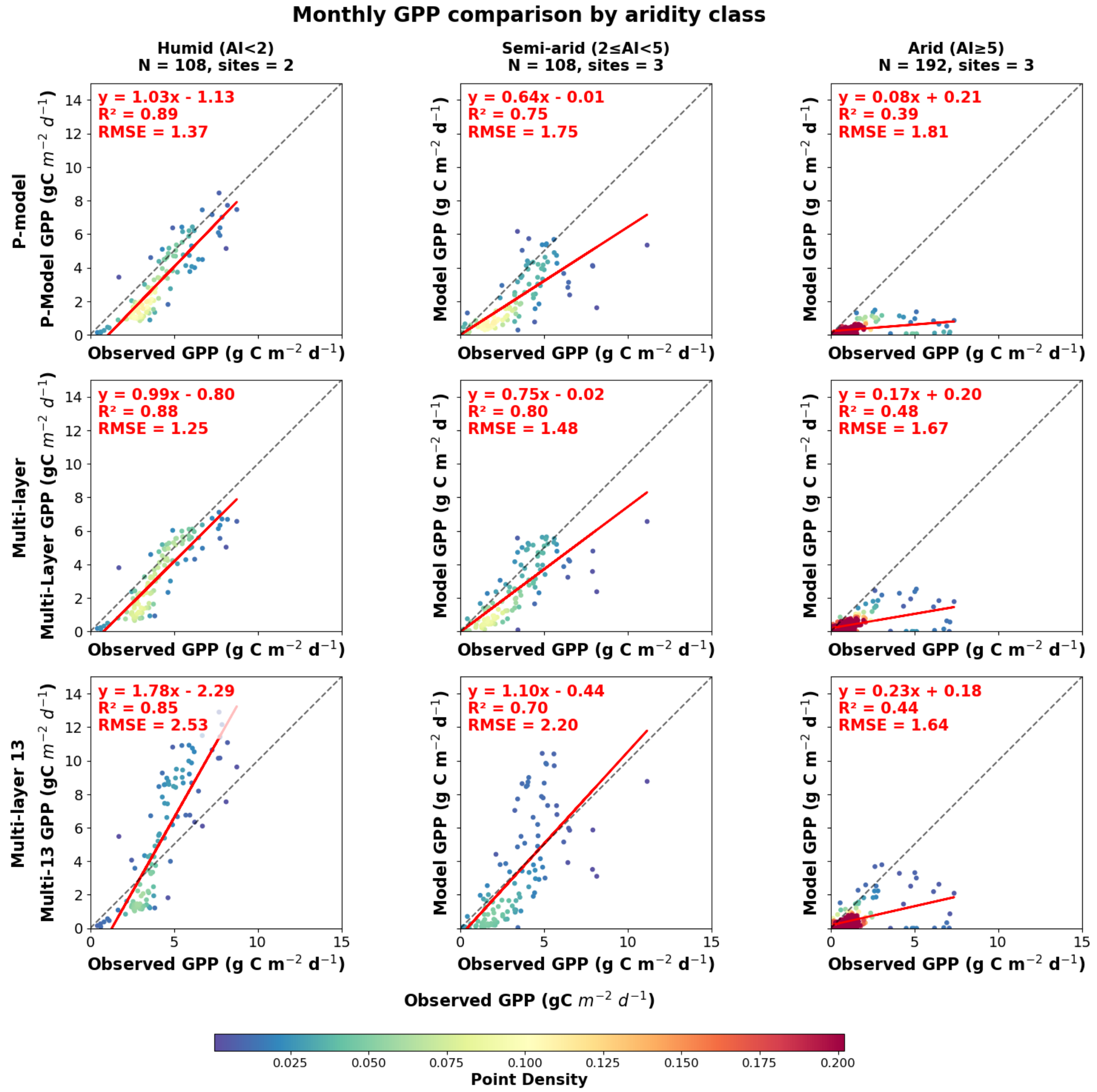


Monthly C4 GPP

PJULES: R^2 = 0.79, RMSE = 1.69
GL7.0: R^2 = 0.82, RMSE = 1.52
UKESM1: R^2 = 0.77, RMSE = 2.06

- PJULES slope = 0.72: comparable to the 5-PFT multi-layer scheme (0.77)
- UKESM1 (13 PFTs) overestimates by ~20% (slope = 1.21) at high C4 GPP

C4 humid-site performance similar to all schemes collapse at arid C4 sites



- PJULES sits closest to 1:1 at humid C4 sites (slope = 1.03, R^2 = 0.89)
- UKESM1 (13 PFTs) inflates humid C4 GPP by ~80% (slope = 1.78)
- All three schemes lose skill at semi-arid and collapse at arid ($R^2 < 0.5$, slope < 0.25)
- Same aridity bottleneck as C3: soil-moisture stress function (β) is the shared next step

What this means for JULES

Parameter-sparse

Replaces Collatz–Jacobs photosynthesis while keeping the wider JULES land-surface framework.

Carbon gains, water intact

Improves GPP with no degradation of water fluxes.

A clear next priority

Dry-site failure points to soil-moisture stress (β) as the process to fix next.

Looking Ahead: a JULES development pathway

1. Global configuration

   Align interfaces, namelists and diagnostics; add documentation and regression tests

   Site to global offline benchmarking

2. Coupled run

   coupled sensitivity, with GPP, ET and energy diagnostics with GCMs

3. Strengthen JULES drought responses

   Test aridity-adapted β and carbon–water coupling across dry sites and extremes

4. Dynamic LAI; phenology

   Prognostic LAI from the P-model optimality framework, coupled to the sub-daily scheme

Scan for the paper

C_3 and C_4 share the optimality framework but differ in biochemical constraints

C3

$$\xi = \sqrt{\frac{\beta (K + \Gamma^*)}{1.6\,\eta^*}}$$

$$\chi = \frac{\Gamma^*}{c_a} + \left(1 - \frac{\Gamma^*}{c_a}\right)\frac{\xi}{\xi + \sqrt{D}}$$

$$m_j = \frac{c_a - \Gamma^*}{c_a + 2\,\Gamma^*}$$

$$m_c = \frac{c_i - \Gamma^*}{c_i + K}$$

$$\beta \approx 146 \;\; (\mathrm{C_3\ constant})$$

C4

$$\xi = \sqrt{\frac{\beta K}{1.6\,\eta^*}}$$

$$\chi = \frac{\xi}{\xi + \sqrt{D}}$$

$$m_j = 1$$

$$m_c = \frac{\chi}{\chi + K/c_a}$$

$$\beta \approx 146/9 \approx 16.2 \;\; (\beta_{C_3} : \beta_{C_4} = 9 : 1)$$

MECHANISTIC INTERPRETATION • C_3 retains photorespiration (Γ^*) and Rubisco limitation; C_4 represents CO_2 concentration by setting $\Gamma^* \approx 0$ and modifying β. • Both pathways retain environment-driven χ/ξ and acclimation. • This is a parsimonious pathway distinction—not a claim that C_3 and C_4 are physiologically identical.