Carbon “IN” to terrestrial ecosystems

The P model: challenges we face and plan to address

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Posted on
26th February 2025

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Upscaling: From Leaf to Canopy

The P-model helps us to understand plant photosynthesis "writ large" (known as gross primary production, GPP) and so to bridge the gap from leaf-level processes to ecosystem-level measurements and global predictions. It starts with a pretty big assumption – the *big leaf approximation*. Essentially, we treat the entire canopy as if it's just one giant leaf. There's logic behind this – first articulated by (the late) Piers Sellers in the 1990s, although Graham Farquhar may have been the first to spell out the underlying mathematics.

Many empirical models use remotely sensed data on "greenness" to link GPP to absorbed light. Absorbed light is the product of incoming light and the fraction absorbed by green tissues, known as fAPAR, which is available from an increasing number of satellite-borne sensors. So-called light-use efficiency (LUE) models assume that GPP is equal to the product of absorbed light and LUE. This assumption has a strong empirical basis in findings on crop growth by John Monteith back in the 1970s. However, there are now many LUE models, which differ in how they estimate LUE.

At first sight, it seems counter-intuitive that GPP should be proportional to absorbed light. After all, it is well known that the response of photosynthesis to incident light is non-linear, saturating at high light. But that's the instantaneous response, which doesn't take account of the slower variation in photosynthetic capacity (known as photosynthetic acclimation) as light availability changes through the season; nor the analogous process by which leaves subject to different degrees of shading adopt photosynthetic capacities appropriate to their light environment. It turns out that for every light level, there is a photosynthetic capacity that yields a maximum rate of photosynthesis – once the finite cost of maintaining that capacity has been accounted for. And if leaves adopt that optimal capacity, the

https://research.reading.ac.uk/lemontree/the-p-model-challenges-we-face-and-plan-to-address/

Light use efficiency models

- GPP is the product of the absorbed PAR (PAR*fAPAR) and the efficiency by which PAR is converted to carbon (or LUE; µmol CO_2 µmol PAR^{-1})

$$GPP = LUE \ * PAR * fAPAR$$

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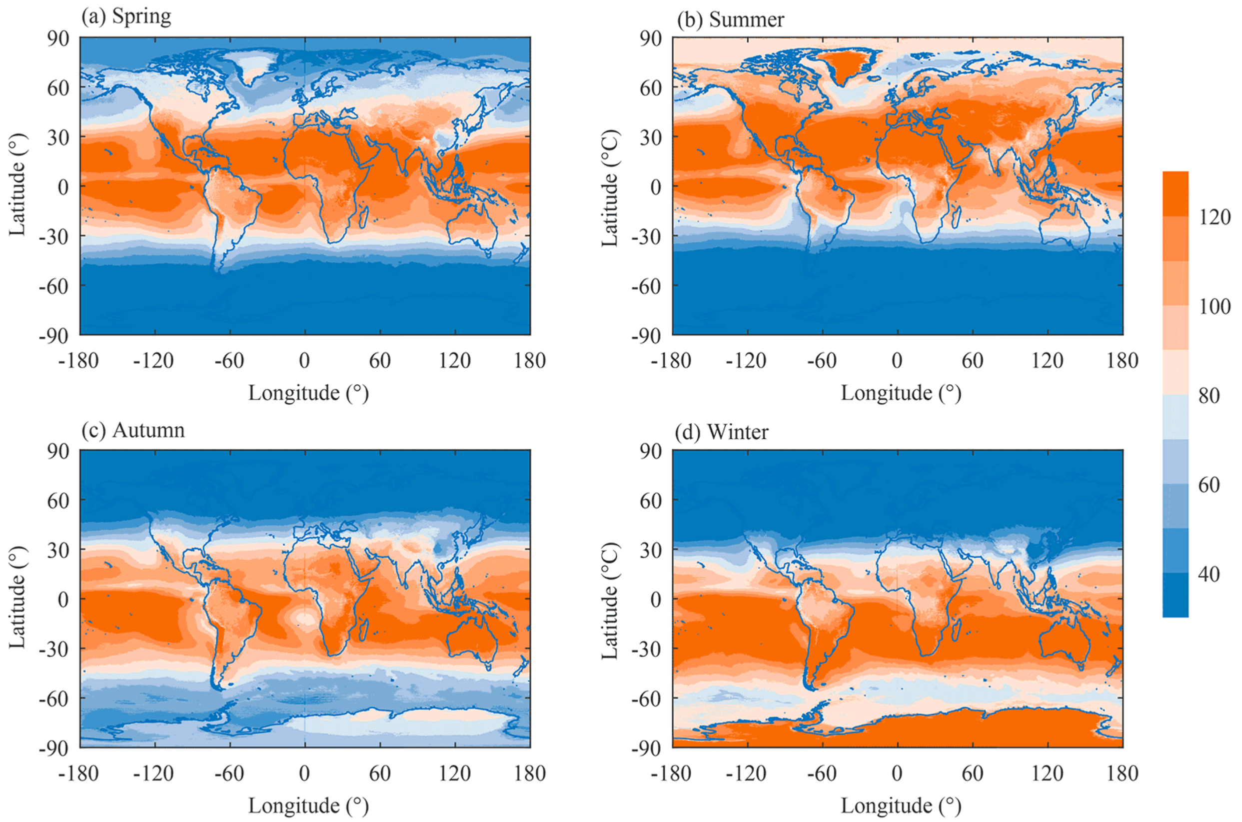
PAR

- Photosynthetically active radiation reaching the top of the canopy



Tang et al. (2022)

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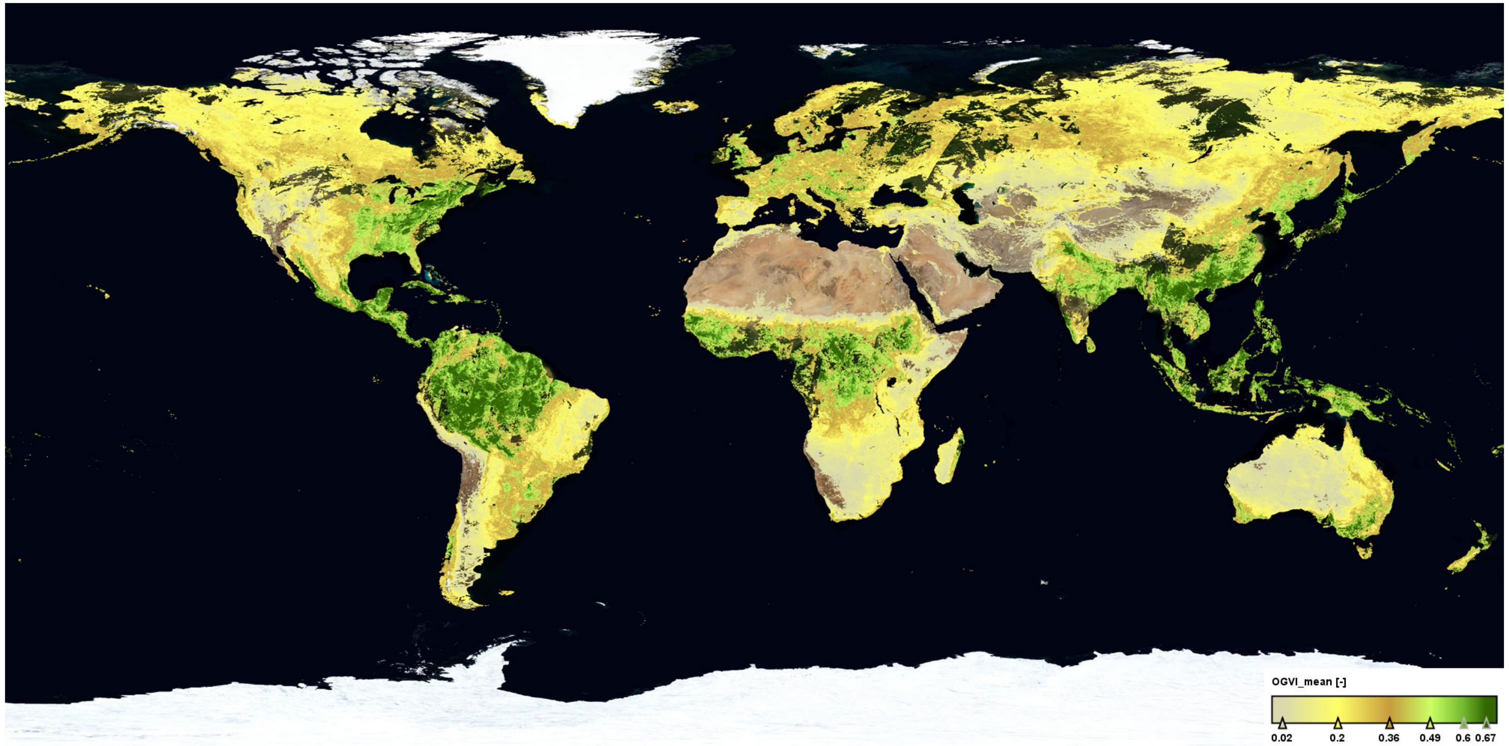
fAPAR

- Fraction of absorbed photosynthetically active radiation
- How much PAR is absorbed by the canopy relative to how much hits the canopy



Sentinel (ESA)

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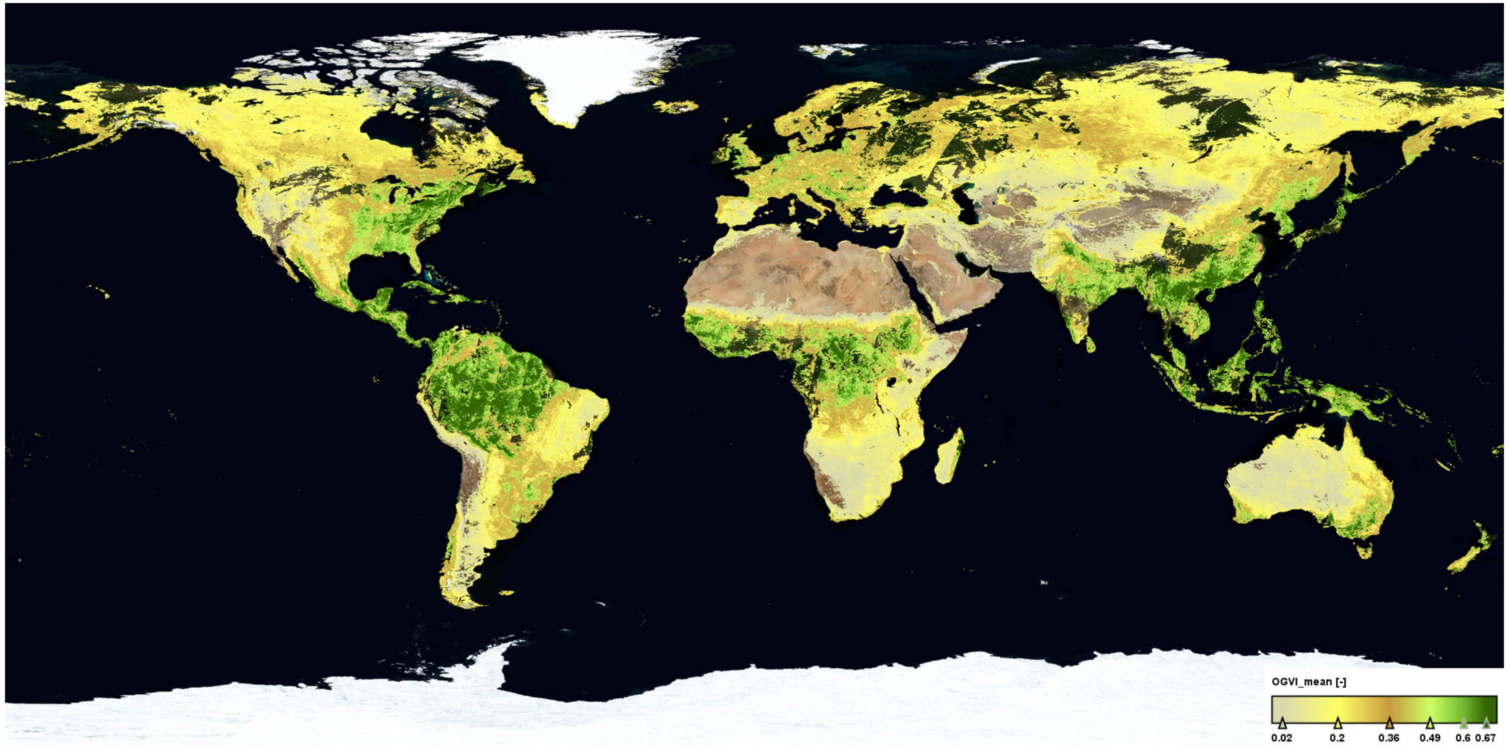


What drives fAPAR variability?

Sentinel (ESA)

Light use efficiency models

- GPP is the product of the absorbed PAR (PAR*fAPAR) and the efficiency by which PAR is converted to carbon (or LUE; µmol CO_2 µmol PAR^{-1})

$$GPP = \color{red}{LUE} * PAR * fAPAR$$

Light use efficiency

- This is a critical term in the model that generally tends to:
  - Increase with decreasing light
  - Vary parabolically with temperature
  - Increase with CO_2
- Depends on
  - Photosynthetic biochemistry
  - Stomatal conductance
  - Intrinsic quantum efficiency of photosynthesis

An approach for mechanistically modeling GPP across scale: the P-model

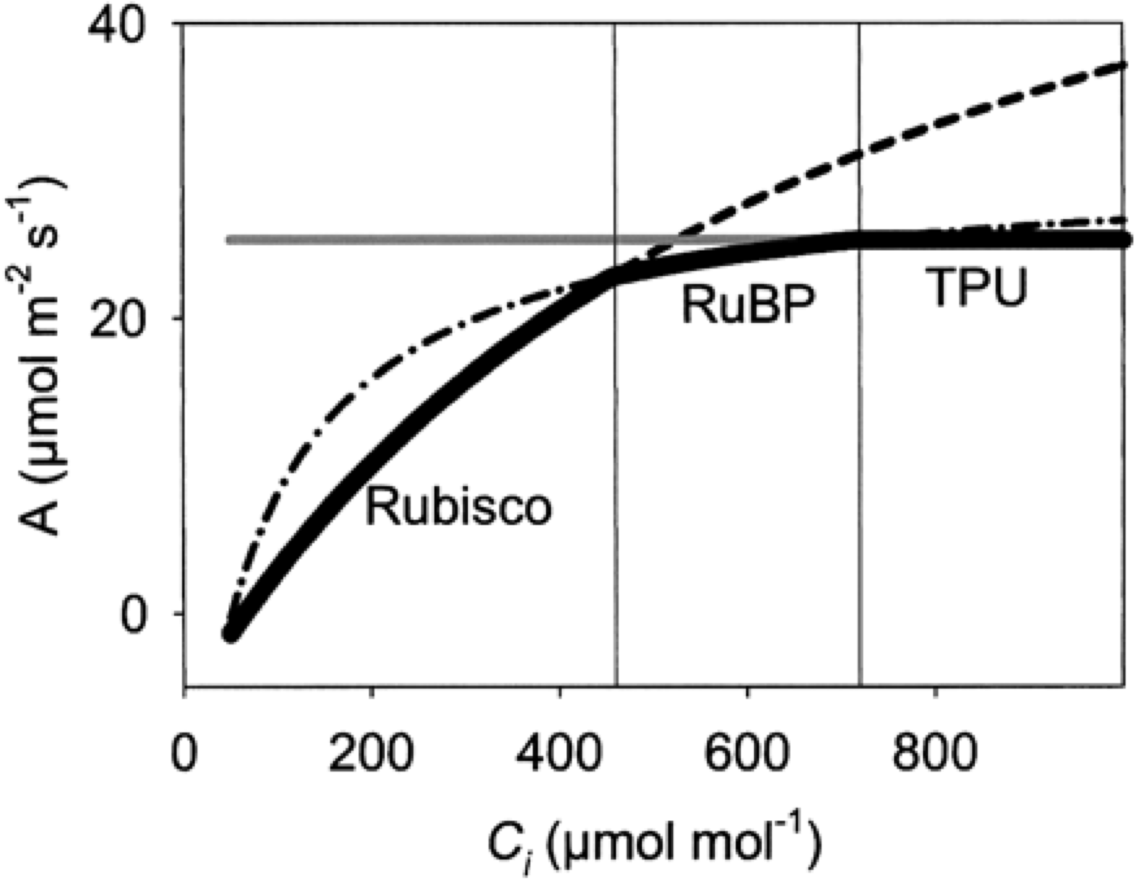
The Farquhar von Caemmerer and Berry (1980) or FvCB model

The FvCB model

$$A = min\{A_c, A_j\}$$

$$A_c = V_{cmax}\frac{c_i - \Gamma^*}{c_i + K}$$

$$A_j = \varphi I\frac{c_i - \Gamma^*}{c_i + 2\Gamma^*}$$



Long et al. (2003)

The FvCB model

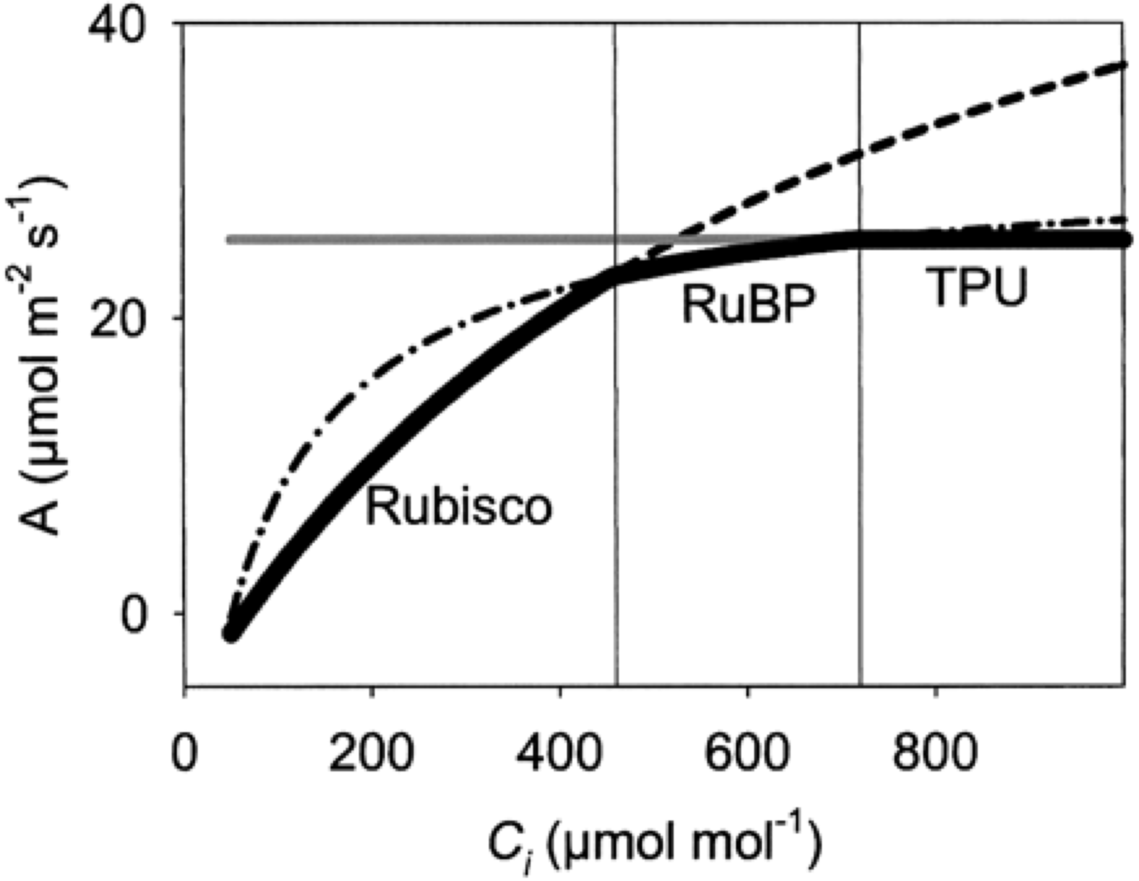
Some variables have known environmental dependencies

Some can be predicted by EEO

$$A = min\{A_c, A_j\}$$

$$A_c = V_{cmax} \frac{c_i - \Gamma^*}{c_i + K}$$

$$A_j = \varphi I \frac{c_i - \Gamma^*}{c_i + 2\Gamma^*}$$



Long et al. (2003)

Key trait predictions

Optimally…

- $A_c = A_j$
  - This allows for a lot of simplifications!
- $a \frac{\delta \frac{E}{A}}{\delta x} + b \frac{\delta \frac{Vcmax}{A}}{\delta x} = 0$
  - $\chi = \frac{\xi}{\xi + \sqrt{D}}$
  - $\xi = \sqrt{\frac{b(k + \Gamma^*)}{1.6a}}$
  - $\chi = \frac{c_i}{c_a}$

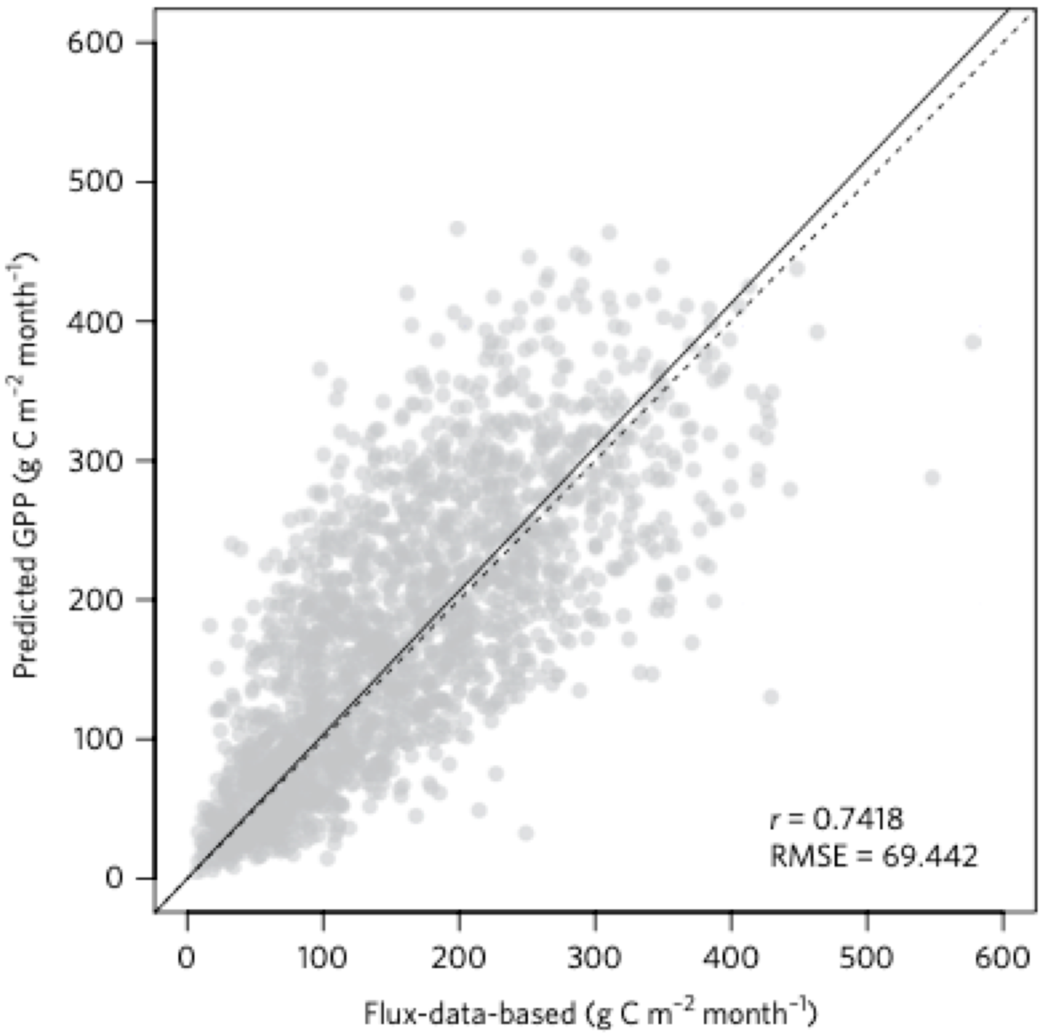


Fig. 3 | Monthly GPP at flux sites. Predictions from equations (2) and (3); observations based on CO_2 flux data in the FLUXNET archive. The solid line is the regression through the origin; the dashed line is the 1:1 line.

Wang et al. (2017)

Tying back to LUE

$$GPP = LUE \; * PAR * fAPAR$$

$$GPP = \varphi * m * m' * PAR * fAPAR$$

$$m = \frac{c_i - \Gamma^*}{c_i + 2\Gamma^*}$$

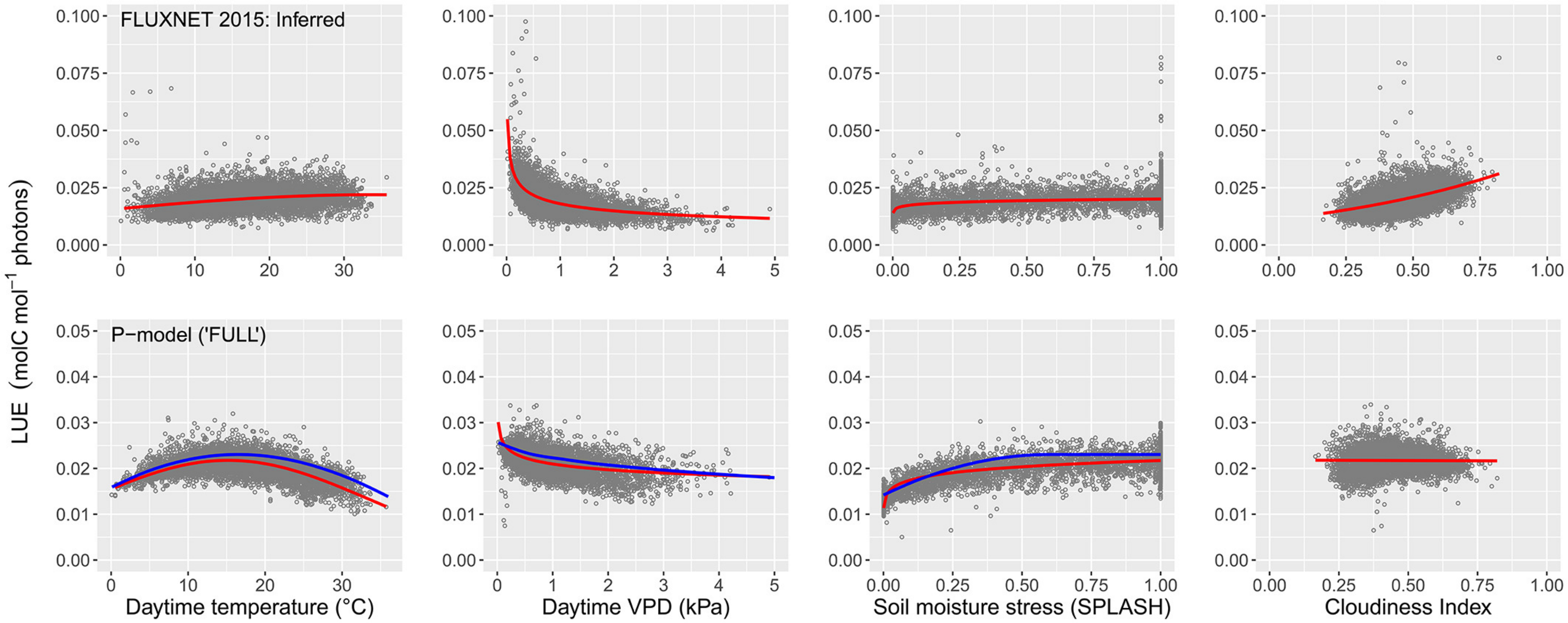
$$m' = \sqrt{1 - \left(\frac{c}{m}\right)^{2/3}}$$

Strengths of the P-model

- No PFTs
- Applicable to any environment
- Requires
  - fAPAR (can be satellite derived)
  - Light, temperature, atmospheric pressure, VPD

Challenges and limitations

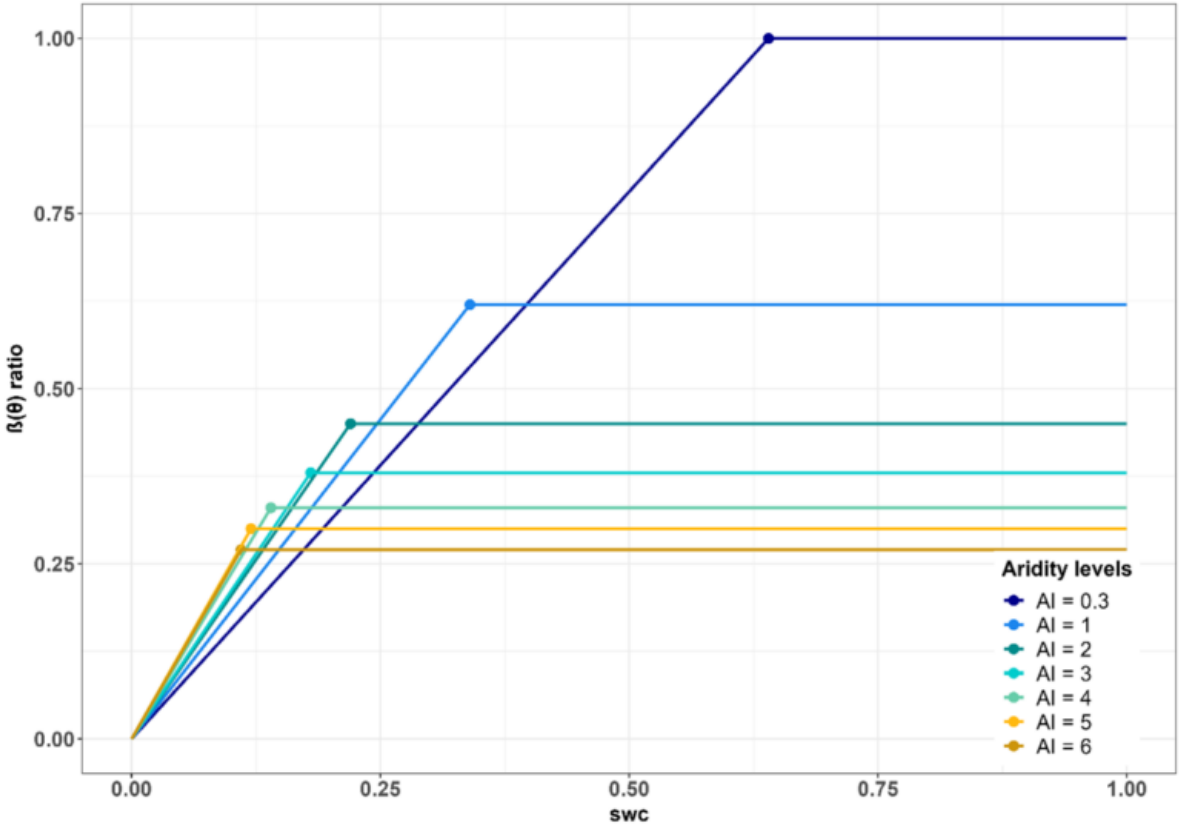
- Temperature dependence of ϕ
- Diffuse radiation



Bloomfield et al. (2023)

Challenges and limitations

- Temperature dependence of ϕ
- Diffuse radiation
- Soil water stress
- Soil nutrients



Mengoli et al. (2025)