

Response to Reviewers

Article Ref.: *essd-2026-161*

Mapping Plant Growth Index (PGI) over Australia from 1990 to 2024

Earth System Science Data

Reviewer #2

In the manuscript “Mapping Plant Growth Index (PGI) over Australia from 1990 to 2024”, Retkute et al. designed the Plant Growth Index (PGI), which is primarily constrained by meteorological conditions across different plant functional types, and used PGI to characterize vegetation productivity patterns across the Australian continent. The topic is important, and the results and figures are generally clear and easy to follow. However, in its current form, the manuscript is not yet suitable for publication in *Earth System Science Data* because the methodological novelty and robustness remain insufficiently demonstrated.

Response:

We thank the reviewer for the insightful suggestions, feedback, and the time they have dedicated to review our manuscript. We have provided a point-by-point response below, addressing each specific comment and suggestion.

Major comments

R2MC1

A major methodological concern is that the proposed PGI framework may not be suitable for representing vegetation productivity across the strong bioclimatic heterogeneity of Australia. As the authors themselves note, Australia spans a wide range of climate and ecosystem types, from tropical systems to temperate woodlands, arid deserts, and alpine environments. The dominant controls on plant growth are therefore unlikely to be spatially uniform. For example, tropical ecosystems may be more strongly constrained by energy availability, whereas inland arid systems are primarily water-limited.

In this context, defining PGI as the simple product of the Light Index, Temperature Index, and Moisture Index imposes a common structural assumption across all regions. Even if each component is normalized to a 0–1 range, the framework still assumes that these three controls can be integrated in the same multiplicative way across ecosystems with fundamentally different limiting mechanisms. This assumption is not sufficiently justified in the manuscript.

Response:

We thank the reviewer for this thoughtful critique. We agree that Australia exhibits strong bioclimatic and ecological heterogeneity, and that dominant controls on vegetation growth are unlikely to be spatially uniform. The PGI framework does not assume identical vegetation responses across Australia; rather, it attempts to partially account for ecosystem differences through the explicit incorporation of plant functional type fractions and seasonally varying component responses. Nevertheless, we acknowledge that a common multiplicative formulation may not capture all biome-specific growth controls equally well.

Action:

In the revised manuscript, we provide a stronger ecological justification for the multiplicative formulation. We have clarified that the framework assumes partially independent and multiplicative limitations, and discuss how the suitability and limitations of this assumption may vary across ecosystems and biomes

R2MC2

Importantly, the authors' own evaluation results appear to support this concern. The reported correlations between PGI and GPP vary substantially across sites, ranging from $r = 0.08$ to 0.94 , with a median of $r = 0.66$. In several ecosystems, especially the Wet Tropics ($r = 0.12$ – 0.25) and some coastal and semi-arid regions, the relationship is weak, indicating that PGI does not consistently capture productivity dynamics across biomes. These results suggest that the performance of PGI is highly ecosystem-dependent, rather than robust at the continental scale. This weakens the claim that PGI can serve as a general indicator of vegetation productivity patterns across Australia.

Response:

We agree that benchmarking performance varies across sites and ecosystems, and that some environments (e.g. Wet Tropics and several coastal or semi-arid systems) exhibit relatively weak PGI–GPP relationships. However, this ecosystem dependence is not unique to PGI. We

conducted comparable benchmarking analyses for NDVI, SPEI and Aussie-GRASS and observed similar patterns of spatially variable performance across sites and biomes.

We acknowledge that OzFlux GPP represents the best available benchmarking dataset, but it also has important limitations. GPP is not directly measured; it is inferred from eddy covariance measurements of net ecosystem exchange (NEE), and the tower footprint typically extends to only hundreds of metres, whereas PGI is evaluated at 12 km spatial resolution. Ideally, benchmarking would involve vegetation productivity or biomass observations at spatial scales comparable to the index itself, but we are not aware of any such dataset with continental Australian coverage.

Action:

In the revised manuscript, we have expanded the Discussion to more explicitly address ecosystem-dependent benchmarking performance, including strengths, limitations and differences across sites and biomes.

R2MC3

The manuscript should provide a much stronger ecological justification for using a uniform multiplicative framework, and should more explicitly discuss the limitations of applying the same index structure across water-limited, energy-limited, and seasonally constrained ecosystems. Additional biome-specific evaluation or sensitivity analysis would also be needed to demonstrate robustness. The authors could also highlight the novelty regarding detailed design of TI that incorporates PFT, and be more specific in recommending the reliability of PGI, i.e., whether they are most reliable in grasslands or across different biomes and climate zones.

Response:

We thank the reviewer for these constructive suggestions. We agree that the ecological applicability of a common multiplicative framework across strongly contrasting Australian ecosystems merits clearer justification and discussion. We also agree that the design of the Temperature Index, including explicit incorporation of PFT information, represents an important feature of the framework that could be better highlighted.

Action:

In the revised manuscript, we have strengthened the ecological justification for the multiplicative formulation, we have expanded discussion of its biome-dependent strengths and

limitations, and now more clearly discuss the role of the PFT-based TI design and the likely domains of strongest PGI applicability across ecosystems and climate zones.

R2MC4

A second major concern is that the PGI framework only considers contemporaneous meteorological conditions and therefore cannot capture important lagged ecological responses or major disturbance effects. In many Australian ecosystems, vegetation productivity is not determined solely by current-day light, temperature, and moisture conditions. Instead, it is often influenced by antecedent environmental conditions, including prior rainfall, soil moisture storage, plant physiological carryover, and broader lag effects that can persist from weeks to seasons. A substantial body of literature (e.g. <https://doi.org/10.1029/2022JG007144> , <https://doi.org/10.5194/bg-19-1913-2022>) has shown that such lagged effects can be as important as, or even more important than, concurrent climate drivers in regulating vegetation productivity.

Response:

We thank the reviewer for highlighting this important concern. The cited studies (Cranko Page et al., 2022, 2023) demonstrate that antecedent meteorological conditions, particularly rainfall and soil moisture, can significantly influence ecosystem productivity and carbon–water fluxes, and that such lagged effects may be as important as concurrent drivers. We fully acknowledge that vegetation productivity in Australian ecosystems is shaped by prior rainfall, soil moisture carryover, plant physiological memory, and major disturbance events such as fire.

The current PGI framework is intentionally designed as a contemporaneous index of meteorological suitability for plant growth, rather than as a full ecosystem or vegetation dynamics model. Its purpose is to provide a transparent, real-time and forward-looking indicator based on current and near-future meteorological conditions, rather than to simulate lagged ecological responses, disturbance recovery, or long-term ecosystem memory.

Action:

In the revised manuscript, we have expanded the Discussion to more explicitly address the absence of lagged ecological processes and disturbance effects in the current PGI framework, including the implications, limitations, and potential directions for future model development. We have also clarified the role of PGI as a contemporaneous index of meteorological suitability for plant growth, rather than as a full ecosystem or vegetation dynamics model.

R2MC5

In addition, the framework does not account for fire disturbance, which is a major driver of vegetation dynamics in Australia, particularly in northern savanna ecosystems. Fire strongly affects canopy structure, biomass, phenology, and post-disturbance recovery, and can therefore decouple observed productivity from the meteorological conditions represented in PGI. Ignoring fire disturbance is likely to reduce the ecological realism of the index in fire-prone regions and may partly explain some of the weaker PGI-GPP relationships reported across sites.

These omissions raise further concerns about the robustness of PGI as a continent-wide representation of vegetation productivity. The authors should more clearly acknowledge that PGI reflects only immediate meteorological suitability, and should discuss the implications of excluding lag effects and disturbance processes. Ideally, they should also evaluate how these factors may affect PGI performance across different biomes.

Response:

We agree that fire is a major driver of vegetation dynamics in many Australian ecosystems, particularly savannas and other fire-prone regions. Fire can strongly alter canopy structure, biomass, phenology and recovery trajectories, and may therefore weaken or decouple relationships between meteorological suitability and observed vegetation productivity.

However, the current PGI framework is intentionally designed as a **meteorological suitability index**, rather than a vegetation disturbance or ecosystem dynamics model. Accordingly, processes such as fire disturbance, post-fire recovery and lagged ecological responses are not explicitly represented. Incorporating such processes would require additional datasets and modelling components (e.g. burned area, vegetation recovery trajectories).

Action:

In the revised manuscript, we have expanded the Discussion to more explicitly address the implications of excluding lagged ecological responses and fire disturbance from the current PGI framework, including potential effects on benchmarking performance across ecosystems and biomes.

R2MC6

Another important methodological concern is the inconsistent treatment of plant acclimation across the three PGI components. For the Temperature Index (TI), the manuscript adopts plant

functional type (PFT)-specific thermal response parameters, including T_{min} , T_{opt} , and T_{max} . This implicitly acknowledges that plant responses to temperature are not universal, but differ among vegetation types and may shift through physiological acclimation and ecological differentiation. This is a reasonable and ecologically meaningful choice.

However, a similar level of ecological realism is not applied to the Light Index (LI) or Moisture Index (MI). This is problematic because acclimation to light and water availability is also fundamental to plant growth and productivity. Both light and moisture responses, like temperature responses, often involve an optimum range rather than a simple monotonic “more is better” relationship. For light, photosynthesis commonly saturates beyond a certain level, and the most favourable radiation environment depends on canopy structure, shade tolerance, and acclimation state <https://doi.org/10.1038/s41559-020-1258-7>. For soil moisture, both insufficient and excessive water availability can constrain growth, and the effective optimum may differ among ecosystems and vegetation types <https://doi.org/10.1038/s41467-024-54156-7>. Therefore, maximum light availability or maximum soil moisture should not automatically be interpreted as the most favourable conditions for plant growth.

Response:

We agree with the reviewer that acclimation to light and moisture are important aspects of plant physiology, and that responses to both drivers may involve optima, saturation effects and ecosystem dependence. In the current framework, the treatment of temperature is more explicitly PFT-dependent than the treatments of light and moisture.

For LI, the relationship with irradiance is not necessarily monotonic, because daily irradiance is rescaled relative to the 95th percentile for each pixel and day of year, which acts as a partial censoring of excessive light availability (i.e. a light saturation effect). By contrast, the current MI formulation is intentionally simpler and does not explicitly represent moisture acclimation, excess water limitation, or ecosystem-specific moisture optima.

Action:

In the revised manuscript, we now more explicitly discuss the differing treatment of acclimation across TI, LI and MI, including the rationale, limitations, and implications of not explicitly representing light and soil moisture acclimation in the current framework.

R2MC7

The current framework appears conceptually unbalanced. The TI formulation recognizes that vegetation-specific responses matter and explicitly represents an optimum-based response curve, yet LI and MI appear to rely on a much more generalized representation of light and moisture limitation. If the authors argue that temperature responses require PFT-specific parameterization because of acclimation and ecological differences, then it is unclear why comparable acclimation, optimum ranges, or trait-based differentiation are not considered for light and moisture. This asymmetry weakens the ecological consistency of the PGI framework and raises concerns about whether PGI provides an ecologically balanced representation of plant growth constraints across Australia.

Response:

We agree that there is asymmetry between the parameterisation of TI, LI and MI. Temperature responses are comparatively well studied and parameterised across plant functional types, whereas light and moisture responses are often more complex, context dependent, and less consistently represented at continental scale. We also acknowledge that this asymmetry may affect the ecological balance of the framework.

Action:

We have revised the MI methodology to use multi-layer soil moisture information with PFT-dependent weighting across soil depths, providing a more ecologically differentiated treatment of moisture limitation. In the revised manuscript, now explicitly clarify the remaining asymmetries between TI, LI and MI, including their rationale and limitations.

Minor comments

R2mC1

L75: The factor should be 0.0036 rather than 0.036.

Response:

We thank the reviewer for catching this typo. The correct factor is indeed 0.0036.

Action:

This has been corrected in the revised manuscript.

R2mC2

L100: The manuscript should explain why the ESA CCI PFT product was selected, rather than other possible alternatives such as IGBP-based PFT classifications or the Australian NVIS dataset. Because PFT information directly affects the TI parameterization and hence PGI, this is an important methodological choice that deserves clearer justification.

Response:

Two key factors in our choice of the ESA CCI PFT dataset were its temporal coverage (1992–2020) and the availability of fractional PFT cover information. By contrast, the IGBP-based MODIS MCD12Q1 product covers 2001–2024 but provides only a dominant annual PFT class. The Australian NVIS dataset offers higher (~100 m) spatial detail but is largely static, representing a more limited temporal snapshot of vegetation distribution. Given that PFT information directly affects TI parameterisation, we agree that this methodological choice warrants clearer justification.

Action:

In the revised manuscript, we have added a brief paragraph in the Methods section explicitly justifying the selection of the ESA CCI PFT product relative to alternative datasets.

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R2mC3

L130: The authors should clearly specify which GPP partitioning product was ultimately used for the flux tower validation (e.g., LT/DT, or SOLO).

Response:

For the flux tower validation, we used the **LT (light-use efficiency)** GPP partitioning product.

Action:

In the revised manuscript, we explicitly specify this in the Methods section.

R2mC4

L150: The symbol used for Pearson’s correlation coefficient is usually r rather than ρ . Using ρ may cause confusion, as it is often reserved for the population correlation coefficient or Spearman’s rank correlation.

Response:

We thank the reviewer for their recommendation.

Action:

We have changed **p** to **r** throughout the manuscript to avoid confusion with population or rank correlation notation.

References

Cranko Page, J., De Kauwe, M. G., Abramowitz, G., Cleverly, J., Hinko-Najera, N., Hovenden, M. J., ... & Ogle, K. (2022). Examining the role of environmental memory in the predictability of carbon and water fluxes across Australian ecosystems. *Biogeosciences*, *19*(7), 1913-1932.

Cranko Page, J., De Kauwe, M. G., Abramowitz, G., & Pitman, A. J. (2023). Non-stationary lags and legacies in ecosystem flux response to antecedent rainfall. *Journal of Geophysical Research: Biogeosciences*, *128*(5), e2022JG007144.