
Author response

How beech ecophysiology shapes temperate forest gross primary productivity – Part 1: A wavelet-based framework for extracting seasonal dynamics

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Dear Editor and Referees,

We sincerely thank you for your constructive comments and suggestions, which helped us improve the quality and clarity of the manuscript. In the following pages, we provide a detailed response to all referee comments and indicate the corresponding changes made in the revised manuscript. The content is identical to that already provided in the author comments posted during the interactive discussion but has been reorganized to facilitate the assessment of manuscript changes.

For ease of consultation, this document is organized into two categories according to the extent of the resulting revisions: major changes and minor changes. Within each category, comments are presented following the chronological order of the corresponding sections in the manuscript. Comments addressing the same section of the manuscript have been regrouped while preserving separate responses for each referee. For conciseness, figures have been omitted from the present document, as all updated figures are included in the revised manuscript.

Throughout the document, referees are identified using **R#** (e.g. R1, R2) followed by:

- i. **C#**: general comment number, according to the structure adopted by the referee;
- ii. **L#**: line-by-line comment referring to the corresponding line number;
- iii. **Figure #**: comment related to a specific figure;
- iv. **Table #**: comment related to a specific table.

For line-by-line, figure and table comments, numbering refers to the preprint version of the manuscript.

All modifications made in the manuscript are indicated at the end of each response and introduced by the symbol “↔”. References to sections, figures, and tables in the revised manuscript are highlighted in **blue**. Line numbers in **blue** refer to the tracked-changes version of the revised manuscript.

Sincerely,

The authors

Major changes

Indicator definition and methodological refinement

R1; C1: “Refining interpretation and reducing uncertainties: In Section 2.2, the selection procedure involves adjusting the WT to align coefficient values with a given interpretation, while a wide range of possible alternatives exists and is described in Supplement S3. However, none of these alternative approaches are tested using the data presented in the manuscript, nor is a clear justification provided for the selection of the specific method adopted by the authors.”

We thank the referee for raising this point, which highlights the need to clarify the role of the refinement step and its relationship with the Supplement.

The strategies described in Supplement S3 are not independent or unused options; rather, they are explicitly implemented within the definition of the three indicators (Sect. 2.3.3):

- IRise combines wavelet modification (DOG1), adjustment of the analysis period (3 months) and signal normalization (amplitude).
- IPeak combines wavelet modification (Gaussian-based) and adjustment of the analysis period (7 months).
- IDrop implements a combination of coefficients (ratio between June and November coefficients).

More generally, Supplement S3 defines a methodological framework for adapting the wavelet transform so that coefficients isolate specific signal features. The indicators used in this study correspond to targeted implementations of these strategies, chosen for their clear ecophysiological interpretation and their ability to describe complementary phases of the GPP seasonal cycle.

As shown in Sect. 2.3.3 and Supplement S4, alternative constructions produce comparable results, provided they remain consistent with the underlying signal feature. This behavior is expected, as the wavelet transform can be interpreted as a filtering operation: different wavelets with similar structures act as comparable temporal filters and extract similar features. To further address this point, we have complemented the manuscript with a quantitative sensitivity analysis, demonstrating that the indicators remain robust across a range of wavelet types and analysis periods (see comment n°2). This confirms that the ecological interpretation is not sensitive to specific parameter choices, if consistency between wavelet shape and signal structure is maintained.

The purpose of introducing multiple possibilities in Supplement S4 was therefore not to suggest arbitrariness, but rather to illustrate the versatility and extensibility of the framework. In the present study, we deliberately focused on three indicators because they directly map onto key phases of the seasonal GPP cycle, provide a coherent and complementary description of seasonal dynamics and remain robust and interpretable across sites.

⇒ **Changes in Manuscript:** To clarify these points in the manuscript, we have:

- i. **Sect. 2.3.3 (L262; L271–310); Supplement S3:** strengthened the methodological link between Sect. 2.3.3 and Supplement S3, explicitly relating each indicator to the refinement strategies described in Supplement S3;
 - ii. **Sect. 2.3.3 (L263–267):** expanded Sect. 2.3.3 to provide a clearer justification for the selection of IRise, IPeak and IDrop with respect to their ecophysiological meaning;
 - iii. **Supplement S4:** restructured Supplement S4 to present alternative metrics as tested but non-retained constructions, with justification;
 - iv. added a sensitivity analysis to quantitatively demonstrate the robustness of derived indicators (see response to **R1; C2** and **R2; C1**).
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Wavelet selection and sensitivity analysis

R1; C2: “*Selection of coefficients: In Section 2.3.3, I believe that the potential impact of the wavelet selection on the derived indicators has not been sufficiently analyzed. The choice of wavelets appears somewhat arbitrary, and no references or previous studies supporting these selections are provided in this section.*”

We agree that wavelet selection is a central methodological issue in wavelet analysis, and we appreciate the opportunity to clarify both its theoretical basis and its implementation in our framework.

The difficulty highlighted by the referee is well known: wavelet choice is inherently linked to the features one aims to extract from the signal. This issue has been extensively discussed in the literature (e.g. Farge, 1992; Torrence and Compo, 1998; Lilly and Olhede, 2009), which emphasizes the need to match the analyzing function to the temporal structure of the signal. However, despite these general recommendations, no strict or universally accepted guidelines exist for selecting a specific wavelet in ecological applications, and systematic comparisons remain scarce in environmental sciences.

Our approach builds on these principles but introduces an additional constraint: wavelet selection is guided by interpretability within the WAI framework, which relies on the explicit visualization of how the wavelet interacts with the signal (Sect. 2.2). In this sense, the WAI framework reduces arbitrariness by enforcing consistency between wavelet shape and signal structure in a transparent and intuitive way, rather than relying on abstract parameter/wavelet tuning. In this context, we deliberately focused on the DOG (derivative of Gaussian) family, because these wavelets are well documented and widely used, their shapes are simple and directly interpretable and their weighting structure (positive and negative lobes) can be visually linked to specific signal features. We also note that part of the originality of this study lies in extending the use of wavelets beyond the most applied functions in environmental studies (e.g. Morlet, Mexican Hat), and in systematically tailoring them to the structure of forest GPP signals. This includes the use of different DOG wavelets and Gaussian-based weighting functions to isolate specific phases of the seasonal cycle.

To directly address the concern regarding the impact of these choices, we have added a quantitative sensitivity analysis evaluating the influence of both wavelet type and analysis period on the derived indicators. This analysis shows that indicators remain highly correlated across a range of wavelets and that differences are primarily driven by how well the wavelet shape matches the targeted signal feature.

Finally, we acknowledge that wavelet selection remains a methodological choice that requires careful consideration. To make this explicit and guide future applications, we have also added a limitations section (end of Sect. 4.5) discussing the conditions under which inappropriate wavelet or scale selection may lead to biased estimates.

R2; C1: “*The only major question is whether the selection of the wavelets and of the period length can be underpinned with a more quantitative approach. The text provides good qualitative arguments why a specific wavelet is more suited than another, similar why a certain period length is most appropriate. But we lack clear quantitative arguments. It would be nice to see how sensitive the final indicators are for these choices. Providing here a more systematic quantitative approach would make it easier to transfer the approach to dataset from other sites.*”

We thank the referee for this constructive comment. We fully agree that complementing the qualitative justification of wavelet and scale selection with a more quantitative assessment is essential to strengthen the methodological robustness and facilitate transferability of the approach.

In the revised manuscript, we have addressed this point by introducing a sensitivity analysis, specifically designed to evaluate the impact of both the wavelet type and the analysis period on the three indicators. For each indicator, alternative configurations were generated by varying the wavelet family (DOG1, DOG2, Gaussian-based) and the period within a plausible range consistent with the temporal extent of the targeted feature. Indicator values obtained under these configurations were then compared to the reference definitions using correlation metrics.

This analysis shows that all indicators remain highly robust across a broad range of parameter choices, with correlations generally exceeding 0.90 and often 0.95, while revealing contrasted sensitivities depending on the type of indicator (higher for IRise, lower for IPeak and IDrop).

In addition to providing quantitative support, this analysis clarifies that the method does not require precise parameter tuning and that transfer to other datasets primarily relies on matching wavelet shape and scale to the temporal characteristics of the signal, rather than reproducing exact parameter values.

Finally, to further address the referee's comment, we have strengthened the justification of wavelet selection in Sect. 2.2 and 2.3.3 and included a discussion of methodological limitations and best practices (end of Sect. 4.5).

⇒ **Changes in Manuscript:** To address these comments, we have:

- i. expanded Supplement S3 and Sect. 2.3.3 to clarify the principles guiding wavelet selection and their connection to the WAI framework (see response to **R1; C1**);
 - ii. **Sect. 2.2 (L214–216)**: clarified the rationale for focusing on the DOG family of wavelets;
 - iii. **Sect. 2.3.4 (L316–326)**; **Sect. 3.2 (L488–514)**; **Sect. 4.1 (L599–614)**: introduced a sensitivity analysis quantifying the influence of wavelet type and analysis period on the indicators;
 - iv. **Sect. 4.1 (L601–602)**; **Supplement S3**: added references to classical wavelet selection approaches (consistently with Sect. 2.1) and connected the use of the Gaussian window to the Gabor transform in Supplement S3;
 - v. **Sect. 4.5 (L812–820)**: added a limitations section to explicitly discuss methodological constraints and best practices for applying the approach.
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Reference metrics and benchmarking approach

R1; C3: *“Computation of smoothed-GPP references indicators: It is understandable that the authors require reference data to compare against the derived indicators. However, the proposed smoothed-GPP approach is not sufficiently justified. Several questions arise regarding this procedure. For instance, the manuscript does not clearly specify which smoothing method has been applied to the GPP data, despite the fact that GPP time series are typically very noisy and that the choice of filtering method may critically affect the extraction of the indicators. Furthermore, the definition of the indicators is not adequately introduced, and additional references to previous scientific studies should be included.”*

We thank the referee for this comment and agree that the smoothed-GPP benchmark required clearer introduction and justification.

In the revised manuscript (Sect. 2.4.3), we have substantially clarified both the rationale and implementation of this approach. We now explicitly state that no universally accepted method exists for extracting phenological metrics from EC-derived GPP time series, and that different smoothing and threshold choices can lead to substantially different estimates, as highlighted in previous studies (e.g. Panwar et al., 2023).

The smoothing procedure is now better specified and justified: daily GPP was smoothed using a 2-week sliding median, chosen for its robustness to outliers and its ability to preserve rapid transitions in the signal (e.g. during spring), while reducing high-frequency variability. The choice of window length reflects a compromise between noise reduction and temporal precision and is consistent with the temporal scale used for CUS in the WAI-based analysis.

We have also clarified the definition of phenological markers. These are now explicitly introduced as threshold-based descriptors of specific phases of the seasonal GPP trajectory, as these approaches are widely used in both EC and remote sensing studies (e.g. White et al., 1997; Caparrós-Santiago et al., 2021; Zeng et al., 2020). Thresholds were selected within commonly used ranges and were chosen to match the temporal features targeted by the WAI framework, rather than to approximate a unique “true” phenological date. In particular, we used:

- an intermediate threshold (30 %) to capture the onset of sustained carbon uptake and the rapid growth phase,
- a low threshold (20 %) to identify the end of the growing season while avoiding mid-season fluctuations,
- and a high threshold (90 %) to detect early deviations from peak-season conditions.

We have additionally redefined the reference indicators as values derived from these markers to specifically preserve a consistent ecological interpretation with the WAI framework.

Accordingly, we emphasize that the smoothed-GPP approach is not intended as a definitive reference, but rather as a pragmatic and internally consistent baseline. The objective of the benchmarking is primarily to assess whether the WAI-derived indicators capture identified functional features of seasonal GPP dynamics.

R2; L365: *“Why where the GPP data smoothed? How much would the results change if the data had not been smoothed? What are the implications of the smoothing when we have fast changes in GPP in spring?”*

We thank the referee for this important clarification request.

The smoothed GPP series is used to construct reference indicators and phenological dates and is not part of the WAI framework itself.

Smoothing serves two main purposes: (1) reducing high-frequency noise inherent to EC data, and (2) stabilizing threshold-based definitions of phenological events. Without smoothing, threshold-based detection becomes highly sensitive to short-term fluctuations, which can lead to spurious crossings of thresholds, earlier or delayed detection of phenological transitions, and increased variability in derived metrics. This sensitivity highlights one of the motivations for the WAI approach, which does not rely on smoothing but instead uses a tailored wavelet representation to extract seasonal features.

Regarding the impact of smoothing, we acknowledge that it may dampen rapid increases in GPP, particularly during spring. However, our objective is to characterize the main seasonal phases of ecosystem activity rather than short-lived fluctuations. The smoothing is therefore designed to retain the overall seasonal structure while filtering out high-frequency variability, which ensures that the derived metrics are comparable to the temporal features captured by the WAI framework.

More generally, this illustrates an inherent limitation of threshold-based approaches applied to EC data: phenological dates derived from GPP are sensitive to both smoothing and threshold choices. For this reason, the smoothed-GPP approach is not intended as a definitive reference, but rather as a pragmatic and internally consistent baseline against which the WAI-derived indicators can be evaluated.

⇒ **Changes in Manuscript:** In the revised manuscript, we have:

- i. [Sect. 2.4.3 \(L397–434\)](#): fully rewritten Sect. 2.4.3 to clarify and justify the smoothing procedure (2-week sliding median), the thresholds used and the definitions of indicators;
 - ii. [Sect. 2.4.3 \(L395–404, L428–429 and L435–438\)](#): clarified the conceptual role of the smoothed-GPP approach as a consistent benchmark aligned with WAI-derived features, rather than a unique reference;
 - iii. [Sect. 2.4.3 \(L398–402 and L414\)](#): added references on smoothing methods and threshold-based phenological extraction;
 - iv. [Sect. 4.1 \(L623–626\)](#); [Sect. 4.5 \(L802–805\)](#): expanded the discussion of benchmarking results to explain why phenological markers showed larger discrepancies than indicators and to clarify the methodological advantages of the WAI-based approach over traditional threshold-based methods.
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Statistical modelling of temporal trends

R1; C4: *“Evaluating annual trends: I believe the proposed method (line 395) is not well introduced nor justified. References or scientific works where this approach is used should be included.”*

We used linear mixed-effects models, which are widely employed in ecological studies to analyze hierarchical and temporally structured data.

In our study, observations were collected at multiple sites over several years, and measurements made during the same calendar year may share unmeasured environmental influences, such as regional climate anomalies. To account for this dependence, we included a random intercept for calendar year, allowing the model to capture year-to-year fluctuations common to all sites. Site, centered year (YearC), and their interaction were included as fixed effects, enabling us to quantify differences among sites, estimate temporal trends, and assess whether these trends differed among sites.

Compared with standard linear models, this framework offers two main advantages:

1. It accounts for the non-independence of observations arising from shared environmental forcing.
2. It enables simultaneous inference on both site differences and site-specific temporal trajectories, which is central to our objectives.

In environmental time series such as flux data, where interannual variability is strongly influenced by climate, ignoring this dependence structure may lead to underestimated uncertainty and an overestimation of the amount of independent information. Linear mixed-effects models provide a robust and well-established framework to address these issues.

⇒ **Changes in Manuscript:** In the revised manuscript, we have substantially revised Sect 2.4.4 to:

- i. **Sect. 2.4.4 (L444–456 and L465–469):** explicitly introduce the LME framework and describe model structure;
 - ii. **Sect. 2.4.4 (L458–462):** clarify the advantages of LME compared to linear regression in relation to our dataset;
 - v. **Sect. 2.4.4 (L444–446, L455, L464 and L466–467):** add references supporting the use of mixed-effects models in ecological time-series analysis, including their application to interannual variability, as well as references related to inference procedures (e.g. fixed-effect significance and estimated marginal means).
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Transferability of the WAI framework

R1; C5: *“Discussion: I believe that this section should include a brief discussion on if this method could be applied to other types of land cover.”*

We thank the referee for this suggestion. We agree that explicitly discussing the applicability of the framework to other land-cover types strengthens the scope and relevance of the study.

This aspect was already partly addressed in Sect. 4.5, but we have revised the section to clarify both the generality of the approach and the conditions for its transferability. We now explicitly state that the WAI framework is applicable beyond temperate deciduous forests, including ecosystems such as grasslands with multiple growth cycles and disturbance-driven systems (e.g. drought- or fire-affected ecosystems).

We also clarify that transferability depends on the temporal structure of the signal. For ecosystems with relatively well-defined and recurrent seasonal cycles, the method can be applied directly. In contrast, for systems characterized by weak, irregular or event-driven dynamics, its application requires a more exploratory approach, with greater reliance on WAI visualization to identify relevant features and less systematic definition of indicators.

These additions provide both concrete examples and clear methodological guidelines for applying the approach across ecosystems, thereby improving the scope and practical relevance of the study.

⇒ **Changes in Manuscript:** To address this point, we have:

- i. **Sect. 4.5 (L776–778):** expanded the first paragraph of Sect. 4.5 to explicitly include additional land-cover types (e.g. grasslands, disturbance-driven ecosystems);
 - ii. **Sect. 4.5 (L778–781):** added a distinction between direct transferability (well-defined seasonal cycles) and exploratory application (irregular or event-driven systems) and clarified the methodological adjustments required for applying the framework beyond temperate forests;
 - iii. **Sect. 4.5 (L821–826):** added a limitations paragraph to further specify the conditions under which the method can be reliably transferred across ecosystems.
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Data validation and correction of anomalies

R2; Figure 9: “*For the year 2014 and 2023 DE-Hai showed unusually high DOY for MSD. Why*”

We thank the referee for this attentive observation, which helped us identify and clarify anomalous cases.

Two distinct situations explain the unusually high MSD values observed at DE-Hai.

For 2023, the anomaly results from a data issue. A gap at the beginning of the growing season, although gap-filled, led to unrealistic GPP behavior (notably persistent nighttime NEE values), which in turn distorted the wavelet-based positioning of phenological features. Consequently, several indicators and phenological markers (CUS, MSD, IRise, IPeak and IDrop) were affected. We therefore excluded this year from the corresponding analyses. Similar, although more limited, cases had already been filtered in other site-years. Importantly, excluding 2023 does not alter the overall interpretation of the results, although it slightly affects the statistical significance of the Site×Year interaction for IRise.

For 2014, the late MSD reflects a genuine ecological signal rather than a methodological artifact. That year was characterized by a pronounced early-season reduction in GPP associated with high vapor pressure deficit, elevated temperatures, and declining soil water content. This resulted in a temporary suppression of carbon uptake during early summer, followed by a later recovery. Consequently, the seasonal peak of GPP is effectively shifted later, and the mid-season decline identified by the wavelet approach also occurs later in the season, closer to senescence. Such behavior illustrates that MSD does not necessarily correspond to a fixed phenological stage but rather reflects an emergent feature of the seasonal carbon dynamics that can shift substantially under stress conditions.

More generally, this case highlights the greater sensitivity of phenological dates to short-term anomalies, especially for metrics such as MSD that depend on mid-season dynamics, as discussed in the manuscript. In contrast, integrated indicators are more robust as they capture broader seasonal behavior.

All site-years were systematically checked, and no other anomalies were identified.

⇒ **Changes in Manuscript:** We have:

- i. Sect. 2.4.2 (L376–383 and L389–391): added methodological clarifications in the manuscript;
 - ii. Figs. 8–10; Fig. S7; Tables 2–3; Sect. 3.1 (L475); Sect. 3.3 (L518, L529 and L531); Sect. 3.4 (L542–550); Sect. 3.5 (L582–584, L587–588 and L593); Sect. 4.3 (L666–667): updated figures, tables and associated values in the manuscript following data exclusion and correction (these changes do not affect interpretations);
 - iii. Figs. 8–9; Table 3; Sect. 3.4 (L544, L555–556, L558–560): added units for all indicators as well as revised the definition of IPeak (scaled by a factor of 2 for consistency in energy normalization), while clarifying that indicator units should not be directly interpreted;
 - iv. Sect. 3.5 (L589–590); Sect. 4.4 (L757–761): expanded the discussion of MSD interpretation by examining the late MSD observed in 2014 at DE-Hai and clarifying the conditions under which this metric should be interpreted with caution at the annual scale.
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Minor changes

R2; Figure 3: “*Fig. 3 is very helpful. I suggest adding a bit more text to the caption so that the figure can stand for itself.*”

We agree that the figure would benefit from a more self-contained caption.

⇒ **Changes in Manuscript (L203–211):** We have expanded the caption of Fig. 3 to briefly describe the objective of each step (selection, interpretation, refinement) and how they are connected in the workflow.

R2; L412: “*“which implies more CO₂ emission proportionally to absorption over years”: maybe rephrase to e.g. “which implies less CO₂ uptake over the years”.*”

⇒ **Changes in Manuscript (L478):** We agree and will adopt the suggested clearer wording.

R2; Entire manuscript: “*Please check for CO₂ and place 2 in subscript.*”

⇒ **Changes in Manuscript (L478 and L680–685):** Corrected.
