Responses to comments from reviewer #1
(Manuscript number: egusphere-2025-1243)

We sincerely thank Reviewer 1 for the thoughtful and constructive comments. In response, we have revised the manuscript to clarify parameterization strategies, explain the integration of process-based modeling with data assimilation, and refine the definitions and representations of soil P pools. Reviewer comments are shown in blue italic, followed by our detailed responses. We hope these revisions address all concerns satisfactorily.

Comment 1A: *This is a nicely written and well-executed work implementing phosphorus cycle and data assimilation framework into a process-based ecosystem model (TECO). The novelty of this work lies in the model development and its coupling with data assimilation. By comparing CNP model against observations and their respective C-only and CN coupled models, the authors show a superior performance of the newly developed model. Overall, I enjoy reading the manuscript, and support its publication. There are several occasions where I think some justifications/modifications would further improve the quality of the manuscript. Below I list my main questions/concerns.*

Response: We sincerely appreciate your positive assessment of our manuscript and the constructive feedback provided. We have carefully considered all the questions and concerns raised by the reviewer and have made substantial revisions to address these points.

Comment 2A: *There are certain processes where N and P interact. For example, some models consider N to have an effect on soil P biochemical mineralization rate (e.g. ORCHIDEE, ELM, etc.). It does not seem that the authors have adopted these NP interacting processes in their model. Furthermore, others consider N and P to have joint effect on C processes, such as photosynthesis. In this work, it seems that nutrient effect on photosynthesis is realized via downregulation of leaf surface area. There have been some empirical relationships derived on how N and P affects photosynthetic traits (e.g. Vcmax, Jmax; Ellsworth et al., 2022; Walker et al, 2014), and these relationships have been incorporated into models. What is the authors' consideration on not following these conventional approaches?*

Response: Thank you for raising this important point regarding nitrogen-phosphorus (N-P) interactions and nutrient regulation of photosynthesis. We acknowledge that N-P interactions are central to ecosystem function and have explicitly incorporated two key mechanisms into the TECO-CNP model: (1) nitrogen-limited phosphorus uptake regulated by a nutrient balance scalar (Eqs. 26-27), and (2) a cost-benefit mechanism for phosphatase production (Eq. 43), whereby plants optimize P acquisition strategy based on nitrogen cost. We have now clarified these processes in the revised manuscript (Section 2.2.2, L364; Section 2.2.3, L470-480) and added a general summary in Section 2.2.2 (L278-281) to improve readability.

We agree with you that TECO-CNP currently offers a partial representation of N-P interactions, reflecting broader challenges in coupled CNP modeling (Achat et al., 2016). Although recent studies have advanced our understanding of N-P coupling mechanisms (Luo et al., 2022; Krouk & Kiba, 2020; Hu & Chu, 2019), their integration into models remains limited by both incomplete mechanistic knowledge and the scarcity of empirical data for parameterization. For example, complex relationships such as the coordination between biological nitrogen fixation and phosphatase production (Batterman et al., 2018) and the reciprocal effects of nitrogen and phosphorus availability on nutrient resorption dynamics (See et al., 2015; Li et al., 2019) are still poorly understood. Thus, we view advancing the representation of N-P interactions as a key priority for future model development. We will continue to incorporate these processes as our mechanistic understanding deepens and more comprehensive datasets become available. We have added several sentences in the revised version to discuss this point in the revised version (L829-833, L840-852).

Regarding the empirical relationships developed by Ellsworth et al. (2022) and Walker et al. (2014) linking N and P to photosynthetic parameters (V_{cmax}, J_{max}), we agree that these empirical relationships would be an advancement for CNP models, and we carefully considered incorporating these relationships after receiving your comments. However, we ultimately decided to adopt this approach in our future versions due to two reasons. First, we tested these relationships, which are mainly derived from large-scale and cross-biome analyses, at our site. As shown in the Table S5, adding these empirical relationships resulted in significant overestimation of photosynthetic parameters. Second, our site-specific dataset was insufficient to robustly generate similar relationships between photosynthetic parameters and leaf nutrient content, and applying unvalidated relationships could introduce additional uncertainty into model simulations. Therefore, we implemented nutrient limitation on photosynthesis indirectly through plant growth regulation (Eq. 1, L173-189), which we believe is more appropriate for our site-scale application given the available data constraints. We refine our discussion about the nutrient-regulated photosynthesis capacity in Section 3.1.1 at L747-757 as follows:

"The observed reduction in LAI represents a decrease in photosynthetic capacity achieved through nutrient limitation of plant growth, which reduces the photosynthetic leaf area rather than directly affecting leaf-level photosynthetic physiological parameters. The relationships between leaf nitrogen and phosphorus concentrations and photosynthetic traits (e.g., Vcmax, Jmax) are well established (Walker et al., 2014; Ellsworth et al., 2022) and have been incorporated into some land surface models (e.g., JULES-CNP). However, these large-scale emergent relationships significantly overestimated photosynthetic parameters at our study site (Table S5). At the same time, our site-specific dataset was insufficient to derive robust empirical relationships between nutrient concentrations and photosynthetic capacity. Future studies with more comprehensive site-level measurements could enhance this aspect of the model to represent nutrient-carbon interactions better"

Comment 3A: *Solution P is part of labile P, and some work suggests the need to explicitly model solution P in addition to labile P (e.g. Reed et al., 2015). In this work, how does the author consider this suggestion and what is the rationale for only simulating labile P?*

Response: Thank you for this important question regarding the rationale for inorganic P (Pi) pool representation in TECO-CNP. Also, many thanks for recommending the great paper, i.e., Reed et al., (2015). We agree with you and Reed et al. (2015) that more detailed representation of Pi pools could enhance model performance. In this revised version, we cited Reed et al., (2015) and clearly explained why only labile P was simulated at our site. Here are two brief reasons:

First, Pi extracted by resin bags or strips (resin-Pi) and extracted by $NaHCO_3$ (Hou et al., 2018) are typically considered as phosphorus readily available to plants and microorganisms, and they exhibit highly correlated dynamics with similar bioavailability characteristics (Hou et al., 2019). Employing a single P pool to represent the rapidly accessible phosphorus for plants and microorganisms in soil is common practice in ecosystem modeling studies (Wang et al., 2010, Wang et al., 2018; Hou et al., 2019; Nakhavali et al., 2022; Knox et al., 2024). However, as pointed out by Reed et al. (2015), solution P need to explicitly modeled in addition to labile P. We have added several sentences to discuss this topic in this version (L510-520).

Second, most field datasets provide total labile P rather than separated fractions, as in our study (see Section 2.3.2 in the revised manuscript, L626-631). Therefore, implementing more complex processes without sufficient supporting data could increase model uncertainty without significantly improving model performance. At this stage, utilizing a single labile P pool rather than including a separate solution P pool represents a robust and conservative approach. In future developments, more detailed model structures will be considered as relevant research data become available.

Furthermore, to clarify the definitions of these Pi pools, we have revised the description at L286-290 as follows:

> "Labile P represents readily bioavailable inorganic phosphate for rapid biological uptake. Sorbed P is weakly bound to soil surfaces in dynamic equilibrium with labile P. Through petrochemical processes, sorbed P transforms into secondary mineral P, which eventually becomes occluded P with minimal bioavailability"

Comment 4A: *It seems that the data assimilation framework was only applied to the CNP model, and then the authors reported CN and C models to overestimate observations. I find this logic to be a bit problematic. Without data assimilation, does CNP model still achieve better match with observations? Alternatively, how does C-only model coupled with data assimilation perform relative to observations? If it can achieve similar performance as compared to CNP model, what benefits of having a CNP model?*

Response: Thank you for raising these important questions regarding model comparison and the application of data assimilation. Please find our point-by-point replies as below:

(1) *Does the CNP model achieve better agreement with observations even without data assimilation*? Yes, as shown in Section 3.1 (Fig. 5, Table 5), the CNP model outperformed both the CN and C-only models in simulating observed carbon, nitrogen, and phosphorus pools and fluxes without any parameter optimization. This supports our initial hypothesis that including explicit N and P cycles improves model fidelity at the site level.

(2) *How does the C-only model perform when data assimilation is applied?* We conducted a supplementary analysis applying data assimilation to the C-only model and found that its performance in simulating carbon fluxes (e.g., GPP) was similar to that of the CNP model (Fig. RA1; Fig. S1 in revised supplementary materials). This result illustrates the well-known issue of equifinality, where structurally different models can achieve comparable predictive accuracy by compensating with different parameter sets.

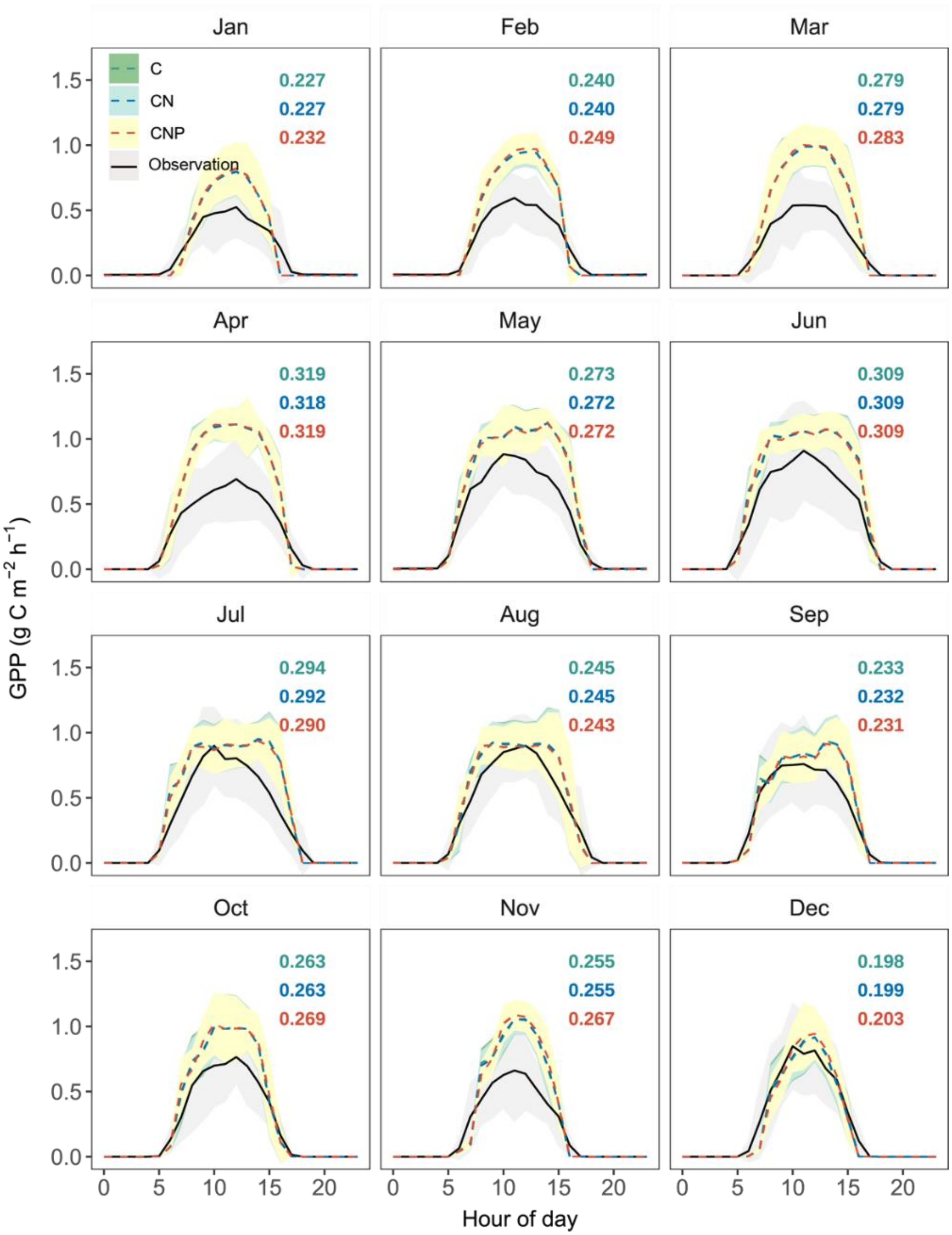

Figure S1. Diurnal GPP patterns across months simulated by three model configurations (C, CN, CNP) versus observations. RMSE values for each model (green: C, blue: CN, red: CNP) are shown in the upper right of each panel. Black lines with grey shading represent observations (± 1 SD); colored lines and shading represent model means ± SD.

(3) *What is the added value of the CNP model, if performance appears similar?* The critical distinction lies in mechanistic realism. Although the optimized C-only model fits the observations, it does so by using ecologically implausible parameter values. For instance, the constrained specific leaf area (SLA) in the C-only model deviates substantially from the observed community-level distribution, unlike the CNP model (Fig. RA2; Fig. S2 in revised supplementary materials). This limits the ecological interpretability and transferability of the optimized C-only model, especially under changing environmental conditions where nutrient dynamics play a key role.

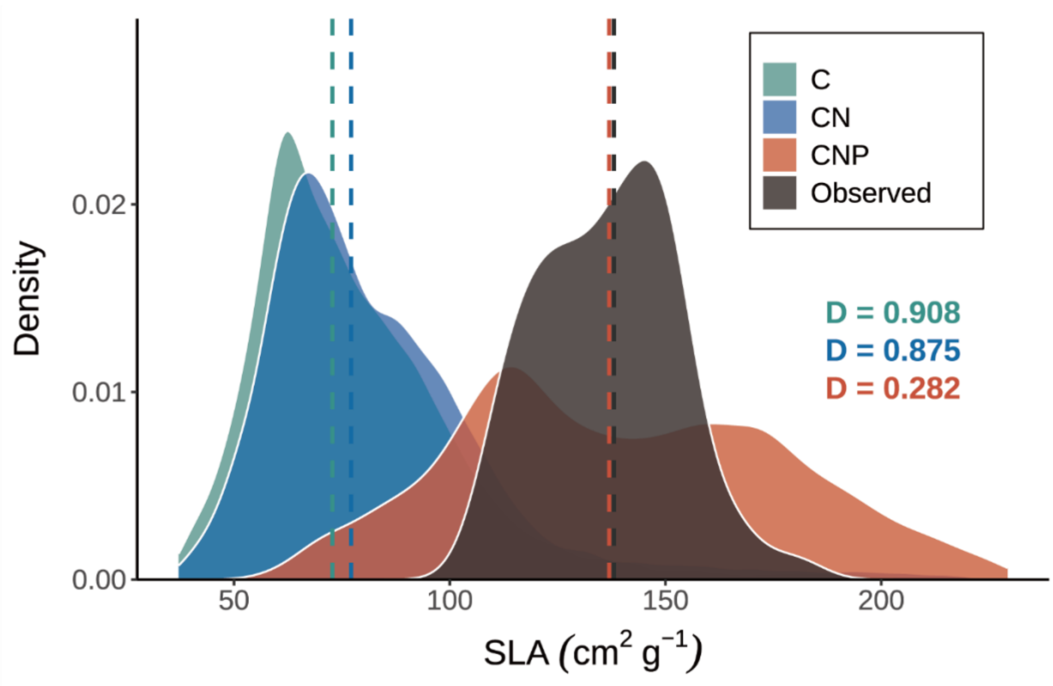

Figure S2. Posterior distribution of constrained specific leaf area (SLA) and observed community-level SLA distribution. Green, blue, red, and gray represent C, CN, CNP models and observations, respectively. Vertical lines represent distribution means. D, Kolmogorov-Smirnov statistic.

Therefore, the CNP model not only improves baseline simulation accuracy but also preserves mechanistic fidelity, enabling more reliable predictions under future climate and nutrient limitation scenarios. We have added further discussion on this point in Section 3.2 of the revised manuscript and detailed parameter comparison results in the Supplementary Materials (Text S1, Figs. S1–S2).

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