Responses to comments from reviewer #2
(Manuscript number: egusphere-2025-1243)

We sincerely thank Reviewer 2 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 1B: *This study developed a coupled carbon-nitrogen-phosphorus model, TECO-CNP Sv1.0, based on the Terrestrial ECOsystem (TECO) model. The developed model was used to simulate C, N, and P pools and fluxes in a phosphorus-limited subtropical forest site in East China. In addition, a parameter optimization algorithm was also incorporated into the model framework to improve the model's performance. Overall, the manuscript provides detailed information on the model structure, parameters, and performance. However, I still have some questions on the soil pool structure and calibration processes of the model.*

Response: Thank you for your constructive review and valuable comments on our TECO-CNP model development. We are committed to addressing your concerns and providing clarifications that will strengthen our manuscript.

Comment 2B: *Four inorganic P pools, including labile P, sorbed P, secondary P, and occluded P, are set in TECO-CNP. This structure is different from other CNP models. For example, the labile P pool in ORCHIDEE-CNP includes both dissolved and sorbed P. In CLM-CNP, inorganic P pools include labile P (including solution P), secondary P, and occluded P. In a global P dataset developed by He et al. (2023) Biogeosciences, the soil inorganic P is divided into labile P, moderate P, and occluded P. Can you explain the differences in inorganic P pool structure among these models? I am confused about the definition of labile P pool. In addition, how did you initialize these inorganic P pools ?*

Response: We have added the detailed description of labile P pool in revised version (L286-290, L626-631). The key difference among models in the soil inorganic P pools is how they define and term the most available inorganic P pools (Table RB1). In some model studies, labile P serves as the directly plant-available pool (e.g., TECO-CNP, CASA-CNP, JSBACH-CNP) and maintains dynamic equilibrium with the sorbed pool over short timescales. In contrast, other studies tend to use terms like "solution" or "dissolved" to represent the solution-phase P (e.g., CLM-CNP, ORCHIDEE-CNP, E3SM-CNP), while also setting up another pool that equilibrates with it. The model structure is comparable to experimental approaches. Experimentally, "labile P" represents the inorganic P extracted by resin and $NaHCO_3$, and "secondary mineral P" represents NaOH-extracted inorganic P, which some studies term "moderately available P" (He et al., 2023).

We initialized inorganic P pools using site measurements. Labile P was determined from 0-10 cm soil samples collected in 2023 from a nearby forest stand of similar stand age (~200 yr) dominated by the same species as the Tiantong forest dynamic plot. Secondary P and occluded P values were obtained from available literature data for the same study site (Table S3). The initialization method is refined in the revised version (L625-634).

Table RB1. Comparison of inorganic phosphorus (P) pools in ORCHIDEE-CNP, CLM-CNP, and TECO-CNP. Bold text highlights the main differences among models.

ORCHIDEE-CNP	CLM-CNP	TECO-CNP	General description
Dissolved labile P	Solution P	Labile P	Most readily available P and only source for plants uptake; can be adsorbed or lost by leaching
Sorbed labile P	Labile P	Sorbed P	P reversibly adsorbed onto soil particles; maintains equilibrium with the most readily available P pool
Secondary mineral P	Secondary mineral P	Secondary mineral P	Moderately stable P; can be slowly dissolved to enter labile pool or become occluded
Occluded P	Occluded P	Occluded P	Most stable P form; encapsulated by Fe/Al oxides; extremely slow release over geological timescales

Comment 3B: *What is the advantage of TECO-CNP compared with other CNP models?*

Response: Thank you for this insightful question. In this revised version, we have made it clearer that TECO-CNP has three major advantages compared with other CNP models. First, TECO-CNP tightly couples vegetation carbon processes with soil nutrient cycling. It simulates dynamic plant growth responses to both soil nutrient availability and internal physiological traits by modifying growth rates (Eq. 1) and allocation patterns (Eqs. 9-11). This allows for a more mechanistic representation of nutrient-limited growth dynamics.

Second, unlike many current CNP models that omit non-structural carbohydrate (NSC) pools (e.g., JULES-CNP, CABLE, ELMv1-ECA; Nakhavali et al., 2022; Haverd et al., 2018; Zhu et al., 2019), TECO-CNP explicitly represents NSC dynamics. This enables a more realistic representation of how plants adjust allocation between growth and storage under nutrient stress (L103-106; Hartmann et al., 2020; Merganičová et al., 2019).

The third advantage of TECO-CNP compared to other CNP models lies in its capacity to integrate in situ observations with process-level forecasting. Site-scale models like TECO-CNP can fully leverage rich, localized datasets, including forest inventory records, experimental manipulations, and eddy covariance measurements, to constrain model parameters and processes. This integration is crucial because unobserved or weakly observed processes cannot be reliably constrained through data assimilation alone (Luo et al., 2011). TECO-CNP is designed to facilitate the fusion of such multi-process information, thereby enabling more mechanistic and robust representations of ecosystem C-N-P dynamics. In contrast, global-scale models often rely on aggregated or remote-sensing data and typically lack the resolution or flexibility to assimilate detailed, site-specific measurements. By bridging observational data and predictive capacity at the process level, TECO-CNP provides a powerful tool for advancing both model accuracy and ecological understanding at ecosystem-relevant scales. We have emphasized these features more clearly in the revised manuscript (L773-777; L949-958).

Comment 4B: *How were the soil P pools at the Tiantong site measured? Did you compare the measured soil P pool with other studies? They seem lower than other studies (Fig. 5c).*

Response: Soil phosphorus (P) pools at the Tiantong site were measured using systematic sampling across 185 grid points (each 20 × 20 m) within the permanent Tiantong forest plot (a member site of ForestGEO; https://forestgeo.si.edu; Fig. 3). At each grid point, soil samples were collected at three depth intervals (0-20, 20-40, 40-60 cm) using a 5 cm diameter auger, with three replicates per depth.

The measured soil P pool for the 0-60 cm profile was 181.59 ± 60.18 g P m^{-2} (Table S3), which is well captured by the TECO-CNP simulation (157.7 g P m^{-2}; Fig. 5c). These values fall within the typical range reported for forest ecosystems in China (220.15, interquartile range: 130.74-341.98 g P m^{-2}; Zhu et al., 2020), suggesting our field-based estimates are robust.

Please note that some values in Figure 5c were rescaled for visualization purposes. To avoid confusion, we have now added an explanatory note to the figure caption (L789-790). Further details on the soil sampling methodology have also been provided in the revised text (L625-639).

Comment 5B: *The simulation results of C-only, CN, and CNP versions were compared in this study to prove the good performance of the CNP model. Did you calibrate these three versions individually? Was the same parameter optimization algorithm applied to all three versions? Or you just calibrate the only CNP model, and apply the same parameters to other versions. Did you simulate the C cycle in this site by using C-only or CN versions before the development of CNP? How well did these two models perform? Many parameters are constant values, such as Vre. I guess these parameters were not calibrated but derived from the literature. Were these parameters suitable for subtropical forest ecosystems?*

Response: Thank you for these detailed questions. In this revised version, we have provided the following clarifications regarding model calibration, parameter sources, and the rationale for using a CNP model:

(1) *Model calibration and parameterization strategy*: All three model versions (C-only, CN, and CNP) were calibrated using the same set of site-specific parameters derived from a measurement-informed approach. Key parameters, including specific leaf area (SLA), V$_{cmax}$, J$_{max}$, plant height, nutrient resorption fractions, and stoichiometric ratios, were obtained from in situ field measurements at the Tiantong site (Section 2.3.2; Tables S1-S3). This unified calibration ensures that differences in model performance reflect structural differences rather than inconsistencies in parameterization.

For parameters not directly measurable on-site, such as occluded P release rate (ν_{re}), as noted by the reviewer, we used values informed by experimental studies and calibrated land surface models appropriate for the vegetation type (Table 4). For instance, the classification of Tiantong soils as *Ultisols* (Song & Wang, 1995) informed our selection of parameters for P weathering and sorption (e.g., K$_s$ and S$_{max}$), while the subtropical evergreen broadleaf forest context guided the parameterization of P mineralization and allocation processes (e.g., Wang et al., 2010; Arora & Boer, 2005). To ensure ecological relevance, all literature-derived parameters were carefully evaluated against site-specific characteristics. This combined approach preserves mechanistic realism while incorporating the best available knowledge. We have clarified this approach in the revised text at L291-294 and L602-624

(2) *Model independence and comparison procedure*: Although the C-only model served as the structural foundation for model development, the C-only, CN, and CNP versions were implemented as independent configurations. Each version was run separately after spin-up using

the same calibrated parameter set, and no parameters were shared post-optimization. Model comparisons were based on simulations prior to data assimilation (Section 2.3.4), allowing an unbiased evaluation of structural differences (Fig. 5, Table 5). The results show that the CNP model achieved the closest agreement with observed carbon, nitrogen, and phosphorus pools and fluxes. We have made this finding clearer in this revised version (L744-746, L828-833, and L862-864).

(3) *Data assimilation and parameter equifinality*: Only the CNP model was subjected to data assimilation in the original version of this study, as our focus was on evaluating the performance of the fully coupled structure. However, to address the reviewer's question, we conducted a supplementary analysis applying data assimilation to the C-only model. We found that the optimized C-only model achieved performance similar to the CNP model in terms of flux predictions. This similarity, however, stems from compensatory parameter behavior. For example, Fig. RB1 (Fig. S2 in revised supplementary materials) shows that the C-only model required SLA values far outside the observed community-level distribution, whereas the CNP model constrained parameter values consistent with field data. This reflects the well-documented issue of equifinality (Luo et al., 2016; Sierra et al., 2015), where simpler models can match outputs by adjusting unrelated parameters, thereby losing ecological interpretability. We have added sentences to make this point clearer in this version (L949-958 and Text S1).
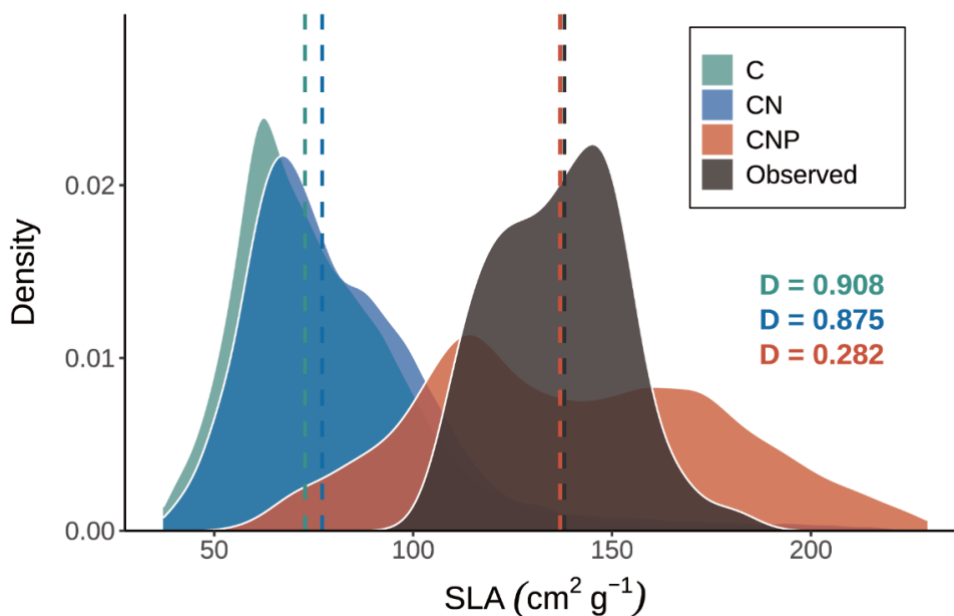

Figure S2. Posterior distribution of constrained specific leaf area (SLA) and observed community-level SLA distribution. Green, blue, red, and gray represent C, CN, CNP models and observations, respectively. Vertical lines represent distribution means. D, Kolmogorov-Smirnov statistic.

Comment 6B: *The vegetation and soil pools simulated by the three versions were compared in section 3.1. What about C and nutrient fluxes? In Fig.7, I cannot identify the simulated NEE by the three model configurations.*

Response: Thank you for pointing this out. In the revised manuscript, carbon and nutrient fluxes are more clearly illustrated in the revised Table 5 and described in lines 758-761, 828-833 and 862-864 in Section 3.1. These additions illustrate the expected effects on carbon fluxes under phosphorus limitation in the CNP model, and the lower nitrogen mineralization due to reduced

litter input and constrained microbial activity. To further support transparency, we have included simulated nitrogen and phosphorus flux data in the supplementary repository for potential use in future comparative studies.

Regarding the original Figure 7, we have corrected the caption to clarify that it shows results from the CNP model before and after data assimilation, rather than from the three model versions. We apologize for the earlier misstatement and have updated the caption accordingly (Line 922).

Table 5. Observed and simulated carbon, nitrogen and phosphorus fluxes with C, CN and CNP configurations. The plant litterfall rate is the sum of litterfall of leaf, wood and reproductive pool.

C, N and P fluxes	C-only	CN	CNP	Observation	Unit
C transfer from leaf to litter	0.43	0.38	0.25	0.26±0.06	kg C m^{-2} yr^{-1}
C transfer from plant to litter	0.98	0.86	0.54	0.44±0.04	kg C m^{-2} yr^{-1}
N transfer from plant to litter	-	11.36	7.44	6.74±0.68	g N m^{-2} yr^{-1}
P transfer from plant to litter	-	-	0.24	0.79±0.24	g P m^{-2} yr^{-1}
Soil respiration	1.72	1.59	1.13	0.99±0.07	kg C m^{-2} yr^{-1}
Net N mineralization	-	18	12.3	13.14±0.73	g N m^{-2} yr^{-1}
Net P mineralization	-	-	0.54	0.67±0.14[a]	g P m^{-2} yr^{-1}

[a]Jiang et al., 2024

Minor comments

Comment 7B: *L491-493. Please list the equations of P loss from SOM pools.*

Response: Done. We have added the Equation 44 to represent soil P loss from SOM pools at lines 481-484 in the revised manuscript.

Comment 8B: *Equation 54. What is the meaning of Pl*

Response: 'Pl' should be 'P$_{lab}$' representing the labile phosphorus pool. This has been corrected in the revised manuscript.

Comment 9B: *L607. Please correct the reference of Xu et al.*

Response: Corrected.

Comment 10B: *Fig 8. What is the meaning of the posterior distribution of parameters? Do they change with time?*

Response: In the revised version, we have explained the posterior distribution of parameters and its independence upon time (L675-677). The posterior parameter distribution represents our updated knowledge about parameter values after incorporating observational data through Bayesian inference, quantifying both the most likely parameter estimates and their associated uncertainties. In the context of our model, these distributions show which parameter values (e.g.,

Q_{10}, turnover times) are most consistent with observed carbon flux data and provide confidence intervals for those estimates.

Regarding temporal behavior, posterior distributions in our study do not change with time. We employed batch data assimilation (Evensen, 2009), processing the entire observational time series simultaneously to generate a single posterior distribution for each parameter. This approach assumes parameters are time-invariant ecological properties and yields static probability distributions representing the best parameter estimates constrained by all available observations. Sequential assimilation approaches that update posteriors over time are possible but were not employed in this study, as our objective was to characterize fixed ecosystem parameters rather than track temporal parameter evolution.

Comment 11B: *Table. How did you identify these target parameters? Did you conduct a sensitivity analysis?*

Response: Yes, we conducted a preliminary sensitivity analysis to support the selection of target parameters for data assimilation. As shown in Table RB2 (added to the revised supplementary materials as Table S6), parameters related to photosynthesis (SLA and V_{cmax}) and ecosystem respiration (Q_{10}) exhibited high sensitivity indices (> 0.1) with respect to GPP, ER, and NEE. These parameters were therefore selected for assimilation. In addition, we included all carbon pool turnover parameters (T_1–T_9) without pre-screening, as these govern carbon residence times and are crucial for matching observed pool dynamics, even if their sensitivity indices were lower. In summary, we selected assimilation parameters based on both sensitivity analysis and their direct link to observed ecological processes, rather than relying solely on pre-screening. We have made it clear in the revised version at lines 654-660.

Table RB2. Sensitivity index of selected parameters. SI_{GPP}, SI_{ER}, and SI_{NEE} represent the sensitivity indices of gross primary productivity (GPP), ecosystem respiration (ER), and net ecosystem exchange (NEE) to each parameter, respectively. Bold values indicate sensitivity indices > 0.1.

	SI_{GPP}	SI_{ER}	SI_{NEE}
Q10	0.009	**0.554**	**0.750**
SLA	**0.112**	**0.110**	**0.115**
Vcmax	**0.820**	**0.210**	**1.669**
T1	0.023	0.027	0.091
T2	0.000	0.036	0.050
T3	0.008	0.025	0.055
T4	0.000	0.026	0.037
T5	0.004	0.039	0.065
T6	0.004	**0.185**	**0.268**
T7	0.008	**0.239**	**0.313**
T8	0.001	**0.110**	**0.150**
T9	0.000	0.005	0.006

Reference

Arora, V. K., & Boer, G. J. (2005). A parameterization of leaf phenology for the terrestrial ecosystem component of climate models. Global Change Biology, 11, 39–59. https://doi.org/10.1111/j.1365-2486.2004.00890.x

Evensen, G. (2009). Data Assimilation: The Ensemble Kalman Filter. Springer-Verlag, Berlin Heidelberg, pp. 22-37.

Hartmann, H., Bahn, M., Carbone, M., & Richardson, A. D. (2020). Plant carbon allocation in a changing world – challenges and progress: Introduction to a Virtual Issue on carbon allocation. New Phytologist, 227(4), 981–988. https://doi.org/10.1111/nph.16757.

Haverd, V., Smith, B., Nieradzik, L., Briggs, P. R., Woodgate, W., Trudinger, C. M., Canadell, J. G., & Cuntz, M. (2018). A new version of the CABLE land surface model (Subversion revision r4601) incorporating land use and land cover change, woody vegetation demography, and a novel optimisation-based approach to plant coordination of photosynthesis. Geoscientific Model Development, 11, 2995–3026. https://doi.org/10.5194/gmd-11-2995-2018

Luo, Y., Ogle, K., Tucker, C., Fei, S., Gao, C., LaDeau, S., Clark, J. S., & Schimel, D. S. (2011). Ecological forecasting and data assimilation in a data-rich era. Ecological Applications, 21(5), 1429–1442. https://doi.org/10.1890/09-1275.1.

Merganičová, K., Merganič, J., Lehtonen, A., Vacchiano, G., Sever, M. Z. O., Augustynczik, A. L. D., Grote, R., Kyselová, I., Mäkelä, A., Yousefpour, R., Krejza, J., Collalti, A., & Reyer, C. P. O. (2019). Forest carbon allocation modelling under climate change. Tree Physiology, 39(12), 1937–1960. https://doi.org/10.1093/treephys/tpz105.

Nakhavali, M. A., Mercado, L. M., Hartley, I. P., Sitch, S., Cunha, F. V., Di Ponzio, R., & Camargo, J. L. (2022). Representation of the phosphorus cycle in the Joint UK Land Environment Simulator (vn5.5_JULES-CNP). Geoscientific Model Development, 15, 5241–5269. https://doi.org/10.5194/gmd-15-5241-2022.

Song, Y. C., & Wang, X. R. (1995). Vegetation and flora of Tiantong National Forest Park Zhejiang Province. Shanghai Scientific and Technical Document Publishing House.

Wang, Y. P., Law, R. M., & Pak, B. (2010). A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere. Biogeosciences, 7, 2261–2282. https://doi.org/10.5194/bg-7-2261-2010.

Zhu, J., Wu, A., & Zhou, G. (2021). Spatial distribution patterns of soil total phosphorus influenced by climatic factors in China's forest ecosystems. Scientific Reports, 11, 5357. https://doi.org/10.1038/s41598-021-84166-0.

Zhu, Q., Riley, W. J., Tang, J., Collier, N., Hoffman, F. M., Yang, X., & Bisht, G. (2019). Representing Nitrogen, Phosphorus, and Carbon Interactions in the E3SM Land Model: Development and Global Benchmarking. Journal of Advances in Modeling Earth Systems, 11(7), 2238–2258. https://doi.org/10.1029/2018MS001571.