Response to Anonymous Referee #2

This study conducts a comprehensive sensitivity analysis of parameterization schemes on Gross Primary Productivity (GPP) simulations based on the Noah-MP land surface model, focusing on four core physical processes across diverse ecosystems in China. The methodological design, including an ensemble simulation framework, model validation against ChinaFlux and PML-V2 datasets on site scale and regional scale, and the adoption of the Sobol' total sensitivity index, is technically robust. Nevertheless, given the notable shortcomings in research novelty and mechanistic interpretation that limit its suitability for publication in this journal, I regret that I cannot recommend the acceptance of this manuscript. The detailed comments are provided below.

We sincerely thank the reviewer for the careful evaluation of our manuscript and for recognizing the technical robustness of the study design. We appreciate the reviewer's concerns regarding the novelty and mechanistic interpretation of the original manuscript.

In response, we have substantially revised the manuscript to clarify the specific contribution of this study, strengthen the process-based interpretation of GPP simulation performance and uncertainty, and improve the overall structure and discussion. Detailed responses to each comment and the corresponding revisions are provided below.

Major Comments

Q1. Numerous studies have been conducted on the sensitivity analysis of Noah-MP parameterization schemes. This manuscript lacks distinct innovation and highlights, and most of the simulation results are predictable and conventional. Furthermore, the physical mechanisms and underlying causes responsible for the model evaluation results are not sufficiently discussed and elaborated throughout the manuscript.

We sincerely thank the reviewer for this important and constructive comment. We agree that the original manuscript did not sufficiently articulate the specific contribution of this study relative to previous Noah–MP multi-physics and parameterization-sensitivity studies, and that the physical interpretation of the model evaluation results was not adequately developed.

In response, we substantially revised the Introduction, Results, and Discussion sections to clarify the novelty, strengthen the process-based interpretation, and avoid overstating the implications of the sensitivity analysis.

First, we revised the Introduction to more clearly identify the research gap addressed by this study. Previous Noah–MP multi-physics studies have mainly focused on hydrological and energy-related variables, including soil moisture, evapotranspiration, runoff, and snow processes. Studies considering carbon-cycle variables have often been conducted at a limited number of sites or over relatively short periods. In contrast, this study combines a 48-member Noah–MP multi-physics ensemble with Sobol' total sensitivity analysis to quantify the contributions of radiation transfer, soil-moisture limitation, turbulent exchange, and runoff generation to uncertainty in simulated GPP across major ecosystem types in China during 2001–2020. The revised manuscript further emphasizes the comparison of ecosystem- and season-dependent sensitivity patterns, together with evaluations at both flux-tower and national scales.

Second, we clarified the interpretation of the Sobol' sensitivity results. In the revised manuscript, these results are described as identifying the relative contributions of alternative Noah–MP parameterization schemes to uncertainty in simulated GPP, rather than as identifying universal ecological controls on actual ecosystem GPP. This clarification prevents overinterpretation and better defines the scope of the present study.

Third, to strengthen the mechanistic interpretation of model performance, we added a site-level process-based diagnostic analysis. In addition to GPP, we evaluated the temporal agreement, normalized errors, and seasonal cycles of available flux-tower-derived absorbed photosynthetically active radiation (APAR), latent heat flux (LE), sensible heat flux (Hs), and soil water content (SWC) at representative forest, grassland, and cropland sites. The new results indicate that GPP biases are associated with different combinations of radiation, water, and energy-process errors among ecosystems and sites. For example, the poor performance at the DHF forest site was accompanied by substantial discrepancies in APAR, LE, Hs, and SWC, suggesting that biases in canopy radiation absorption, soil-water regulation, and surface-energy partitioning jointly contributed to overly favorable simulated conditions for carbon assimilation. In contrast, grassland and cropland sites showed distinct error patterns, indicating that model performance cannot be attributed to a single common process or vegetation category alone.

Fourth, we reorganized the Discussion to provide a more systematic interpretation of: (1) site-level GPP performance and the causes of low TSS values; (2) the magnitude and seasonal patterns of differences between Noah–MP simulations and the PML GPP product; (3) ecosystem- and season-dependent sensitivity patterns; and (4) remaining uncertainties associated with meteorological forcing, land-cover representation, spin-up, flux partitioning, and model structural assumptions.

We acknowledge that some broad sensitivity patterns identified in this study, such as the importance of soil-moisture-related parameterizations in water-limited environments, are consistent with previous understanding. Therefore, the contribution of this study is not the identification of an entirely unexpected dominant process. Rather, its contribution lies in providing a consistent, long-term, nationwide quantification of how Noah–MP parameterization-related GPP uncertainty varies across ecosystems, seasons, and regions of China, while linking these uncertainty patterns to diagnosed errors in radiation, water, and energy processes.

These revisions have been incorporated into the revised Introduction, Sections 2.2–2.3, Sections 4.1–4.2, and Sections 5.1–5.4.

Q2. Prior to determining the physical processes for uncertainty analysis, a comprehensive introduction to all physical processes incorporated in the Noah-MP land surface model should be provided. The current manuscript only explains the reasons for selecting the four targeted physical processes, while neglecting to illustrate why other physical processes are excluded from the analysis. For instance, it is necessary to clarify why the uncertainty associated with the parameterization schemes for surface resistance to evaporation does not need to be considered in this study.

We thank the reviewer for this important comment. We agree that the original manuscript did not sufficiently describe the broader range of physical processes represented in Noah-MP or clearly justify why only four process groups were included in the uncertainty analysis.

In the revised manuscript, we expanded the model-description and experimental-design sections to introduce the major energy, water, and carbon processes represented in Noah-MP, including radiation transfer, photosynthesis and stomatal regulation, turbulent exchange, dynamic vegetation, soil-water and soil-thermal processes, runoff and groundwater, snow and frozen-soil processes, and surface resistance to evaporation and sublimation.

We clarified that the four selected processes were chosen because they provide direct pathways linking parameterization choices to simulated GPP through canopy radiation absorption, soil-moisture stress on stomatal conductance, canopy–atmosphere exchange, and root-zone water availability.

We further clarified that surface resistance to evaporation and sublimation was not considered negligible. It was held fixed because it primarily regulates ground evaporation and sublimation and affects GPP indirectly through topsoil moisture and surface-energy partitioning. The present factorial design was intentionally restricted to four process groups to retain computational tractability and facilitate attribution of parameterization-related GPP uncertainty. Its potential influence has been explicitly acknowledged as a limitation.

In addition, because dynamic vegetation was activated in all simulations, the Noah-MP framework requires the Ball-Berry canopy stomatal-resistance scheme. Therefore, canopy stomatal-resistance uncertainty could not be independently sampled using alternative parameterizations. These revisions have been incorporated into Section 2.2 and Section 5.4.

Major Comments

Q1. Line 21: Correct the typo “gobering” to “governing”.

We thank the reviewer for identifying this typographical error. The word “gobering” has been corrected to “governing” in the revised manuscript (Line 21). We also carefully proofread the entire manuscript and corrected other typographical, grammatical, and formatting inconsistencies where identified. We appreciate the reviewer’s careful reading and helpful suggestion.

Q2. Lines 28–29: Quantify the degree of “overestimation” with specific statistical metrics, such as bias or percentage error relative to observational data.

We thank the reviewer for this helpful suggestion. We agree that the original statement describing GPP overestimation was overly qualitative. In the revised Abstract, we quantified the magnitude of the Noah–MP–PML differences. Specifically, multi-year mean Noah–MP GPP was 68.5%, 107.1%, and 106.4% higher than the PML GPP

product in evergreen broadleaf forests, deciduous broadleaf forests, and croplands, respectively.
We also clarified in the manuscript that PML is a model-based benchmark product rather than direct observational data. Therefore, the national-scale discrepancies are described as differences relative to PML, whereas site-level model bias is evaluated against flux-tower-derived GPP using TSS, correlation coefficient, nRMSE, and PBIAS. The flux-tower evaluation further indicates that Noah–MP overestimated GPP at several individual sites. These revisions have been incorporated into the Abstract and Sections 4.1.1-4.1.2.

Q3. Lines 108–109: The cited references here should focus on the original development and improvement of the Noah-MP model. Representative studies including Niu et al. (2011) and He et al. (2025) are recommended for supplementation.
We thank the reviewer for this helpful suggestion. We agree that the references in this section should focus on the original development and subsequent improvement of the Noah–MP model. In the revised manuscript, we supplemented the model-description section with the original Noah–MP development study by Niu et al. (2011) and the recent evaluation of the refactored Noah–MP version 5.0 by He et al. (2025). We also retained Yang et al. (2011) to support the description of the model framework and parameterization options. These references have been added to Lines 109-110.

Q4. Line 109: Replace the word “conficting” with “different”, as diverse parameterization schemes do not necessarily conflict with one another.
We thank the reviewer for this helpful comment. We agree that alternative parameterization schemes do not necessarily represent conflicting assumptions. Therefore, the word “conflicting” has been replaced with “different” in the revised manuscript (Line 111).

Q5. Lines 125–127: Clearly specify the variable whose simulation uncertainty is discussed in this section.
We thank the reviewer for pointing out this ambiguity. We agree that the original wording did not clearly distinguish the simulated variable examined in the cited study from that investigated in the present study. In the revised Introduction, we explicitly clarify that You et al. (2020) examined uncertainty in Noah–MP-simulated snow depth. The relevant text has been revised accordingly in Lines 126–131.
“You et al., (2020) conducted 20,736 Noah–MP physics-ensemble simulations at each site to evaluate the sensitivity of simulated snow depth to alternative physical parameterization schemes. Their results showed that the uncertainty range of simulated snow depth was primarily associated with the parameterizations to which the model was most sensitive, and that these sensitivities varied among sites.”

Q6. Lines 224–227: Revise and clarify the logical relationship between the two sentences: when the dynamic vegetation option is activated in Noah-MP, only the Ball-Berry scheme can be adopted.

We thank the reviewer for this helpful comment. We revised the relevant text to clarify the logical relationship between the dynamic vegetation option and the canopy stomatal-resistance scheme in Noah–MP. Specifically, when the dynamic vegetation option is activated, Noah–MP permits only the Ball–Berry scheme for canopy stomatal resistance. Therefore, alternative stomatal-resistance parameterizations could not be independently included in the present sensitivity analysis. The revised text is provided in Lines 245–250.

"Canopy stomatal resistance schemes may influence GPP simulations; however, in Noah-MP, when the dynamic vegetation option is activated, only the Ball–Berry scheme (Ball et al., 1987) is available. Therefore, no alternative stomatal resistance parameterizations were included in this study."

Q7. Line 237: Correct the redundant double punctuation error "..".

We thank the reviewer for identifying this typographical error. The redundant double punctuation ("..") at Line 237 has been corrected in the revised manuscript.

Q8. Lines 275 and 281: Unify the writing format of "ERA5-Land" throughout the manuscript to maintain consistency.

We thank the reviewer for this helpful comment. The writing format of "ERA5-Land" has been checked and unified throughout the revised manuscript to ensure consistency.

Q9. Lines 298–301: Please explain the rationale behind the adopted spin-up strategy. Additionally, clarify why the cyclic simulation starts from the year 2000, rather than running a continuous simulation from 1999 during the final spin-up cycle.

We thank the reviewer for this important comment. We apologize that the original description did not clearly distinguish the cyclic spin-up, the transition run, and the production simulation.

The cyclic spin-up did not start from the year 2000. Instead, the meteorological forcing for 1999 was repeatedly cycled for 30 loops before each ensemble simulation. This procedure was designed to reduce the influence of uncertain initial conditions on soil water, soil temperature, carbon fluxes, and representative vegetation states. The restart state generated at the end of the final 1999 cycle corresponds to 1 January 2000.

This restart state was then used to drive Noah–MP once with the actual meteorological forcing from 1 January 2000 to 1 January 2001. Thus, the year 2000 was used as a one-year transition period rather than an additional cyclic spin-up year. This transition run allowed the state obtained under repeatedly cycled 1999 forcing to adjust to the actual meteorological conditions immediately preceding the analysis period and generated the restart state for 1 January 2001. The production simulations were subsequently conducted continuously from 2001 to 2020; therefore, the year 2000 was excluded from the final analysis.

Repeating the 1999 forcing for an additional final cycle would only reproduce the same meteorological conditions already used for equilibration and would not generate an initial state conditioned on the actual forcing in 2000. The adopted two-stage strategy therefore avoids an abrupt transition from the repeated 1999 forcing to the production period.

We additionally evaluated spin-up convergence using water-, energy-, carbon-, and vegetation-related variables. During the final 10 spin-up loops, the absolute normalized trends and mean relative inter-cycle changes for GPP, ET, soil moisture, deep soil moisture, latent heat flux, and sensible heat flux ranged from 2.05×10^{-5} to 2.91×10^{-4} and from 2.96×10^{-5} to 3.31×10^{-4}, respectively. For leaf area index, leaf mass, fine-root mass, stem mass, net primary productivity, and total photosynthesis, the corresponding values ranged from 2.86×10^{-8} to 5.88×10^{-4} and from 2.33×10^{-8} to 5.93×10^{-4}, respectively. All evaluated metrics were below the predefined threshold of 1.0×10^{-3}, indicating that the evaluated water, energy, carbon, and representative fast-response vegetation variables approached quasi-steady conditions before the production simulations.

These clarifications and convergence diagnostics have been added to Section 3.1 and Figures 1-2.

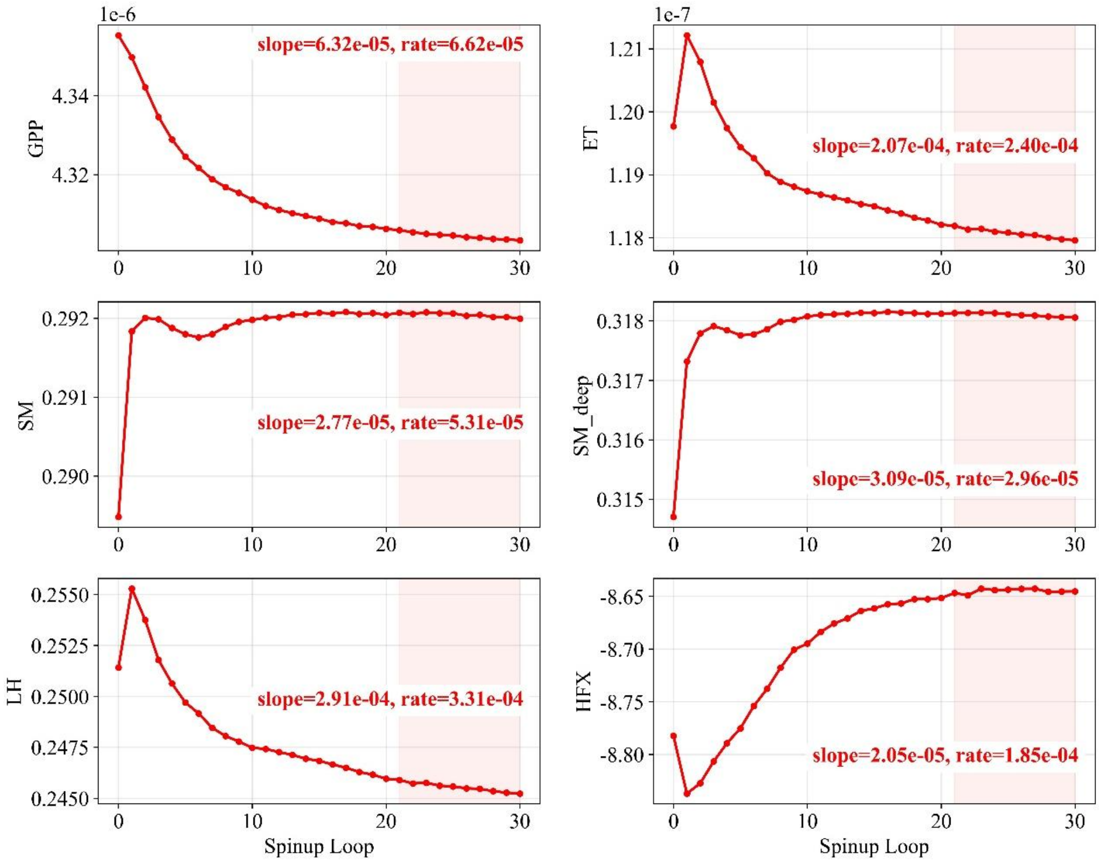

Figure 1. Spin-up convergence of carbon, water, and energy variables for the MODIS-initialized simulation. Each point represents the cycle-mean value for one spin-up loop. Shaded areas indicate the final 10 cycles used for convergence assessment. The annotations show the absolute normalized linear trend and the mean relative inter-cycle change rate. All diagnostic variables satisfied the predefined convergence criterion of 1.0×10^{-3}.

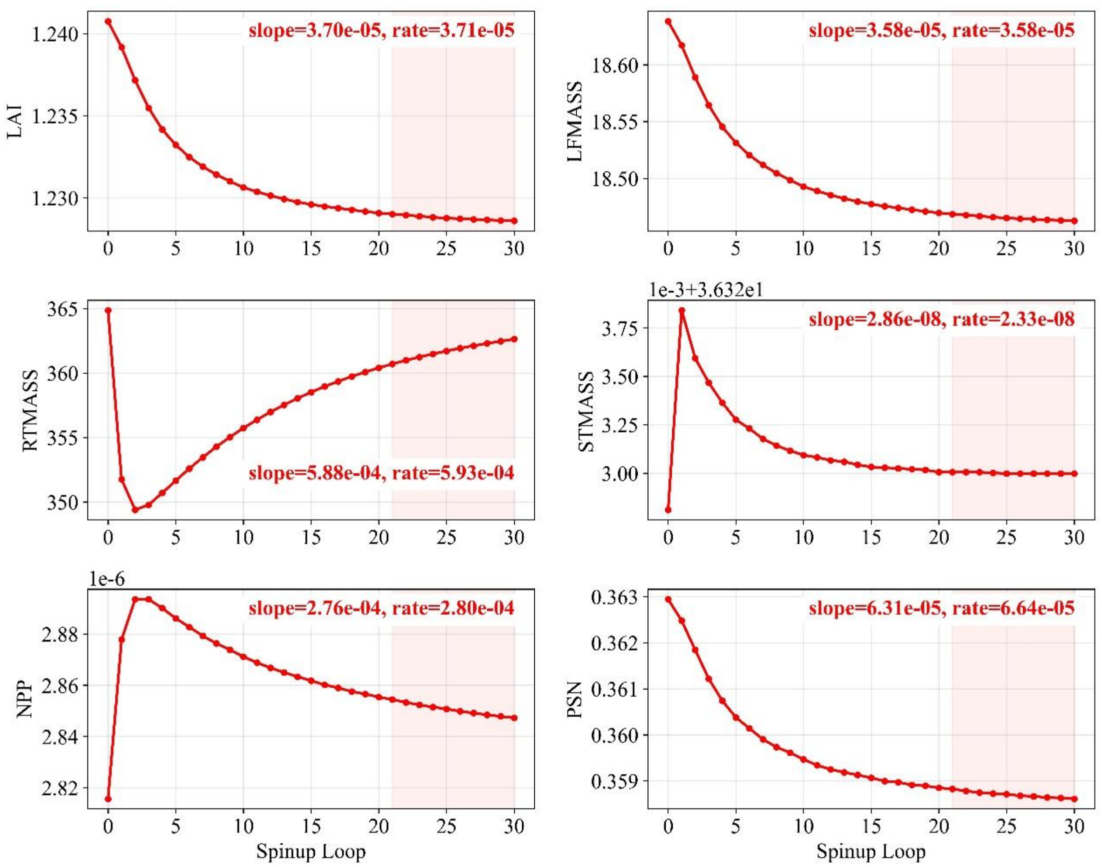

Figure 2. Convergence of vegetation structural variables and biomass/carbon pools during the MODIS-initialized spin-up. Each point represents the cycle-mean value for one spin-up loop. The shaded area denotes the final 10 cycles used to evaluate convergence. Stable LAI, vegetation cover, biomass/carbon pools, and vegetation turnover indicators demonstrate that the dynamic vegetation state reached a quasi-steady condition before the main simulations.

Q10. Equations (3) and (4): Define the variable σf before presenting the relevant formulas.

We thank the reviewer for pointing out this logical issue. Following the reviewer's suggestion, we have reorganized the sequence of equations in the revised manuscript. Specifically, we now define the standard deviation of the model simulations (σ_f) before presenting the formulas for the correlation coefficient R (Equation 3) and the normalized standard deviation $\widehat{\sigma_f}$ (Equation 4).

In the revised version, Equation (1) defines σ_o and Equation (2) defines σ_f. Then, Equation (3) uses these defined variables to calculate R. This ensures that all variables are defined prior to their use.

We believe this revision has improved the logical clarity of the methodology section. Please see the updated text in Section 3.2. We hope this addresses the reviewer's concern.

Q11. Line 360: Add in-depth discussion to interpret the underlying reasons for the low TSS values obtained in the results.

We thank the reviewer for this important comment. We agree that the original manuscript did not provide sufficient discussion of the underlying causes of the low

TSS values at several flux-tower sites.

In the revised manuscript, we added an ecosystem-stratified, process-based diagnostic analysis and expanded the discussion of site-level model performance in Sections 4.1.1 and 5.1. In addition to GPP, we evaluated the temporal agreement and normalized errors of available tower-derived absorbed photosynthetically active radiation (APAR), latent heat flux (LE), sensible heat flux (Hs), and soil water content (SWC), and examined their monthly seasonal cycles at representative forest, grassland, and cropland sites (Figs. 3-5). The following figures summarize the diagnostic evaluation results. Figure 3 shows the correlation coefficients (R) for GPP and the four diagnostic variables across sites. Figure 4 presents the corresponding normalized root-mean-square errors (nRMSE). Figure 5 illustrates the monthly climatological seasonal cycles at representative forest, grassland, and cropland sites.

The analysis indicates that low TSS values cannot be attributed to a single common source of uncertainty or to one individual parameterization scheme. At DHF, for example, the poor GPP performance (R=0.40; nRMSE = 7.63) coincided with weak agreement and large errors in APAR (R=0.22; nRMSE = 8.39), as well as substantial discrepancies in Hs, LE, and SWC. Although SWC showed relatively high temporal correlation at this site (R=0.78), its nRMSE remained high (2.28), indicating that temporal correspondence did not necessarily imply accurate magnitude. The seasonal cycles further showed that Noah–MP substantially overestimated growing-season APAR and GPP at DHF. These results are consistent with interacting errors in canopy radiation absorption, soil-water regulation, and surface-energy partitioning, which may together create overly favorable conditions for simulated carbon assimilation.

The grassland sites showed a different pattern. For example, DLG captured the broad seasonal timing of GPP but substantially overestimated its seasonal amplitude, whereas NMG and XLG showed weak temporal agreement in GPP. These results suggest that low TSS values in grasslands may involve site-specific differences in phenology, canopy development, radiation interception, soil-water regulation, and vegetation physiological responses, rather than a uniform soil-moisture-related error.

We also clarified that contrasting performance among sites cannot be explained by vegetation category alone. For instance, DHF and CBF are both represented as mixed forests in Noah–MP but occur under different hydroclimatic conditions. This suggests that fixed plant-functional-type parameters and the simplified Ball–Berry stomatal-conductance formulation may not fully represent site-specific canopy–atmosphere coupling and water-stress responses.

Rather than masking these biases through site-specific recalibration, which would compromise the objective of the nationwide multi-physics sensitivity analysis, we addressed them through process-based diagnosis, ecosystem-stratified evaluation, and an expanded discussion of the model processes requiring further improvement.

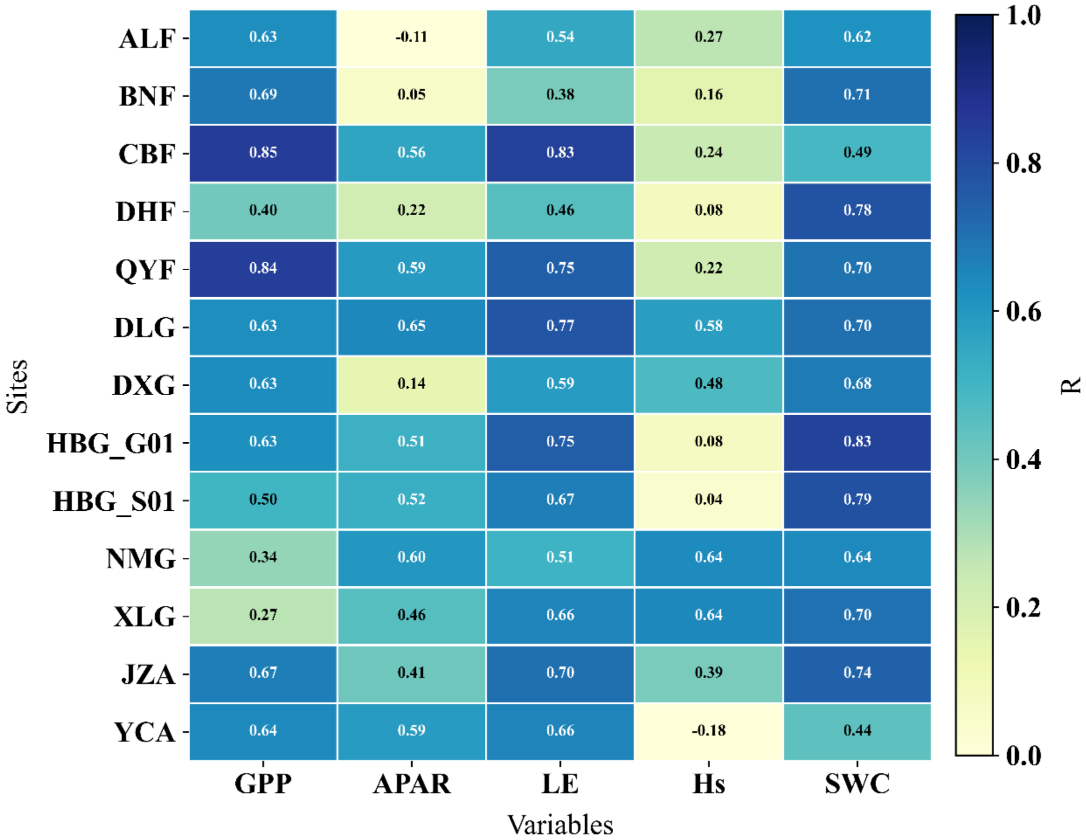

Figure 3. R for GPP, APAR, latent heat flux (LE), sensible heat flux (Hs), and soil water content (SWC).

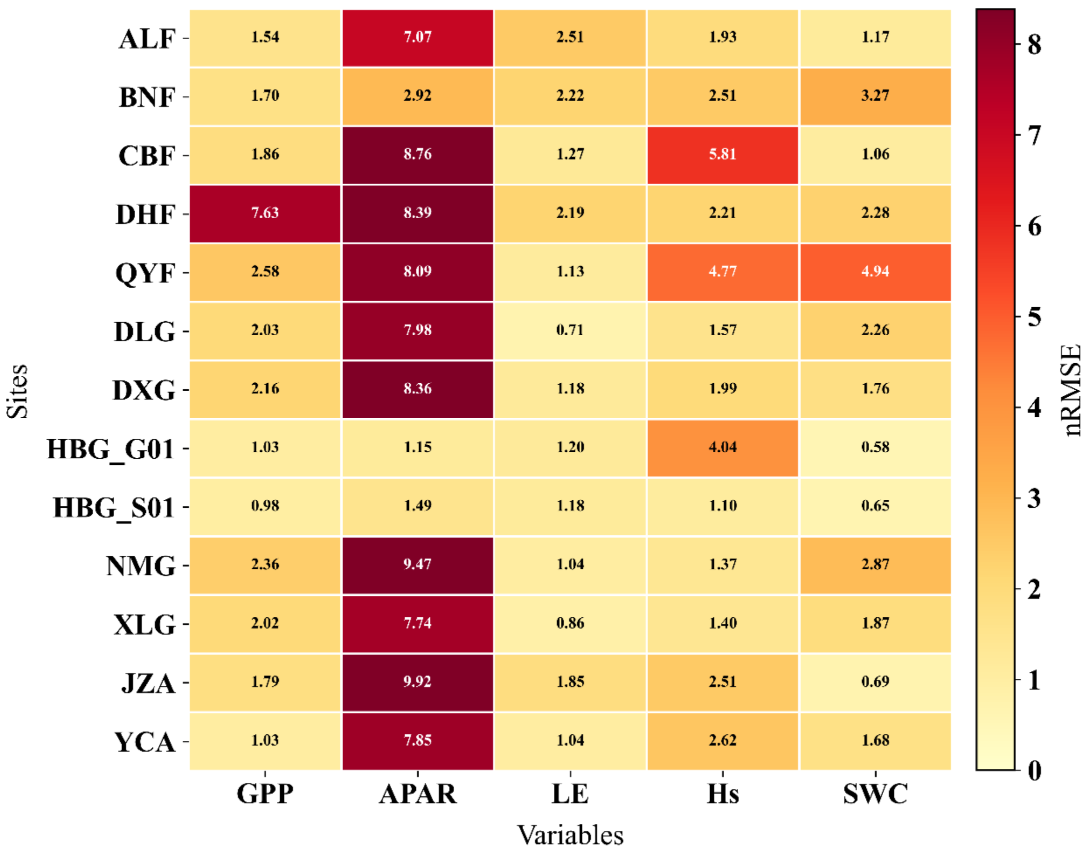

Figure 4. Normalized root-mean-square errors (nRMSE) for GPP, APAR, latent heat flux (LE), sensible heat flux (Hs), and soil water content (SWC).

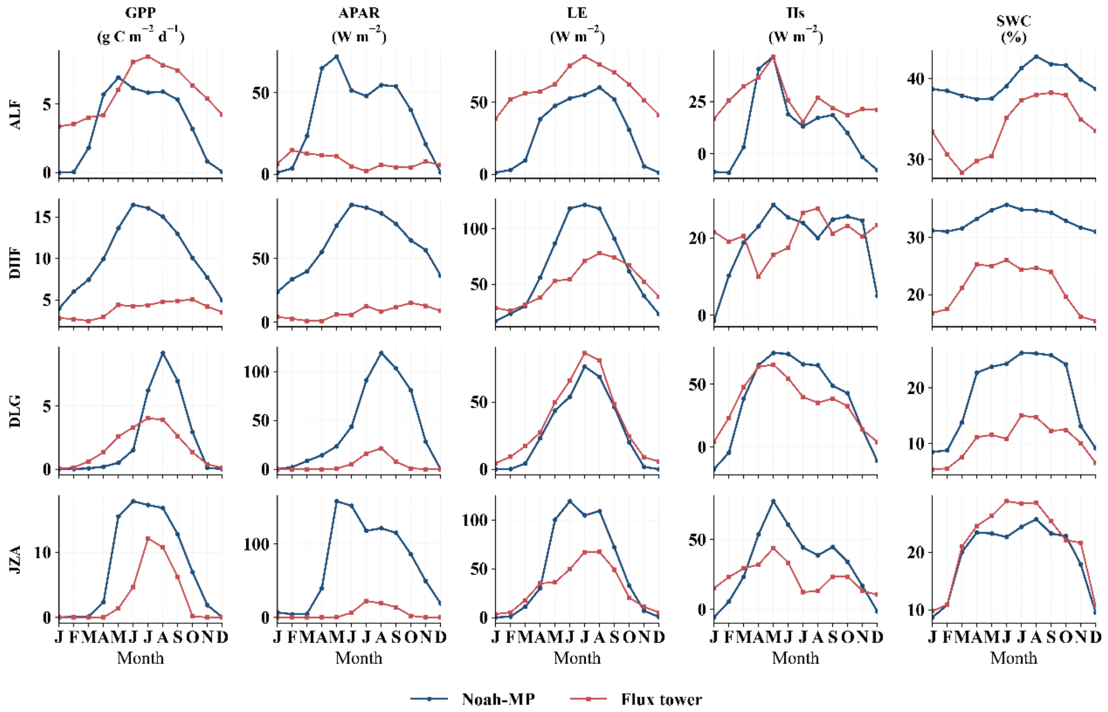

Figure 5. Monthly climatological seasonal cycles of GPP and diagnostic variables at representative flux-tower sites. Blue and red lines represent Noah-MP simulations and flux-tower-derived estimates, respectively. ALF, DHF, DLG, and JZA represent forest, forest, grassland, and cropland sites, respectively.

Q12. Section 4.1.2: Correct the figure citation error; the referenced Figure 3 should be revised to Figure 4.

We thank the reviewer for catching this citation error. We have corrected the figure reference in Section 4.1.2, changing the incorrect citation of "Figure 3" to "Figure 4" in the revised manuscript.

Q13. Line 379: Modify the inappropriate expression. Model simulation outputs should not be referred to as "dataset" in this context.

We thank the reviewer for pointing out this terminological issue. We agree that model simulation outputs should not be referred to as "dataset" in this context. We have revised the wording in Line 379 of the revised manuscript, replacing "dataset" with "simulation results" to more accurately describe the model outputs.

"The PML dataset and the Noah-MP simulation results both revealed clear seasonal GPP patterns, characterized by summer peaks and winter valleys, highlighting climate phenology carbon uptake."

Q14. Section 4.2: This section lacks a detailed description of the seasonal variation characteristics illustrated in Figure 6. Additionally, Figure 7 also summarizes the seasonal variations in the sensitivity of different parameterization schemes. To avoid redundant presentation, it is recommended to retain only one set of the seasonal variation figures and delete the duplicate content.

We thank the reviewer for this helpful suggestion. We agree that Section 4.2 lacked a detailed description of the seasonal variation characteristics shown in Figure 6, and that Figure 7 largely repeated the same seasonal information.

To address this issue, we have made the following revisions:

We have substantially expanded the description of seasonal sensitivity patterns in Section 4.2, providing a detailed interpretation of the seasonal variations presented in Figure 6.

To avoid redundancy while retaining the seasonal information for interested readers, we have moved the original Figure 7 to the Supplementary Material (now Figure S1). The main text now focuses on the key seasonal patterns, with additional details available in the Supplement.

We believe this revision improves the clarity and conciseness of the main text while preserving the full seasonal analysis for reference.

Q15. Line 496: Correct the redundant double punctuation error "..".

We thank the reviewer for pointing out this typographical error. We have corrected the redundant double punctuation ".." to a single period "." at Line 496 of the revised manuscript.

Q16. Line 683: Correct the typo "uncertaintie" to "uncertainties".

We thank the reviewer for noting this spelling error. We have corrected "uncertaintie" to "uncertainties" in Line 683 of the revised manuscript.