Response to Reviewer 2 Comments

Synthesis: This manuscript presents an improved Coupled Carbon and Water (CCW) model incorporating dynamic water use efficiency (WUE) to disentangle the effects of climate change, vegetation dynamics, and atmospheric CO_2 on water yield (WY) across China during 1982–2017. The study addresses an important research gap by explicitly accounting for CO2 effects and providing a robust attribution analysis at both national and regional scales. The integration of scenario-based attribution and elasticity analysis is innovative and valuable for water resource management and climate adaptation strategies.

The study is generally well-structured, with clear objectives, methods, and results. However, there are a few areas where further clarity, elaboration, and enhancement could improve the overall impact and rigor of the paper. I provide specific comments and suggestions below:

Response: Thank you very much for your thorough and constructive evaluation of our manuscript. We sincerely appreciate the time and effort you have devoted to assessing our work. Your positive recognition of the study's innovation—particularly the improved Coupled Carbon and Water (CCW) model with dynamic water use efficiency (WUE) and the integration of scenario-based attribution with elasticity analysis—encourages us greatly. We have carefully considered all your valuable comments and those from the other reviewers, and we have revised the manuscript accordingly to enhance its clarity, depth, and scientific rigor. A detailed, point-by-point response to all comments is provided below, where the reviewers' comments are presented in black and our responses are provided in deep sky blue.

Abstract:

1: The abstract effectively summarizes the study, but it is rather dense with technical terms and numerical results. Consider slightly rebalancing it by adding one or two sentences that emphasize the practical implications (e.g., relevance for water resource management and ecological restoration) so that non-specialist readers can more easily grasp the significance.)

Response: Thank you for your constructive comment. We agree that the abstract was originally dense with technical terms and numerical results, which may limit accessibility for non-specialist readers. To improve readability and highlight the broader significance, we have added one sentence at the end of the abstract emphasizing the practical implications of our findings for water resource management and ecological restoration. The revised abstract now provides a more balanced presentation between technical content and applied relevance.

Relevant text reads (line 12-33): The rapid environmental changes, including climate change, escalating atmospheric CO_2 concentration ([CO_2]), and vegetation dynamics, have been significantly impacting hydrological processes. Yet disentangling the respective contributions of climate, vegetation, and [CO2] change to water yield (WY)—especially clarifying [CO2]-driven physiological effects—remains difficult. Therefore, this study improved the coupled carbon and water (CCW) model integrating dynamic water use efficiency (WUE) better capture CO_2-physiological feedbacks.; Using scenario analysis, WY changes across China from 1982 to 2017 were attributed to climate, vegetation, and [CO_2] drivers. The results showed that climate change (especially precipitation change) emerged as the dominant driver, directly affecting over 70% of China's land area. The vegetation change was the second largest factor to reduce WY, especially in central China. The effect of the escalating [CO_2] was relatively small. Spatial analysis aligned with isohyetal lines further revealed that vegetation change and [CO_2] exerted greater influence within the 400–1600 mm precipitation range. In addition, the elasticity analysis showed that the sensitivity ranking of impact factors is precipitation > [CO_2] > NDVI for the whole China. Therefore, CMIP6 SSP585 projections indicate that accelerating [CO_2] rise will amplify its hydrological effect to a +1.29% annual WY increase by 2100, surpassing vegetation influences. This study refines WY attribution by coupling dynamic WUE with ecohydrological modeling, valuable insights for optimizing regional water resource allocation and developing adaptive ecosystem management strategies under future climate scenarios.

Introduction and Background:

1: While the introduction clearly outlines the motivation, it would be useful to more explicitly highlight what distinguishes this study from other model applications. For example, a brief comparison with previous studies could emphasize the novelty of incorporating CO_2-induced WUE changes.

Response: Thank you for your constructive comment. We agree that the introduction should more explicitly highlight what distinguishes this study from existing model applications. In the revised version, we have clearly articulated that the novelty of our study lies in the mechanistic incorporation of CO_2-driven dynamic water-use efficiency (WUE) feedback into the coupled carbon and water (CCW) model.

Relevant text reads (line 119-133): Nevertheless, the original CCW model, while robust in capturing vegetation-climate interactions, does not account for CO_2-induced physiological changes, specifically long-term enhancements in water-use efficiency (WUE) resulting from elevated [CO_2], thereby limiting its capacity to isolate [CO_2] fertilization effects from vegetation structural and climatic influences(Adams et al., 2020; Li et al., 2023).

To address this limitation, our study enhanced the CCW framework by incorporating dynamic WUE responses to [CO_2], allowing explicit attribution of runoff changes to three distinct drivers—climate change (eg. precipitation, temperature, and so on), vegetation structural change (NDVI, and land use and land cover (LULC)), and [CO_2]-physiological effects (stomatal optimization). This extension provides a mechanistically grounded capability that prior empirical or regression-based attribution methods could not achieve, offering new insight into how [CO_2] modulates vegetation–hydrology interactions across large spatial scales.

2: The introduction mainly focuses on China, but since similar issues of climate–vegetation–CO_2 interactions exist globally, it may help to briefly situate this work in a broader international context. For example, mentioning comparable studies in other semi-arid or monsoon-influenced regions would show the wider relevance of the improved CCW model.

Response: Thank you for your constructive comment. We agree that positioning the study within a broader international context would strengthen the relevance and generalizability of our work. In the revised Introduction, we have added a concise paragraph highlighting that similar interactions among climate, vegetation, and CO_2 have been widely reported across other semi-arid and monsoon-influenced regions worldwide—such as the Sahel, South Asia, and Mediterranean ecosystems—where vegetation greening and water yield responses to climate and CO_2 forcing have been actively studied. This addition clarifies that, although our analysis focuses on China, the improved CCW model and its explicit integration of CO_2-induced WUE feedbacks are broadly applicable to global ecohydrological research and water resource management in similar climatic zones.

Relevant text reads (line 44-61): The global environment has been undergoing rapid changes, impacting hydrological processes through climate change, escalating atmospheric CO_2 concentration [CO_2], and vegetation dynamics (Piao et al., 2007; Wei et al., 2024). Notably, China has experienced a visible greening trend in recent decades, prompting a heightened focus on ecological and water resource concerns (Chen et al., 2019). Investigating the influence of vegetation changes on runoff has thus emerged as a pivotal research area, aligning with China's increasing emphasis on environmental sustainability. China's diverse climatic zones and pronounced greening make it an ideal natural laboratory for investigating these ecohydrological feedbacks, with insights that are globally relevant yet directly informative for sustainable water resource management and ecological restoration in China(Ogutu et al., 2021; Yang et al., 2019), and for other semi-arid and monsoon-influenced regions such as the Sahel, South Asia, and the Mediterranean Basin(Nkiaka et al., 2025; Rahman et al., 2025; Serrano-Notivoli et al., 2022). Understanding the intricate interplay among vegetation dynamics, climate change, and [CO_2] within the water cycle, particularly concerning runoff therefore it is not only of global relevance but also of profound importance for advancing sustainable water resource management and ecological restoration strategies in China under accelerating environmental change.

Methods:

1: The improved CCW model assumes interception evaporation factor fi equals zero. Since this simplification is acknowledged in the Discussion, please provide a short justification earlier in the Methods section so that readers can immediately understand this limitation.

Response: Thank you for your constructive comment. We agree that the assumption of the interception evaporation factor (f_i) being set to zero should be briefly justified in the Methods section to enhance transparency and reader understanding. We have accordingly revised the section to clarify this simplification and its rationale.

Relevant text reads (line 218-224): In this study, the interception evaporation factor (f_i) was set to zero. This simplification follows previous large-scale ecohydrological studies (Cheng et al., 2017), which reported that canopy interception and soil surface evaporation account for a minor portion of total evapotranspiration at annual to multi-decadal scales. Given that the improved CCW model focused on yearly water yield (WY) dynamics rather than event-scale hydrological responses, neglecting interception loss reduces model complexity without substantially affecting WY estimation.

2: The attribution analysis is based on "trends" in WY under different scenarios, but the exact method of calculating these trends (e.g., linear regression, Mann–Kendall test, or another approach) is not clearly described. Providing details on the trend detection method, as well as the statistical significance criteria, would help readers better assess the robustness of the results.

Response: Thank you for your constructive comment. We agree that the description of trend estimation could be made clearer. Specifically, we quantified the long-term trend in annual WY (1982–2017) using the non-parametric Theil–Sen estimator for the slope.

Relevant text reads (line 267-270): For each scenario, the long-term trend in annual WY over 1982–2017 was quantified using the Theil–Sen estimator, yielding a robust slope. The relative contributions of climate, vegetation, and [CO2] to changes in WY were calculated using the following formula:

Results:

1: Figures 5 and 6 demonstrate spatial heterogeneity in WY drivers. It would help if the authors could provide a more policy-relevant interpretation, e.g., what the findings imply for water resource planning in regions where vegetation dominates versus where climate dominates.

Response: Thank you for your constructive comment. We agree that linking spatial heterogeneity in WY drivers to practical implications can improve the relevance of our findings. Since the Results section primarily presents objective spatial patterns, we have added a short paragraph in the Discussion section to interpret the regional contrasts from a management perspective.

Relevant text reads (line 555-563): From a policy perspective, these spatial contrasts have distinct implications for regional water management. In vegetation-dominated regions such as the Yangtze and Huang river basins, enhancing ecosystem-based restoration, optimizing vegetation composition, and preventing overgreening that may suppress runoff should be prioritized. Conversely, in climate-dominated areas such as Northwest and Southeast China, adaptive measures emphasizing precipitation variability, water storage capacity, and drought resilience are crucial. Recognizing and tailoring water management strategies to these driver-specific regimes can enhance the effectiveness of both ecological restoration and climate adaptation programs across China.

2: The elasticity analysis provides valuable insights into the sensitivity of WY to different drivers. However, the discussion could be enhanced by more explicitly linking the elasticity results to the relative contributions of each driver. For instance, why does CO_2 have a higher elasticity than NDVI yet a smaller overall contribution? Clarifying how elasticity and the magnitude of change jointly determine the net impact would strengthen the interpretation.

Response: Thank you for your constructive comment. We agree that the linkage between elasticity and contribution deserves clarification. In the revised manuscript, we emphasize that elasticity quantifies the sensitivity of WY to a unit change in each driver, whereas contribution reflects the integrated effect of both elasticity and the magnitude of driver change.

Relevant text reads (line 532-543): Elasticity analysis (Section 3.4) revealed distinct sensitivities of WY to environmental drivers: precipitation exhibited the highest elasticity coefficient for the whole China ($\varepsilon P = 1.55$), followed by CO_2 ($\varepsilon CO_2 = 0.55$) and NDVI ($\varepsilon NDVI = -0.44$). However, spatial analysis showed that vegetation and [CO_2] collectively dominated WY changes in 400–1600 mm/yr precipitation zones, despite their lower sensitivity rankings. The joint effect of elasticity and the magnitude of driver change that determines each driver's net contribution. In the 400–1600 mm/yr precipitation zones, NDVI displayed (Fig. 8) a larger relative temporal variation compared with precipitation, which fluctuated within a narrower range.. Consequently, vegetation's stronger relative change amplified its hydrological influence, overriding its lower elasticity. Similarly, CO_2's historical impact was constrained by its slow accumulation rate (0.49%/yr), yet its relatively high elasticity positions it as a latent driver.

Discussion:

1: While the study focuses on climate, vegetation, and CO_2 drivers, other human activities such as reservoir regulation, irrigation, and groundwater extraction can also significantly affect water yield in China. Since these processes are briefly mentioned as limitations, it would strengthen the discussion if the authors could add a short paragraph acknowledging how such anthropogenic factors may interact with the modeled drivers, and whether the improved CCW framework could potentially incorporate them in future work.

Response: Thank you for your constructive comment. We agree that anthropogenic factors such as reservoir regulation, irrigation, and groundwater extraction play an important role in shaping hydrological responses in China. To address this point, we have expanded the existing discussion paragraph.

Relevant text reads (line 590-599): Thirdly, the improved CCW model does not incorporate certain human activities, such as large-scale irrigation, groundwater pumping, and reservoir regulation, which should be incorporated in future studies. For instance, irrigation can sustain vegetation greening during dry seasons, potentially amplifying the vegetation–climate feedback on water yield. Incorporating such anthropogenic processes into the CCW framework through coupled irrigation and water management modules would enable more comprehensive attribution analyses in future studies.

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