Reply to Referee #2 on manuscript EGUSPHERE-2026-1335: "Integrating Ozone–vegetation Damage Schemes into SSiB4/TRIFFID: Evaluation of Six Parameterizations and Refinement of Ozone Decay Process Across Plant Functional Types"

Reply on RC2

We sincerely thank Referee #2 for the thoughtful and constructive review. The comments were particularly helpful for improving the explanation of the refined decay/healing treatment and for clarifying the scope of our modification to the Li2024 framework.

In the revised manuscript, we have clarified the interpretation of the decay and healing terms as complementary attenuation processes for accumulated O_3 stress. The LAI-related healing term represents the rapid dilution of CUO during canopy expansion, whereas the leaf-longevity-based decay term provides a gradual attenuation pathway when LAI is stable or declining. We have also moderated the wording to present this treatment as a trait-constrained refinement within the existing CUO framework, rather than as process-based representation of O_3 injury and recovery.

To support this interpretation, we added further discussion of the physiological basis, the role of leaf longevity, and added additional observational evidence from in the response supplementary figures from O_3 fumigation experiments. We also revised the Methods, Results, Discussion, and relevant figure captions to make the motivation, implementation, and implications of the refinement clearer. The notation has also been updated from "L2024" to "Li2024" throughout the manuscript to avoid confusion with L2015.

A detailed point-by-point response, including supplementary response figures, is provided in the response PDF attached as a supplementary file. In the response PDF, the referee's comments are shown in black, while our responses and the corresponding manuscript revisions are shown in blue. All changes are also shown in the revised manuscript using track changes.

Major comment

Process basis of the refined decay/healing treatment requires clearer justification. My main concern relates to the treatment of the decay and healing processes in the refined Li2024 scheme. Li2024 includes a decay of accumulated POD for all PFTs, intended to represent the effects of leaf turnover and the emergence of new leaves. This is physically understandable in the sense that newly emerged leaves would have near-zero accumulated ozone damage, which would reduce canopy-mean POD. In the revised formulation presented here, the authors appear to extend or reformulate this treatment using a leaf-age-based decay approach for deciduous vegetation as well. The key issue is that the manuscript does not yet provide a sufficiently clear mechanistic basis for this formulation. What exact biological or physiological process is represented by the decay term for deciduous plants? Why is a leaf-age-based treatment appropriate for all PFTs, especially deciduous vegetation? Is there observational or experimental evidence supporting the proposed equations and parameter values?

At present, the refinement appears to be introduced primarily because the original Li2024 configuration produces too strong a late-season suppression of photosynthesis and GPP under cumulative ozone exposure. If this interpretation is correct, then the revised treatment is, at least in part, an empirical adjustment introduced to improve the seasonal cycle. In this case, the manuscript should present it more cautiously. Specifically, this component should not be framed as a robust process-based improvement unless stronger justification is provided. Instead, it would be more appropriate to describe it as a tentative or exploratory refinement, and to move from the Results section to Discussion, with suitably moderated language.

Given the aims of GMD, it is particularly important to distinguish clearly between: a process-based model development supported by theory or observations, and a pragmatic tuning-type modification introduced to reduce a simulation bias. The current manuscript does not yet make this distinction sufficiently clear.

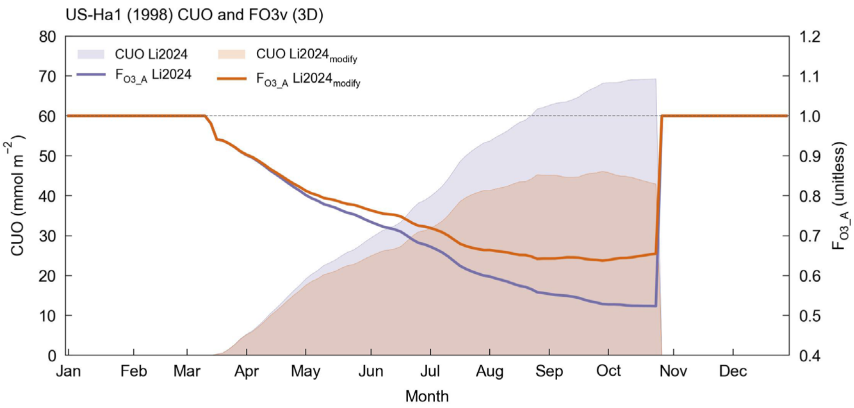
Response:

We thank the referee for this thoughtful and important comment. We appreciate the concern that the biological meaning of reformulation needs to be explained more explicitly, particularly for deciduous vegetation. We also agree that the manuscript should explain more clearly how the decay and healing terms in the $Li2024_{modify}$ framework are interpreted, and how this interpretation differs from an empirical adjustment for the simulated GPP seasonality.

In our implementation, we interpret the decay term (D) and the healing term (H) as two distinct but complementary processes that reduce the accumulated O_3 stress (i.e. cumulative O_3 uptake, CUO) at canopy level. The healing term H is derived from changes in LAI, which represents an attenuation of previously accumulated O_3 stress by newly formed leaves. Therefore, this process is mainly effective during the early-to-middle growing season when LAI is increasing rapidly. Once the LAI reaches its seasonal peak and becomes constant or begins to decrease, H becomes 0.0 and the healing term has no effect on reducing CUO. On the other hand, the decay term D provides a continuous attenuation pathway to reduce the accumulated O_3 injury. By using leaf longevity as a characteristic time to describe the gradual decay of O_3 effects that associated with cellular repair, detoxification, and foliage replacement, this term provides a simplified representation of physiological-related decay process that reduce the accumulated O_3 stress even when LAI is constant or decreasing.

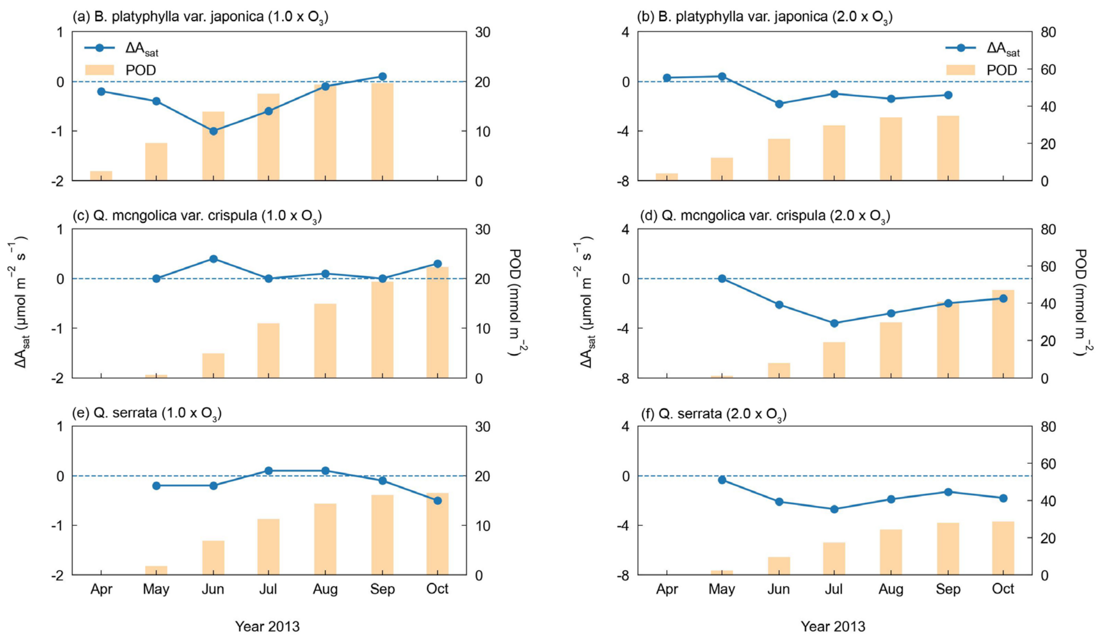
This interpretation generally follows the CUO framework developed by Lombardozzi et al. (2015) and Li et al. (2024) with decay and/or healing processes to mitigate the accumulated O_3 stress. It is also conceptually aligned with the injury-recovery logic of Felzer et al. (2009), which applies a constant healing rate due to cellular repair and replacement of leaves when LAI is constant or decreasing, with a rapid healing term when LAI is increasing. In our implementation, D corresponds to the first component, representing the gradual loss of CUO over a characteristic time constrained by leaf longevity, whereas H corresponds to the rapid healing due to canopy expansion. We use leaf longevity as the characteristic time for the decay process. This choice has a clear physiological meaning: leaf longevity describes how long leaves typically remain active before leaf fall or replacement. Once these leaves complete their life cycle, their accumulated O_3 stress should therefore be removed from the canopy. We recognize that leaf longevity does not explicitly quantify the specific mechanisms of cellular repair or O_3 detoxification. Instead, it provides a simple and observable trait-based constraint on the gradual attenuation of accumulated O_3 stress within the existing CUO framework. From this perspective, the two terms should not be regarded as separate treatments for different vegetation groups, but as complementary processes that may operate at different stages of canopy development. Applying both decay and healing processes to all PFTs therefore extends the original CUO framework in a more consistent way across PFTs. As a result, the refinement keeps the original CUO framework but extends it by treating decay and healing as complementary attenuation pathways across all PFTs, with leaf longevity providing a physiological constraint on the timescale of decay process.

In our SSiB4/TRIFFID implementation, the distinction between the two attenuation pathways becomes important for deciduous vegetation. The LAI-related healing term mainly attenuates CUO during the early growing season, but becomes ineffective once LAI reaches its seasonal maximum and begins to decline. In the absence of a continuous decay pathway, CUO can therefore accumulate through the mid-to-late growing season until it is reset to zero when LAI falls below the prescribed threshold. This behavior is clearly illustrated in our SSiB4/TRIFFID simulation at US-Ha1, a temperate deciduous broadleaf forest site. As shown in Response Supplementary Figure 2, the original Li2024 implementation shows persistent late-season CUO accumulation and a corresponding decrease in the O_3-induced vegetation damage factor (F_{O3_A}). By applying the decay term together with the LAI-based healing term, the refined formulation includes a continuous attenuation pathway during periods of stable or declining LAI, thereby reducing the carry-over effect of accumulated O_3 stress and alleviating the progressive enhancement of late-season O_3 damage.

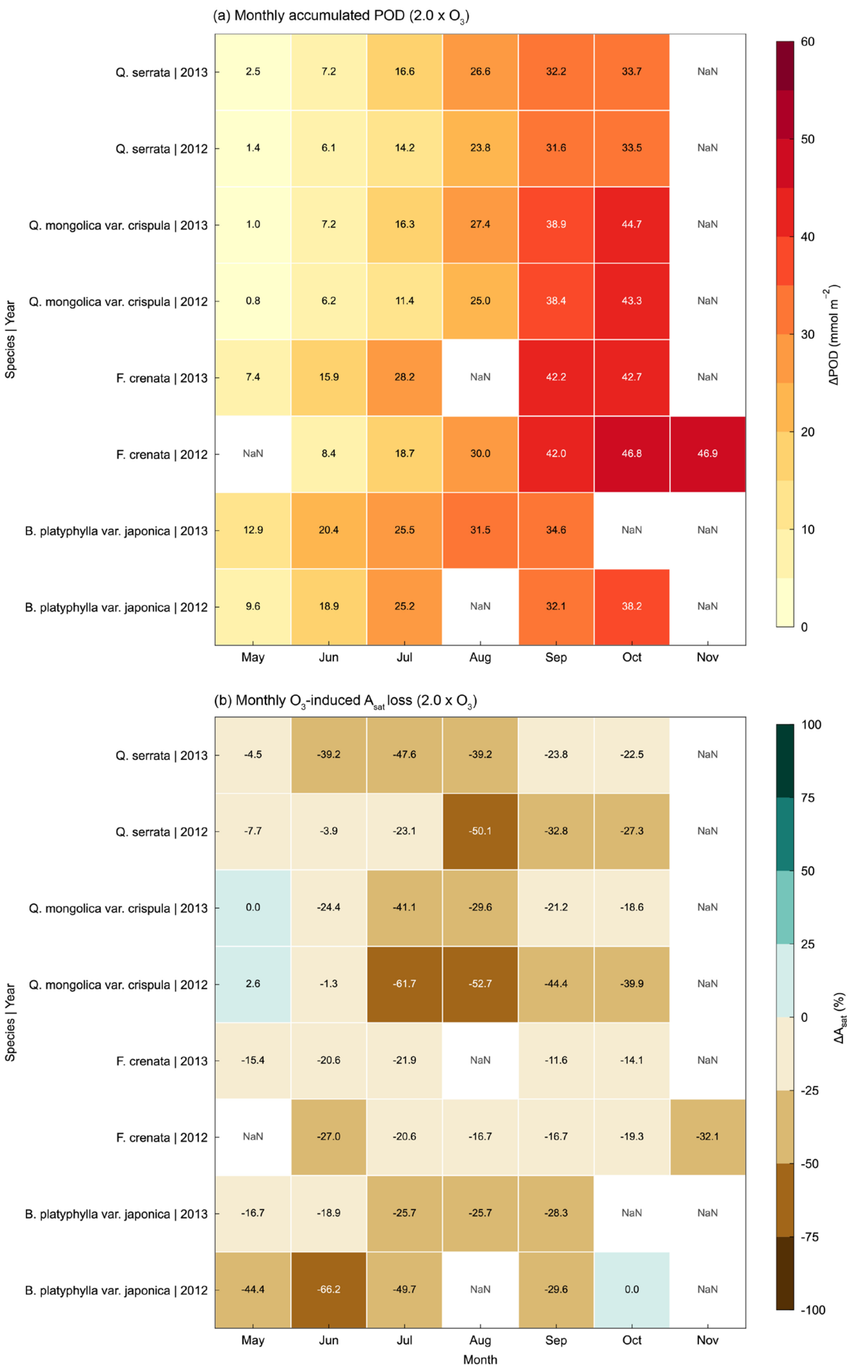


Response Supplementary Figure 2. Seasonal variation of cumulative O_3 uptake (CUO) and the O_3 vegetation damage factor (F_{O3_A}) simulated by the original Li2024 and the refined Li2024 formulation at US-Ha1 in 1998. Shaded areas denote CUO, while solid lines indicate the corresponding F_{O3_A} values. $F_{O3\_A} = 1$ indicates no O_3 damage on photosynthesis, lower F_{O3_A} indicate stronger suppression in photosynthesis. Data were aggregated to 3-day means.

To provide observational basis for our modified formulation, we further examined O_3 fumigation experiments of open-top chamber for deciduous species as reported by Yamaguchi et al. (2019). These observations provide seasonal measurements of light-saturated photosynthesis together with cumulative stomatal O_3 uptake. As shown in Response Supplementary Figures 3 and 4, Phytotoxic O_3 Dose (POD) generally increases throughout the growing season, but the O_3-induced reduction in photosynthesis does not intensify consistently. In several cases, O_3-induced suppression in photosynthesis does not increase continuously as POD accumulates. Instead, it is strong in the early stage of growing season and weakens later. These results suggest that the O_3-induced vegetation damage can be moderated over time, rather than being determined solely by the accumulated O_3 uptake. Although these observations do not resolve the specific mechanisms responsible for the seasonal moderation of O_3 effects, they are consistent with the need for an attenuation pathway that operates over time as implemented in $Li2024_{modify}$, which supports the inclusion of a gradual CUO decay process for deciduous species in addition to the LAI-based healing term that is mainly active during periods of increasing LAI.

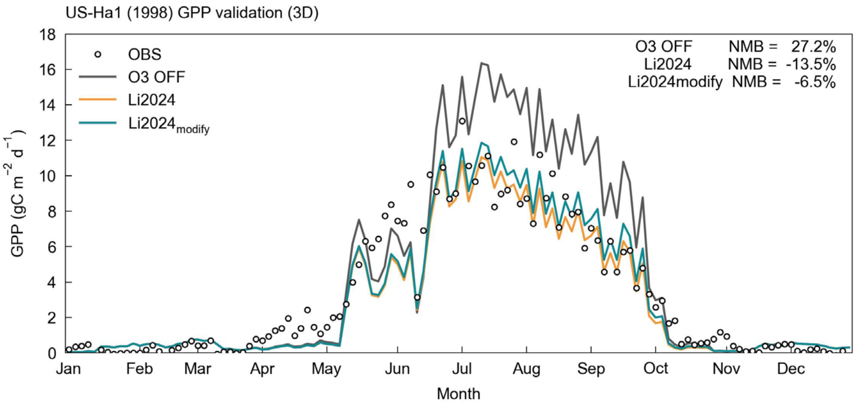


Response Supplementary Figure 3. Monthly values of light-saturated photosynthetic rate (ΔA_{sat}) and cumulated phytotoxic O_3 dose (POD) for 3 deciduous tree species under elevated O_3 exposure in open-top chamber experiments in Japan 2013. Panels show relative changes of photosynthetic rate under 1.0 and 2.0 times of ambient O_3 level treatments relative to charcoal-filtered control experiment. The blue lines denote ΔA_{sat}, and orange bars denote POD. Only records with more than 6 months of valid observations during the growing season were retained.



Response Supplementary Figure 4. Monthly variations in **(a)** cumulative phytotoxic O_3 dose (POD) and **(b)** O_3-induced changes in light-saturated photosynthetic rate (ΔA_{sat}) for deciduous species exposed to 2.0 times ambient O_3 treatment in 2012 and 2013. In panel (b), ΔA_{sat} is normalized within each species-year group to allow comparison of O_3-induced photosynthetic suppression. Missing values are indicated in white cells. Only records with more than 6 months of valid observations during the growing season were retained.

Finally, we evaluated how this refinement affects simulated GPP at US-Ha1, a temperate deciduous broadleaf forest site. As shown in Response Supplementary Figure 5, both Li2024 and $Li2024_{modify}$ improve GPP simulation as compared with the O3OFF experiment. The differences between these two Li2024 formulations occurs mainly during the mid-to-late growing season, which consists with the reduced CUO as shown in Response Supplementary Figure 2. The refined formulation therefore alleviates late-season O_3-induced GPP suppression and leads to a slightly lower bias with similar temporal variation with observations.



Response Supplementary Figure 5. Validation of 3-day mean GPP simulated by O3 OFF, the original Li2024 scheme, and the refined $Li2024_{modify}$ scheme against flux-tower observations at US-Ha1 in 1998. Symbols denote observed GPP, and lines denote model simulations. The normalized mean bias (NMB) values are shown for each simulation.

Overall, the refined treatment is intended as a trait-constrained extension of the existing CUO framework, rather than a simple empirical adjustment of GPP seasonality. This modification generally follows the original CUO framework, but treatS the LAI-related healing and leaf-longevity-based decay processes as two complementary pathways for attenuating CUO accumulations. This interpretation is motivated by the behavior identified in our SSiB4/TRIFFID simulation, where the LAI-related healing term becomes ineffective when LAI reaches its seasonal peak and start to decline, which leads to strong carry-over effect of CUO in the mid-to-late growing season. The fumigation observations further support the need for a gradual attenuation pathway, as O_3-induced damage in photosynthesis does not continuously intensify with cumulative O_3 uptake. We have revised the manuscript accordingly to clarify the interpretation of the decay and healing terms and to present the refinement more clearly and carefully.

Reference:

Yamaguchi, M., Kinose, Y., Matsumura, H., and Izuta, T.: Evaluation of O3 Effects on

Cumulative Photosynthetic CO2 Uptake in Seedlings of Four Japanese Deciduous Broad-Leaved Forest Tree Species Based on Stomatal O3 Uptake, Forests, 10, 556, 2019.

Manuscript revision:

Line 242-267: In addition to the seven experiments described above, we performed an additional simulation, $Li2024_{modify}$, to examine a refined treatment of CUO attenuation within the Li2024 framework. In the original Li2024 implementation, the decay and healing terms are applied differently among PFTs: the decay term is applied for evergreen species while LAI-related healing term is used for other PFTs. In $Li2024_{modify}$, both processes are applied to all PFTs. This treatment is based on the interpretation that these two terms represent complementary pathways for attenuating CUO accumulation at different stages of canopy development. The LAI-related healing term represents a rapid attenuation of CUO when LAI is increasing, which reflects the assumption that newly formed leaves are initially undamaged by O_3 stress. In addition, the decay term represents a gradual attenuation of CUO when LAI is stable or declining. By using leaf longevity to describe how long leaves are exposed to O_3 before leaf fall or replacement, the decay term links the attenuation of CUO to the life cycle of leaves under a natural trait-based constraint.

This modification is conceptually aligned with the injury–recovery framework proposed by Felzer et al. (2009), in which O_3 damage is represented as a prognostic state variable governed by injury and recovery processes. In their framework, recovery comprises two components: (i) a characteristic healing rate indicating gradual physiological recovery due to cellular repair and leaf replacement when LAI is constant or decreasing, and (ii) a rapid healing associated with canopy growth, whereby newly formed leaves replace the damaged foliage as LAI increases. Following this concept, $Li2024_{modify}$ treats the decay and healing terms as complementary attenuation processes rather than separate treatments for different PFTs, which can be expressed as follows:

$$D = \frac{\Delta t}{l_{leaf} \times 3600 \times 24 \times 365} \quad for\ all\ PFTs \tag{12}$$

$$H = \max\left(1 - \frac{LAI_{t-1}}{LAI_t}, 0\right) \quad for\ all\ PFTs \tag{13}$$

Furthermore, we update the key parameter l_{leaf} using observed leaf longevity dataset to better constrain the decay process across PFTs (Wang et al., 2012). Leaf longevity is a key plant trait that reflects typical leaf life span of each PFT, and provides important physiological constraint for representing vegetation turnover in land surface models (Wang et al., 2012; Zhang et al., 2016). By linking the decay term to a measurable physiological trait, this refinement provides a trait-based constraint on the gradual attenuation of accumulated O_3 stress within the existing

CUO framework. This experiment was designed to evaluate how the refined treatment affects CUO accumulation and the O_3-induced vegetation damage in SSiB4/TRIFFID.

Line 430-436: Although the Li2024 scheme performs well in the inter-scheme comparison, our SSiB4/TRIFFID implementation shows strong CUO accumulation, which affects the simulated seasonal cycle of GPP. Unlike S2007 and the LMA-based schemes, which diagnose O_3 damage from instantaneous stomatal O_3 flux, Li2024 links the O_3 damage factor to CUO, which is updated each timestep through uptake, decay, and healing process (see Sect. 2.2). In the original implementation, the LAI-based healing term reduces CUO mainly during leaf area expansion, while deciduous PFTs lack a continuous decay pathway after LAI reaches its seasonal peak. As a result, the accumulated CUO can lead to a persistent increasing suppression of photosynthesis over the growing season (Fig. 8a).

Line 450-452: Overall, the trait-constrained CUO attenuation treatment reduces the late-season CUO carry-over and moderates the associated GPP suppression, with the largest effects concentrated in densely vegetated areas of southern China.

Line 497-505: Our evaluation shows that Li2024 provides the closest agreement with observed O_3 sensitivity among the tested schemes. However, when implemented in SSiB4/TRIFFID, its CUO-based formulation also highlights the importance of how accumulated O_3 stress is attenuated through the growing season. This is particularly important for deciduous vegetation, because the LAI-related healing term mainly operates during periods of canopy expansion. Once LAI reaches its seasonal peak and becomes stable or begins to decline, this healing pathway becomes ineffective to attenuate the accumulated O_3 stress. To reduce this carry-over of CUO, we extended the decay term to all PFTs to provide a gradual attenuation for accumulated O_3 stress. As shown in Sect. 3.4, the refined treatment reduces this carry-over effect and improves the simulated magnitude and seasonality of GPP. These results indicate that treating decay and healing as complementary processes is important for representing the seasonal evolution of CUO.

Line 506-533: Experimental and modelling studies consistently indicate that vegetation responses to O_3 exposure are often nonlinear under chronic exposure, implying a diminishing marginal impact of increasing POD_y as defence and tolerance mechanisms are activated (Heath et al., 2009; Li et al., 2024). For example, Droutsas et al. (2020) showed that accounting for plant acclimation to chronic O_3 stress was necessary to reproduce observed wheat biomass and yield responses, whereas conventional linear exposure–response functions may overestimate O_3-induced yield loss under prolonged O_3 exposure. This nonlinearity likely reflects two complementary pathways: avoidance, through stomatal regulation, and confrontation, through antioxidation, detoxification and repair processes (Sharma et al., 2012; Scimone et al., 2024). On the one hand, exposure to O_3 can severely impair photosynthesis and stomatal functions, with the resulting stomatal closure acting as negative feedback that constraints further O_3 uptake

(Li et al., 2017). On the other hand, elevated O_3 exposure alters hormone regulation and increases apoplastic antioxidants capacity (e.g., ascorbate, phenolic, glutathione), which can directly react with O_3 and scavenge ROS, thereby enhancing the O_3 tolerance (Castagna and Ranieri, 2009; Heath et al., 2009; Li et al., 2023). Consistently, recent evidence from tree species suggests that higher O_3 doses can stimulate antioxidant production, which helps mitigate oxidative stress and enhance O_3 tolerance (He et al., 2025). O_3 is also known to damage leaf cells and accelerate senescence, while plants may partly offset these effects through cellular repair and the production of new leaves (Heath and Taylor, 1997; Grulke and Heath, 2020). Taken together, these mechanisms indicate that O_3 damage is dynamically moderated over time and cannot be fully represented by a fixed POD_y threshold alone (Heath et al., 2009). Motivated by this evidence, we apply the decay term for all PFTs as a simplified representation of the gradual attenuation of O_3-induced oxidative stress, accompanied by the healing term to account for the dilution from emergence of new, undamaged leaves (Felzer et al., 2009; Li et al., 2024). In our refined treatment, the decay term should not be interpreted as an explicit expression of a specific physiological mechanism. Instead, it provides a simplified representation of the gradual attenuation of accumulated O_3 stress within the existing CUO framework. Observational leaf longevity is used here to provide a practical trait-based constraint for this process, as it represents the typical timescale over which O_3 exposure can affect leaves before leaf fall or replacement, after which the accumulated O_3 effect should be removed from the canopy. With these modifications, CUO accumulation is reduced through the growing season, which improves GPP simulations in both spatial patterns and seasonal cycles. This trait-based decay refinement acknowledges that O_3 impacts on vegetation are dynamically regulated by physiological processes and feedbacks, rather than solely controlled by the rise in O_3 uptake. Further studies and observations are needed to better quantify antioxidant regulation, detoxification, and cellular repair under long-term O_3 exposure. Such knowledge would help clarify how vegetation moderates chronic O_3 stress over time and provide a stronger mechanistic basis for modelling vegetation responses to long-term O_3 exposure.

Line 562-564: Furthermore, we refined the Li2024 formulation by applying both decay and healing processes across PFTs and updating leaf longevity with observational constraints. This treatment reduces late-season CUO carry-over and improves the simulated magnitude and seasonal cycle of GPP.

Minor comments

1. Please change L2024 to Li2024 throughout the manuscript. As noted by the authors, L2015 and Li2024 refer to schemes proposed by different authors, and the current notation is potentially confusing.

Response: We have revised the scheme abbreviation throughout the manuscript, figures, tables, and supplementary materials. The Li et al. (2024) scheme is now consistently denoted as Li2024 to avoid confusion with L2015.

2. Please check the model version name. CTSM2.2 should be CTSM5.2.

Response: The model version name has been corrected throughout the manuscript. CTSM2.2 has been revised to CTSM5.2.

3. In Fig. 3c, the colours of the different lines are difficult to distinguish. Please revise the colour palette and/or line styles to improve readability.

Response: Fig. 3c has been revised using a more distinguishable color palette to improve readability and make the differences among schemes clearer.

4. In Fig. 5, it is not clear what the dots represent. Please specify explicitly in the caption whether these correspond to simulations or observations.

Response: We have revised the caption to state explicitly that each point represents one simulated grid-cell year, showing the annual POD_y and the corresponding RGPP derived from the model simulations. We also clarified that the colors denote the dominant PFT of each grid cell. Thus, the dots are simulation results rather than observational samples.

5. In Fig. 8c, please clarify what is meant by OBS. Does this refer to GOSIF, FLUXCOM, or the mean of the two products? If possible, I suggest showing both products separately, or at least including their spread, in order to better reflect observational uncertainty and to provide a more objective benchmark for evaluating model performance.

Response: We have revised Fig. 8b and Fig. 8c to clarify the observational benchmark. In the revised Figure 8c, "OBS" denotes the mean of GOSIF and FLUXCOM, we also added grey shading to indicate the range between these two products. The same OBS mean is used in Fig. 8b for the grid-level comparison. The caption has been revised accordingly to make the description clear.