Response to Referee 2

We sincerely thank the reviewer for the constructive and insightful comments. We appreciate the recognition of the relevance of our work and the helpful suggestions to improve the manuscript. We have carefully considered all comments and will revise the manuscript accordingly. Below we provide a point-by-point response.

General comments

In this manuscript, the authors present a refined vertical soil structure in the LPJ-GUESS-Cryo model, which improves the simulation of aboveground biomass and NPP compared to remote sensing estimates within the study region. The paper falls within the journal's scope and addresses a relevant topic: the representation of permafrost-related processes in global vegetation models.

However, the manuscript would benefit from a more detailed discussion on the choice of development approach. While the model improvements are clearly described and shown to enhance performance, the rationale behind methodological choices remains insufficiently explored.

In addition, the analysis did not address potential impacts on soil carbon storage and permafrost carbon emissions from changes in soil hydrothermal dynamics. Providing a more thorough analysis of the methodological choices and their implications - also for belowground processes and on a regional scale - would substantially strengthen the manuscript.

Response: We thank the reviewer for this constructive and insightful comment. We agree that the original manuscript did not sufficiently explain the rationale underlying several key methodological choices, particularly the extension of soil depth and the incorporation of freeze--thaw-related hydraulic constraints.

In the revised manuscript, we substantially expanded Section 2.3 to clarify the scientific motivation and physical basis of the model developments.

Specifically, in Section 2.3.1 ("***Structural reconstruction of the soil module for permafrost thermal–hydrological processes"***), we clarified that the original 1.5 m soil column in LPJ-GUESS is insufficient to adequately represent freeze–thaw dynamics and subsurface hydrological processes in permafrost-affected ecosystems of Northeast China, where the active layer frequently extends beyond the original model depth. The limited soil depth may constrain vertical soil water redistribution and inadequately represent hydrological processes beneath the primary rooting zone. To address these limitations, we replaced the original two-layer 1.5 m soil column with a 30-layer structure extending to 3 m depth, while also incorporating vertically stratified soil property inputs to improve the representation of vertical heterogeneity in soil thermal and hydrological characteristics.

We revised the manuscript (P5, L115) as follows:

"In the permafrost zone of NEC, the original 1.5 m soil column is insufficient to adequately represent freeze–thaw dynamics and subsurface hydrological processes, particularly where the active layer extends beyond the original model depth. The limited soil depth may constrain vertical soil water redistribution and inadequately represent hydrological processes beneath the primary rooting zone. To address this, we replaced the original two-layer, 1.5 m soil column with a 30-layer structure, each 0.1 m thick, extending the profile to 3 m. We also restructured the model's soil inputs to incorporate vertically stratified property files, thereby removing the assumption of homogeneous soil conditions. This modification enables a more realistic representation of vertical heterogeneity in soil characteristics, such as texture and organic matter content, and substantially improves the accuracy of simulated soil thermal and hydrological processes."

In Section 2.3.2 (***"Physical reconstruction of soil infiltration incorporating permafrost-specific hydrological effects"),*** we further clarified the rationale for replacing the original two-layer bulk hydrological scheme. The original LPJ-GUESS hydrological formulation conceptualizes the soil column as two bulk layers and simulates percolation as water exchange between two conceptual "boxes". Such a simplified structure lacks the vertical discretization required to represent depth-dependent soil water movement and freeze–thaw-driven hydrological processes in permafrost-affected boreal ecosystems. The bulk-layer formulation also limits the simulation of vertical soil water redistribution and active-layer hydrology under freezing conditions. To address these limitations, we implemented a physically based multilayer hydrological framework for the 30-layer soil structure.

We additionally incorporated a dynamic ice-impedance function to represent the influence of frozen conditions on layer-to-layer water movement and to improve the physical realism of freeze–thaw-related soil hydrothermal processes. Although the sensitivity analysis indicated that the direct effects of ice impedance were smaller than those associated with enhanced vertical soil discretization, this process remains important for representing freeze–thaw-controlled infiltration and hydrological constraints in permafrost environments.

We revised the manuscript (P5, L125) as follows:

"The original soil hydrology scheme in LPJ-GUESS, as described by Gerten et al. (2004), conceptualizes the soil column as two distinct layers (0–50 and 50–150 cm) and simulates percolation as a bulk exchange between these two 'boxes'. Such a simplified two-layer scheme lacks the vertical discretization required to represent depth-dependent soil water movement and freeze–thaw-driven hydrological processes in permafrost-affected boreal ecosystems. The bulk-layer formulation also limits the simulation of vertical soil water redistribution and active-layer hydrology under

freezing conditions. To address these limitations, we implemented a physically based multilayer hydrological framework for the 30-layer soil structure...

We further incorporated a dynamic ice impedance function to represent the influence of frozen conditions on layer-to-layer water movement and to improve the physical realism of freeze–thaw-related soil hydrothermal processes.”

We also agree that changes in soil hydrothermal dynamics may have important implications for belowground carbon storage and permafrost carbon emissions. However, a comprehensive assessment of vertically resolved soil carbon decomposition and explicit permafrost carbon emissions is beyond the scope of the present study, which primarily focuses on improving soil hydrothermal process representation and evaluating its effects on vegetation and near-surface hydrothermal dynamics.

To address this limitation, we expanded the ***“Model limitations and future directions”*** section to clarify that the present framework does not yet include a comprehensive representation of coupled permafrost–carbon feedbacks. Processes such as vertically resolved soil carbon decomposition, talik dynamics, and explicit permafrost carbon emissions remain unresolved in the current framework and should be further investigated in future studies.

We revised the manuscript (P20, L500) as follows:

“In addition, the present developments focus primarily on improving selected soil hydrothermal processes relevant to permafrost environments, rather than providing a comprehensive representation of coupled permafrost–carbon feedbacks. To maintain computational efficiency and regional applicability in large-scale DGVM simulations, the current framework prioritizes process-level improvements expected to exert first-order controls on subsurface hydrothermal dynamics. Several important processes, including vertically resolved soil carbon decomposition, talik dynamics, and explicit permafrost carbon emissions, remain unresolved in the current framework. Furthermore, although the revised soil representation improved simulations of vegetation and near-surface hydrothermal dynamics, its implications for belowground carbon storage and long-term permafrost carbon feedbacks were not explicitly evaluated in this study. Given the large soil carbon pools stored in permafrost regions, future work should further investigate the implications of improved soil hydrothermal representation for soil carbon dynamics and permafrost carbon emissions under continued warming.”

Specific comments

Comment 1

Title: The authors could consider specifying their study region (e.g. boreal forests of Northeast China) to mark that their developments have been tested on a site scale

Response: We agree with the referee that the original title did not sufficiently reflect the regional scope and site-scale evaluation context of the present study. In the revised manuscript, we revised the title to explicitly indicate the study region and to better constrain the scope of the model developments and evaluations.

The revised title is:

"Improving Permafrost Soil Representation in a Dynamic Global Vegetation Model Enhances Predictions of Carbon Dynamics and Vegetation Structure in China's Boreal Forests"

Comment 2

Figure 1. Please edit the caption, so that it is self-explanatory, e.g. Study area location in Heilongjiang Province and the Inner Mongolia Autonomous Region (left) and land use classification based on X (right).

Response: We thank the referee for this suggestion. We revised the Figure 1 caption to provide a clearer and more self-contained description of the study area, land-cover information, and spatial context shown in the figure.

Revised caption (P4):

"Figure 1. Location of the study area in Northeast China, including Heilongjiang Province and the Inner Mongolia Autonomous Region (left), and spatial distribution of permafrost zones and land-cover types within the study region (right). The inset map indicates the location of the study region within China. Land-cover classification was derived from Xu et al. (2018)."

Comment 3

Table B1-B2. Please add the abbreviations (e.g. MAE) in the table header.

Response: Thank you for the helpful suggestion. To improve clarity and readability while avoiding overcrowding of the table headers, we added explicit explanations of all abbreviations used in Tables B1 and B2 within the revised table captions.

Revised content:

"Statistical performance metrics for soil temperature across soil depths for LPJ-GUESS and the revised model. Values represent the mean [min, max] across sites. Abbreviations: R, correlation coefficient; SD_{norm}, normalized standard deviation; $RMSD_{norm}$, normalized root mean square difference; Bias, mean bias; MAE, mean absolute error."

"Statistical performance metrics for soil water content across soil depths based on single-site comparisons, including simulations with different soil-layer configurations (2L and 30L). Abbreviations: R, correlation coefficient; S_{Dnorm}, normalized standard deviation; $RMSD_{norm}$, normalized root mean square difference; Bias, mean bias; MAE, mean absolute error."

Comment 4

L50: Consider elaborating on (1) why simplified representations are commonly used in DGVMs, and (2) which specific processes limit their ability to simulate cold-region soil hydrothermal dynamics realistically.

Response: We thank the reviewer for this helpful suggestion. We agree that the original text did not sufficiently explain either the rationale for adopting simplified soil representations in DGVMs or the specific processes that limit their ability to realistically simulate cold-region soil hydrothermal dynamics.

In the revised manuscript, we clarified that simplified soil schemes are commonly adopted in DGVMs because these models are designed for long-term, large-scale ecosystem simulations involving coupled vegetation, hydrological, and biogeochemical processes. To maintain computational tractability and broad applicability across regional to global scales, DGVMs have traditionally relied on simplified soil structures and parameterizations. We also noted that the historical development of many DGVMs has primarily focused on vegetation dynamics and carbon exchange processes, whereas cold-region soil hydrothermal processes have remained comparatively underrepresented.

In addition, we explicitly elaborated on several key processes that are often simplified or insufficiently represented in conventional DGVMs, including vertical soil thermal gradients, freeze–thaw regulation of soil water movement, coupled soil thermal–hydrological interactions, coarse soil layering, frozen-soil permeability constraints, active layer dynamics, and depth-dependent soil water redistribution. These limitations are particularly important in permafrost-affected boreal ecosystems, where freeze–thaw processes strongly regulate subsurface thermal and hydrological dynamics.

Accordingly, we revised the Introduction (P2, L47) as follows:

"However, as the fundamental basis for simulating terrestrial carbon cycles in DGVMs, the physical realism of soil modules remains limited. Owing to the computational demands of long-term, large-scale ecosystem simulations and the historical emphasis of DGVM development on vegetation and carbon exchange processes, many DGVMs adopt simplified soil representations to maintain computational tractability and broad applicability. Nevertheless, these schemes often inadequately represent key cold-region hydrothermal processes, particularly vertical soil thermal gradients, freeze–thaw regulation of soil water movement, and coupled soil thermal–hydrological interactions. This limitation is especially pronounced in permafrost-affected boreal forests, where coarse soil layering and simplified hydrological parameterizations commonly fail to capture active layer dynamics, frozen-soil permeability constraints, and depth-dependent soil water redistribution."

Comment 5

L55: Please clarify what is meant by "high climate sensitivity" and "extensive forest cover," and explain why these characteristics make the study region particularly suitable.

Response: Thank you for the helpful suggestion. We agree that the original wording was overly general and did not sufficiently explain why Northeast China (NEC) is particularly suitable for this study.

In the revised manuscript, we clarified that NEC has experienced rapid warming and widespread permafrost degradation during recent decades, making the region highly sensitive to climate-driven changes in soil thermal and hydrological conditions. Specifically, previous studies have reported regional warming of approximately 0.9–2.2 °C over the past five decades, accompanied by an estimated ~35% reduction in permafrost area since the 1970s, northward retreat of the southern permafrost boundary, thinning of permafrost thickness, and the development of localized thawed zones (Jin et al., 2007; He et al., 2009). These changes have substantially altered regional soil hydrothermal regimes and vegetation dynamics in boreal forest ecosystems.

We also clarified that NEC contains more than 80% of China's boreal forests and stores nearly one-third of the national forest carbon stock (Huang et al., 2021). The coexistence of extensive boreal forests and rapidly degrading permafrost makes the region particularly suitable for investigating interactions among permafrost change, soil hydrothermal dynamics, vegetation responses, and carbon cycling.

Accordingly, the revised manuscript now more clearly explains that NEC serves as a climatically sensitive transitional permafrost region where relatively modest changes in subsurface thermal and hydrological conditions may trigger substantial ecosystem responses, making it an effective testbed for evaluating improved soil hydrothermal representations within LPJ-GUESS.

We revised the corresponding text in the Introduction section (P3, L60) as follows: ***"We focused our simulations on Northeast China (NEC), located at the southern margin of the Eurasian permafrost domain. NEC has experienced rapid warming of approximately 0.9–2.2 °C over the past five decades, accompanied by an estimated ~35% reduction in permafrost area since the 1970s (Jin et al., 2007; He et al., 2009)."***

Comment 6

L76: rephrase: the regions has high vegetation cover…

Response: Thank you for the helpful suggestion. We agree that the original description was overly general and could be expressed more clearly and quantitatively. In the revised manuscript, we replaced the original statement with a more specific description highlighting the ecological and carbon-storage importance of the study region.

We revised the corresponding text in Section 2.1 "Study area" (P4, L88) as follows:

"The region contains more than 80% of China's boreal forests, accounting for approximately 29.9% of the country's natural forest area and storing nearly one-third of the national forest carbon stock (Huang et al., 2021, 2022)."

Comment 7

L90. Permafrost and wetland-related processes had been implemented in LPJ-GUESS based on Wania et al 2009a, 2009b (https://doi.org/10.1029/2008GB003412 https://doi.org/10.1029/2008GB003413).

Response: We thank the reviewer for this important suggestion. We agree that previous developments of permafrost- and wetland-related processes within the LPJ framework should be acknowledged more explicitly in the model description section.

In the revised manuscript, we added a discussion of earlier LPJ-based developments related to peatland and permafrost processes, particularly the studies of Wania et al. (2009a, b). These studies introduced several important high-latitude process representations into LPJ-WHy, including multilayer soil thermal dynamics, freeze–thaw processes, snow insulation effects, active layer dynamics, peatland hydrology, inundation stress, peatland-specific vegetation parameterizations, and peatland carbon accumulation processes. Together, these developments provided an important foundation for representing cold-region hydrothermal and biogeochemical dynamics in LPJ-based models.

We further clarified that the developments presented in the current study differ from Wania et al. (2009a, b) in both process focus and implementation strategy. The previous LPJ-WHy developments were primarily designed for northern peatland and wetland ecosystems, with emphasis on peat hydrology, wetland vegetation dynamics, and anaerobic carbon processes. In contrast, the present study focuses on improving soil hydrothermal representation in permafrost-affected boreal forest ecosystems, particularly within mineral soils. The revised model introduces a deeper and more vertically resolved soil column together with freeze–thaw-related constraints on vertical liquid water movement through an ice impedance formulation affecting frozen-soil hydrology.

We also revised the model description section to better position the present developments within the broader context of previous LPJ-based permafrost and wetland modelling studies.

We revised the corresponding text in Section 2.2 "***The LPJ-GUESS dynamic global vegetation model***" (P4, L105) as follows:

"Detailed representations of soil processes, including soil carbon and nitrogen dynamics as well as soil hydrology, are documented in Smith et al. (2014), Sitch et al. (2003), and Gerten et al. (2004). Previous developments within the LPJ framework have also incorporated peatland and permafrost-related processes. For example, Wania et al. (2009a) introduced multilayer soil thermal dynamics, freeze–thaw processes, snow insulation effects, active layer dynamics, and peatland hydrology into LPJ-WHy, enabling the simulation of permafrost distribution and water table dynamics. Subsequently, Wania et al. (2009b) further incorporated peatland-specific vegetation parameterizations, inundation stress, reduced anaerobic decomposition, and peatland carbon accumulation processes to simulate vegetation and carbon-cycle dynamics in northern peatland ecosystems. These developments established an important basis for representing cold-region hydrothermal and biogeochemical processes within LPJ-based models. However, the standard LPJ-GUESS v4.1 framework still lacks an explicit representation of vertically resolved freeze–thaw hydrology and ice-induced constraints on soil water mobility in permafrost-affected forest ecosystems."

Comment 8

L214. Please rephrase for clarity. e.g. Larger Δ value indicated larger differences between LPJ-GUESS and LPJ-GUESS-Cryo.

Response: Thank you for the helpful suggestion. We agree that the original description was unnecessarily complex and could be clarified.

In the revised manuscript, we simplified the definitions of ΔST and ΔSWT to more explicitly state that they represent the differences between the revised model and the original LPJ-GUESS configuration. We also clarified that larger absolute Δ values indicate larger divergences between the two model configurations in simulated soil thermal and hydrological conditions.

Specifically, we revised the description in Section 2.6.4 "***Attribution of vegetation responses to hydrothermal perturbations"*** (P11, L275) as follows:

"To attribute changes in vegetation structure to hydrothermal modifications introduced by the improved soil representation, we conducted a bivariate conditional response analysis linking inter-model differences in soil temperature (ΔST) and soil water content (ΔSWT) to vegetation responses. Here, ΔST and ΔSWT denote the differences between the improved and original LPJ-GUESS configurations rather than absolute warming or drying. Larger absolute Δ values indicate stronger divergence between the two model configurations in simulated soil thermal and hydrological conditions."

Comment 9

L217. What do you mean by "joint hydrothermal perturbations"?

Response: Thank you for pointing this out. We agree that the phrase "joint hydrothermal perturbations" was unnecessarily abstract and could be unclear to readers.

In the revised manuscript, we replaced this phrase with the clearer expression "combined changes in soil temperature and soil water content" to more directly describe the hydrothermal variables analyzed in the study and their relationship to simulated vegetation responses.

Revised text (P11, L278):

"First, we analyzed changes in broadleaf forest biomass ($\Delta C_{mass,BLF}$) as a continuous response to combined changes in soil temperature and soil water content. "

Comment 10

L380. Regarding study limitations: In addition to their impact on soil thermohydrodynamics, it would be interesting to at least mention how these developments affect simulated carbon balance in these permafrost-underlain areas. It would be important to emphasize that although improving the vertical thermodynamics is important, models in general still lack other processes (e.g. vertical soil carbon storage) that challenge the accuracy of simulated vegetation dynamics and carbon fluxes in permafrost underlain regions.

Additionally, the developments would still need to be tested on a broad regional scale (e.g. Pan-Arctic), to ensure the robustness of improvement in soil temperature and carbon balance estimates.

Response: We thank the reviewer for this important and constructive suggestion. We agree that the limitations section should more explicitly discuss both the implications of the revised soil representation for simulated carbon dynamics and the remaining challenges in representing permafrost carbon processes.

In the revised manuscript, we expanded the Discussion section to clarify that, although In the revised manuscript, we clarified that although the enhanced soil vertical discretization and ice impedance formulation improve the representation of soil thermal and hydrological dynamics, several important processes remain simplified or unresolved, including vertically resolved soil carbon decomposition, cryoturbation, talik dynamics, and explicit permafrost carbon emissions. We therefore clarified that the carbon-related results presented in this study primarily refer to vegetation-related carbon dynamics, including aboveground biomass and NPP, rather than a complete representation of whole-ecosystem carbon cycling or permafrost carbon feedbacks.

We also emphasized that improving soil hydrothermal representation remains an important prerequisite for reducing uncertainties in simulated vegetation dynamics and ecosystem carbon exchange in permafrost-affected regions, while acknowledging that substantial uncertainties associated with belowground carbon processes remain.

In addition, we agree that broader large-scale evaluation is necessary to assess the general applicability of the revised soil representation across different permafrost environments. We therefore clarified that the present study should be viewed as a regional process-oriented model development and evaluation framework for Northeast China rather than a finalized pan-Arctic model application. Future work should further evaluate the robustness of the revised soil representation across broader environmental gradients and permafrost regimes, including pan-Arctic regions.

We added the following discussion to Section 4.3 ("***Model limitations and future directions"***):

"In addition, the present developments focus primarily on selected soil hydrothermal processes relevant to permafrost environments rather than a comprehensive representation of coupled permafrost–carbon feedbacks. To maintain computational efficiency and regional applicability in large-scale DGVM simulations, the current framework prioritizes process-level improvements expected to exert first-order controls on subsurface hydrothermal dynamics. Several important processes, including vertically resolved soil carbon decomposition, talik dynamics, and explicit permafrost carbon emissions, remain unresolved in the current framework. Furthermore, although the revised soil representation improved simulations of vegetation and near-surface hydrothermal dynamics, its implications for belowground carbon storage and long-term permafrost carbon feedbacks were not explicitly evaluated in this study. Given the large soil carbon pools stored in permafrost regions, future work should further investigate the implications of improved soil hydrothermal representation for soil carbon dynamics and permafrost carbon emissions under continued warming.

More broadly, the present evaluation remains regionally constrained to the permafrost-affected forests of Northeast China. Although this region represents a climatically sensitive transition zone characterized by rapid warming and discontinuous permafrost degradation, broader validation across pan-Arctic environmental gradients and permafrost regimes is still required before generalizing model applicability at the circumpolar scale. Future work should therefore combine improved process representation with broader pan-Arctic evaluations and long-term observations to better assess ecosystem carbon dynamics under continued climate warming. Despite these limitations, the present results demonstrate that improved soil hydrothermal representation can substantially influence simulated vegetation dynamics and vegetation-related carbon estimates in permafrost-affected forests."

Comment 11

L420. While the authors correctly highlight the importance of improving soil hydrothermal processes, it would be helpful to clarify that the presented developments represent a step forward rather than a comprehensive solution.

Response: We thank the reviewer for this important and constructive suggestion. We agree that the limitations section should more explicitly discuss both the implications of the revised soil representation for simulated carbon dynamics and the remaining challenges in representing permafrost carbon processes.

In the revised manuscript, we clarified that the developments presented in this study represent process-level improvements to soil hydrothermal representation within LPJ-GUESS, rather than a comprehensive representation of all permafrost-related processes.

We also explicitly acknowledged that several important processes remain simplified or unresolved in the current model framework, including vertically resolved soil carbon dynamics, freeze–thaw effects on decomposition, cryoturbation, lateral hydrological processes, and explicit permafrost carbon emissions. Accordingly, we revised the Discussion and Conclusions sections to more carefully position the current developments as a step toward improving the representation of soil hydrothermal processes in permafrost-affected ecosystems, rather than as a complete solution for permafrost ecosystem modelling.

Our revised summary is as follows (P22 L520):

"In this study, we improved the soil module of LPJ-GUESS to better represent soil hydrothermal processes in permafrost-affected boreal forests of Northeast China (NEC). By increasing soil vertical resolution and introducing a freeze–thaw-related hydraulic constraint on downward liquid water percolation, the revised model improves the representation of vertical soil thermal gradients and subsurface soil water redistribution in permafrost-affected ecosystems.

Validation against site-level observations and regional datasets indicates that the improved LPJ-GUESS configuration generally improves the simulation of soil temperature variability and reduces soil water content biases relative to the original LPJ-GUESS configuration. While both model versions capture the seasonal timing of near-surface freeze–thaw cycles dominated by climatic forcing, the improved configuration also shows more consistent performance across sites and soil depths. Performance gains are most evident in deeper soil layers, where internal soil processes increasingly control variability, underscoring the importance of vertical resolution and physically based subsurface representations.

At the regional scale, these modifications lead to systematic changes in simulated vegetation structure and carbon dynamics. The improved configuration also reduces the overestimation of AGB and NPP, decreasing the regional mean AGB bias from 19.6 to 5.7 t ha^{-1} and the NPP bias from 112.5 to 89.1 g C m^{-2} yr^{-1}, thereby yielding estimates that are substantially closer to remote sensing–derived values. Crucially, the model reproduces the observed large-scale transition from needleleaf-dominated forests in the northwestern permafrost zone to broadleaf-dominated forests toward the southeastern margin. Our analysis identifies that this structural reorganization, which is driven by the sensitivity of vegetation to soil warming and drying, is the primary mechanism improving the carbon bias. By resolving the competitive exclusion of shallow-rooted needleleaf species by broadleaf species in transitional zones, the model eliminates the artificial retention of high-biomass conifers simulated by the original configuration.

Overall, this study suggests that improving subsurface soil hydrothermal representation is an important component for improving simulations of vegetation composition and carbon dynamics in permafrost-affected ecosystems. The improved LPJ-GUESS configuration provides a more suitable basis for simulating boreal forest carbon dynamics at the southern margin of the permafrost region and may contribute to reducing uncertainties in projections of ecosystem structural changes under ongoing climate warming.”

Technical corrections

L7: rephrase: e.g. Our model evaluation shows…

Response: Thank you for the suggestion. We revised the sentence for clarity.

L63: Materials and Methods

Response: Thank you for pointing this out. We revised the section title for consistency with standard formatting.
Revised content: “Materials and Methods”

L64: Study area

Response: Thank you for the suggestion. We revised the subsection title for capitalization consistency.
Revised content: "Study Area"

L184. Structural changes

Response: Thank you for the suggestion. We revised the sentence for improved clarity.
Revised content: "The NPP and AGB datasets provide a robust foundation for assessing vegetation dynamics and changes in vegetation structure."

L187: made to the model

Response: Thank you for pointing this out. We corrected the typographical error and revised the phrase for clarity.

L241: repeated sentence

Response: Thank you for pointing this out. The repeated sentence has been removed in the revised manuscript.

L310: "conditions(Gert"

Response: Response: Thank you for pointing this out. We corrected the formatting by adding a space before the citation.

Revised content: "conditions (Gerten et al., 2004)".

Reference

Xu, X., Liu, J., Zhang, S., Li, R., Yan, C., and Wu, S.: China's Multi-Period Land Use Land Cover Remote Sensing Monitoring Dataset (CNLUCC), Resource and Environment Data Science and Data Center, Chinese Academy of Sciences, Beijing, China, Dataset, 2018.

Huang, C., Liang, Y., He, H. S., Wu, M. M., Liu, B., and Ma, T.: Sensitivity of aboveground biomass and species composition to climate change in boreal forests of Northeastern China, Ecol. Model., 445, 109472, https://doi.org/10.1016/j.ecolmodel.2021.109472, 2021.

Huang, C., Feng, J., Tang, F., He, H. S., Liang, Y., Wu, M. M., Xu, W., Liu, B., Shi, F., and Chen, F.: Predicting the responses of boreal forests to climate–fire–vegetation interactions in Northeast China, Environ. Model. Softw., 153, 105410, https://doi.org/10.1016/j.envsoft.2022.105410, 2022.

He, R., Jin, H., Chang, X., Lü, L., Yu, S., Yang, S., Wang, S., and Sun, G.: Degradation status and causes of permafrost in northern Northeast China, J. Glaciol. Geocryol., 31, 829–834, https://doi.org/10.7522/j.issn.1000-0240.2009.0114, 2009.

Jin, H., Yu, Q., Lü, L., Guo, D., He, R., Yu, S., Sun, G., and Li, Y.: Degradation of permafrost in the Xing'anling Mountains, northeastern China, Permafrost Periglac. Process., 18, 245–258, https://doi.org/10.1002/ppp.589, 2007.

Wania, R., Ross, I., and Prentice, I. C.: Integrating Peatlands and Permafrost into a Dynamic Global Vegetation Model: 2. Evaluation and Sensitivity of Vegetation and Carbon Cycle Processes, Global Biogeochemical Cycles, 23, 2008GB003413, https://doi.org/10.1029/2008GB003413, 2009a.

Wania, R., Ross, I., and Prentice, I. C.: Integrating Peatlands and Permafrost into a Dynamic Global Vegetation Model: 1. Evaluation and Sen sitivity of Physical Land Surface Processes, Global Biogeochemical Cycles, 23, 2008GB003412, https://doi.org/10.1029/2008GB003412, 2009b.