RESPONSE TO REVIEWER #2

The authors address a significant topic by mapping key soil properties across China's forests using a comprehensive dataset. The resulting high-resolution products have the potential to be a valuable resource for the scientific community. However, several methodological and descriptive aspects require substantial improvement to ensure the reliability and reproducibility of the findings.

Response

Dear reviewer #2,

We sincerely thank you for your insightful and comprehensive comments, which have been very helpful in improving the rigor, transparency, and reproducibility of this manuscript. Following your suggestions, we have undertaken substantial revisions.

Specifically, we strengthened the methodological description and expanded the Discussion to more explicitly address sources of uncertainty (e.g., covariate resolution harmonization) and model interpretability across soil depths. We also added new supplementary materials to improve transparency, including covariate maps, sample distribution summaries, and additional quantitative comparisons with existing BD and pH products.

Our point-by-point responses are provided below. All corresponding revisions are marked in **blue** in the revised manuscript.

Best regards,

Jizhen Chen

General comments:

General comments 1

Resampling covariates with diverse native resolutions to a 90-m grid introduces significant uncertainty, particularly for inputs derived from coarser scales. This issue warrants a detailed discussion and quantification to assess the reliability of the final high-resolution maps.

Response

We thank the reviewer for raising this important point regarding uncertainty introduced by harmonizing environmental covariates with heterogeneous native resolutions to a 90-m grid.

In this study, all covariate layers were projected to a common coordinate system and resampled to 90 m using bilinear interpolation, following common practice in national-scale digital soil mapping and consistent with established products (Poggio et al., 2021; Liu et al., 2022; Shi et al., 2025). We acknowledge that resampling, particularly from coarser-resolution inputs, may introduce scale-related uncertainty and smoothing effects, and that the effective spatial resolution of the final predictions is constrained by the coarsest covariates.

In response, we have expanded the Discussion to explicitly address this limitation and its implications for map interpretation ***(Section 4.3, Lines 538–551)***. As noted there, isolating and quantifying uncertainty attributable solely to covariate resampling is methodologically challenging at national scales and is rarely reported in existing large-area DSM studies. Therefore, the resulting maps should be interpreted as conditional estimates that represent the most probable spatial patterns given the available covariates and their effective spatial support, rather than as direct representations of fine-scale soil heterogeneity at 90 m.

Reference:

Liu, F., Wu, H., Zhao, Y., Li, D., Yang, J., Song, X., Shi, Z., Zhu, A., and Zhang, G.: Mapping high resolution national soil information grids of China, Sci. Bull., 67, 328–340, https://doi.org/10.1016/j.scib.2021.10.013, 2022.

Poggio, L., De Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty, Soil, 7, 217–240, https://doi.org/10.5194/soil-7-217-2021, 2021.

Shi, G., Sun, W., Shangguan, W., Wei, Z., Yuan, H., Li, L., Sun, X., Zhang, Y., Liang, H., Li, D., Huang, F., Li, Q., and Dai, Y.: A China dataset of soil properties for land surface modelling (version 2, CSDLv2), Earth Syst. Sci. Data, 17, 517–543, https://doi.org/10.5194/essd-17-517-2025, 2025.

General comments 2

The manuscript provides insufficient discussion on the variable importance for BD and pH across different soil layers. The underlying reasons for these variations require further elaboration.

Response

We thank the reviewer for this comment. We agree that the original manuscript did not sufficiently elaborate on depth-dependent variations in variable importance and the underlying reasons for these patterns.

In response, we substantially revised the interpretability analysis by introducing SHAP (SHapley Additive exPlanations), which enables consistent, depth-comparable quantification of both the magnitude and direction of covariate effects. This revision replaces the previous discussion based on QRF-derived relative variable importance, which primarily supports within-model comparisons and is not directly comparable across depths when the selected feature sets differ.

The revised ***Section 3.5*** now provides a depth-explicit interpretation of key drivers for both BD and pH, and the corresponding methodological update is described in ***Section 2.3***. The updated results are presented in ***Figures 7 and 8***.

General comments 3

Natural and planted forests possess distinct driving mechanisms. Developing separate models for each forest type is advisable to accurately capture these specific variations.

Response

We thank the reviewer for this insightful suggestion. We agree that natural and planted forests often differ in management history, stand structure, and species composition, which may influence soil processes and their responses to environmental drivers.

However, in our compiled forest soil profile database, forest origin (natural vs. planted) is not consistently documented in the original metadata, which prevents a reliable partition of the full dataset by forest type. To evaluate the potential impact of forest origin, we conducted an additional targeted test using an external forest-type dataset to assign forest origin at sampling locations (Cheng et al., 2024), and performed separate modeling for the 60–100 cm layer as a representative case.

The results showed a pronounced decline in predictive performance when models were separated by forest origin, primarily due to substantially reduced sample sizes at this depth (e.g., BD: planted MEC = 0.462, RMSE = 0.598; natural MEC = 0.302, RMSE = 0.632; pH: planted MEC = 0.503, RMSE = 0.482; natural MEC = 0.404, RMSE = 0.402).

Moreover, evidence from the literature suggests that, at regional to national scales, the dominant controls on soil bulk density and pH are largely consistent across natural and planted forests. Broad environmental gradients—particularly climate, parent material, and long-term soil development processes—have been shown to exert primary control on soil physical and chemical properties, while forest origin mainly modulates response magnitude through differences in stand structure or management intensity rather than altering the fundamental driver mechanisms (Luyssaert et al., 2008; Pretzsch et al., 2014) .

Accordingly, separating models by forest origin at the national scale is unlikely to substantially improve predictive performance for BD and pH, while potentially increasing uncertainty due to reduced sample sizes. Given these considerations, together with the national-scale objective of this study, we retained a unified modeling framework to ensure robust, spatially consistent predictions across China's forest domain.

Reference：

Cheng, K., Yang, H., Guan, H., Ren, Y., Chen, Y., Chen, M., Yang, Z., Lin, D., Liu, W., Xu, J., Xu, G., Ma, K., and Guo, Q.: Unveiling China's natural and planted forest spatial-temporal dynamics from 1990 to 2020, ISPRS J. Photogramm. Remote Sens., 209, 37–50, https://doi.org/10.1016/j.isprsjprs.2023.11.003, 2024.

Luyssaert, S., Schulze, E. D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Ciais, P., and Grace, J.: Old-growth forests as global carbon sinks, Nature, 455, 213–215, https://doi.org/10.1038/nature07276, 2008.

Pretzsch, H., Biber, P., Schütze, G., Uhl, E., and Rötzer, T.: Forest stand growth dynamics in Central Europe have accelerated since 1870, Nat. Commun., 5, 4967, https://doi.org/10.1038/ncomms5967, 2014.

General comments 4

Providing spatial distribution maps for every covariate listed in Table S1 is advisable. The figures need to clearly display the value ranges for continuous variables and the distinct spatial patterns for each category within categorical variables. Specifying the number of sample points in both the training and validation sets for each categorical variable is recommended.

Response

We thank the reviewer for this constructive suggestion regarding the presentation of environmental covariates and sample stratification.

In response, we have added spatial distribution maps for all environmental covariates retained after FRFS selection, which are now provided in the ***Supplementary Information (Fig. S1)***. These figures display the value ranges of continuous variables and the spatial patterns of categorical variables, thereby improving transparency and interpretability of the covariate inputs.

In addition, we have quantified the number of soil sampling plots associated with each category of the categorical covariates separately for the training and independent validation datasets, using the surface soil layer (0–5 cm) as a representative overview. These statistics are summarized in ***Tables S2–S4 in the Supplementary Information.***

Together, these additions enhance the reproducibility of the study and provide a clearer basis for assessing the robustness of the modeling framework.

General comments 5

Forest age represents a critical covariate. Incorporating this variable into the analysis is advisable to improve model performance.

Response

We thank the reviewer for this important suggestion regarding the inclusion of forest age as a covariate. We fully agree that forest age is a critical variable influencing forest structure, productivity, and soil processes, and therefore has the potential to improve model performance when reliable and spatially consistent data are available.

During the initial covariate selection stage, we carefully evaluated commonly used forest age datasets for China (Cheng et al., 2024). However, currently available forest age maps are derived products and still exhibit substantial uncertainty at local scales, particularly in cold-temperate coniferous forests, where reported model performance remains relatively low ($R^2 = 0.47$).

More importantly, existing forest age products are developed based on forest domain definitions and source data that differ from those adopted in this study. As a result, their spatial coverage is not fully consistent with the forest domain considered here, leading to notable spatial mismatches and discontinuities when the two datasets are overlaid. Integrating forest age products into a national, wall-to-wall digital soil mapping framework would therefore introduce systematic spatial bias and compromise prediction consistency. Given these considerations, we did not include forest age as a covariate in the present study.

We note that digital soil mapping under conditions of incomplete or spatially inconsistent covariate coverage represents a methodological challenge rather than a purely data-related issue. This challenge is particularly pronounced in national-scale forest soil mapping studies in China, where heterogeneity in data sources and definitions is common. Recent methodological advances, such as the iPSM-based framework proposed by Fan et al. (2020), have demonstrated that covariate incompleteness can be addressed by explicitly accounting for missing variables and their associated uncertainty. Accordingly, we acknowledge this limitation in the Discussion (Show in ***Section 4.3. Line 553-568***) and consider the further development and application of such approaches to be an important direction for improving future forest soil mapping frameworks.

Reference：

Cheng, K., Yang, H., Guan, H., Ren, Y., Chen, Y., Chen, M., Yang, Z., Lin, D., Liu, W., Xu, J., Xu, G., Ma, K., and Guo, Q.: Unveiling china's natural and planted forest spatial–temporal dynamics from 1990 to 2020, ISPRS J. Photogramm. Remote Sens., 209, 37–50, https://doi.org/10.1016/j.isprsjprs.2024.01.024, 2024.

Fan, N. Q., Zhu, A.-X., Qin, C.-Z., and Liang, P.: Digital soil mapping over large areas with invalid environmental covariate data, ISPRS Int. J. Geo-Inf., 9, 102, https://doi.org/10.3390/ijgi9020102, 2020.

General comments 6

Providing the original data is necessary to facilitate the reproducibility of the study by other researchers.

Response

We thank the reviewer for emphasizing the importance of reproducibility. We would like to clarify that the original forest soil profile data used in this study are subject to data confidentiality agreements and access restrictions imposed by the institutions responsible for the national forest soil survey in China, and therefore cannot be publicly released.

Nevertheless, we have made all data that can be legally shared openly available, and access to restricted data may be requested by contacting the corresponding author, subject to the relevant data-sharing policies. To ensure the highest possible level of reproducibility under these constraints, we provide comprehensive documentation of the data processing workflow, quality control and harmonization procedures, environmental covariates, modeling framework, and validation strategy.

In addition, all derived products generated in this study, including gridded maps of soil bulk density and pH and their associated uncertainty estimates, are openly available through a public repository.

We believe that this level of transparency allows other researchers to fully reproduce the methodology and apply it to independent datasets, while respecting the access restrictions governing the original observations.

General comments 7

Comparing the current results with existing soil BD and pH products is recommended. The manuscript needs to clarify specific improvements and explain the reasons for these advancements.

Response

We thank the reviewer for this suggestion. Following it, we conducted additional quantitative comparisons between our forest-specific predictions and existing national and global datasets, including CSDLv2, ChinaSoilInfoGrids, and SoilGrids 2.0. These analyses explicitly quantify differences in predicted BD and pH across depths and regions, and clarify where and why forest-specific mapping provides added value.

The statistical comparisons are summarized in ***Figures S5 and S6 at Supplementray Information***, and spatial contrasts are shown in ***Figures 9 and 10***. The results indicate that our forest-specific maps better capture depth-dependent patterns and ecosystem-specific magnitude differences that are not well represented by generalized products. The underlying reasons for these improvements are discussed in ***Section 4.1***, including the use of forest-only observations, forest-specific covariate–response relationships, and depth-resolved modeling.

General comments 8

Presenting the spatial distribution of sample points for both the training and validation sets is necessary. The manuscript should also address whether these distributions are spatially balanced.

Response

We thank the reviewer for this suggestion regarding the spatial distribution and balance of the training and validation samples.

In response, we have provided a new figure ***(Fig. S2)*** that visualizes the spatial distributions of the training and independent validation datasets for BD and pH across all soil layers, supporting the spatial balance claim.

Additionally, we have added a statement in the Methods section ***(Lines 97–98)*** to clarify that the spatial distributions of the training and validation subsets were explicitly examined to ensure that both subsets maintain spatial balance across regions and soil depths.

General comments 9

A more detailed description of the raw data is necessary. The manuscript should specify the sample sizes and spatial distributions across different temporal periods, soil types, and forest types.

Response

We thank the reviewer for requesting a more detailed description of the raw data. In response, we revised the data description to explicitly report sample sizes and their distributions across forest types, soil types, and temporal periods. Detailed counts by forest type, soil type, and related categories are provided in ***Tables S2–S5*** (referenced in the main text; ***Lines 112***).

In addition, we clarified the temporal coverage of the dataset by reporting the number of soil profiles collected in each survey year from 2018 to 2023 (***Lines 119–120***). These revisions provide a more transparent overview of the dataset composition in terms of time, forest types, soil types, and spatial coverage.

Minor comments:

Minor comments 1

Lines 1-3: The general phrase "Soil properties" creates redundancy with the specific variables "Bulk Density and pH," necessitating a more concise revision such as "High-Resolution, Multi-Depth Mapping of Soil Bulk Density and pH in China's Forests Using Machine Learning".

Response

We thank the reviewer for this helpful suggestion. We revised the title by removing the general phrase "Soil properties" and focusing on the specific variables examined in this study. The revised title is: "High-Resolution, Multi-Depth Mapping of Soil Bulk Density and pH in China's Forests Using Machine Learning." This change is reflected in ***Lines 1–3.***

Minor comments 2

Lines 20-21: The claim of being 'first' is inaccurate due to the existence of prior 90-m products, so the text should be revised to focus on the specific contribution to forest ecosystems instead. and Lines 429-430: The use of "first" is an absolute claim that is prone to dispute.

Response

We thank the reviewer for pointing out that the term "first" is an absolute claim and may be disputable given the existence of prior 90-m soil products. We agree and have revised the text to avoid absolute wording, shifting the emphasis to the specific contribution of this study—namely, forest-specific mapping and depth-resolved estimates of BD and pH. The relevant revisions have been made in ***Lines 18*** and ***Lines 598–599***.

Minor comments 3

Lines 73-74: The phrase "in heterogeneous" is grammatically incorrect.

Response

We thank the reviewer for identifying this grammatical issue. The incorrect phrase has been removed during the revision of the Introduction, and the corresponding sentence has been rewritten for clarity.

Minor comments 4

Lines 109-111: This sentence is redundant and should be deleted.

Response

We thank the reviewer for pointing out this redundancy. We deleted the redundant sentence as suggested and revised the surrounding text accordingly.

Minor comments 5

Lines 111-112: Specify the quality control and data harmonization methods.

Response

We thank the reviewer for this suggestion. We have added a clearer description of the quality control and data harmonization procedures (***Lines 115–116***), including unit standardization, harmonization of depth intervals, and reconciliation of metadata across survey sources.

Minor comments 6

Lines 139-155: The 41 environmental covariates lack necessary citations, and the sources or the data itself should be made accessible to readers to ensure reproducibility.

Response

We thank the reviewer for this comment. In response, we added detailed citations and source information for all 41 environmental covariates in ***Supplementary Table S1*** to improve transparency and reproducibility.

Minor comments 7

Lines 159-160: The number of standardized soil layers should be corrected from four to five.

Response

We thank the reviewer for pointing out this discrepancy. We corrected the number of standardized soil layers from four to five ***(Line 141)***.

Minor comments 8

Lines 222-223: $q50$ denotes the median prediction.

Response

We thank the reviewer for this correction. We revised the manuscript to clarify that q0.50 denotes the median prediction and corrected the notation accordingly (***Line 185***). We confirm that this was a notation issue only; all analyses were conducted using the median (q0.50) prediction, and the correction does not affect the results or conclusions.