Response letter

Dear Editors and Reviewers:

Re: egusphere-2025-3004

We sincerely thank you and the reviewers for providing us with such a valuable revision opportunity. Thus, we can further improve and present our studies. The comments from you and the reviewers were highly insightful and enabled us to greatly improve the quality of our manuscript. We have carefully reviewed the feedback and made corrections that we hope will be met with approval. Revised portions are marked on the revised manuscript. Please note that these resulting revisions did not change the paper's findings.

In the response letter to the editor and reviewers, we firstly summarized the major changes in a cover letter to the editors, and we then itemized our response to editors and reviewers, **in which the blue font indicates the response to each comment and the black font presents the revision from the revised manuscript.**

We hope that the revisions in the revised manuscript and the responses to the comments will suffice to allow our manuscript to be suitable for publication in ***Natural Hazards and Earth System Sciences***.

Sincerely regards,

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Institute of Mountain Hazards and Environment, Chinese Academy of Sciences

Response to Reviewer #3

[Comment 1] The manuscript focuses on understanding and evaluating the key issue of vegetation's mitigating effect on rainfall-induced landslides. However, I confirm what RC1 already observed, that the way in which vegetation is considered is also the main critical point of the study. In fact, although the aim of the study is to better understand its effect on triggering landslides, it has been treated too superficially. Furthermore, the results show an average landslide height of 36 m, so it is not surprising to see a total effect coefficient value of 0.21. For this type of deep landslide, the vegetation's effect is definitely limited. I agree with the comments already made by RC1, so I will try not to be repetitive based on what has already been highlighted.

Response:

We greatly appreciate your constructive perspective on the relationship between landslide depth and vegetation effects, and we recognize the value of these insights for enhancing the scientific rigor of our study. We will carefully revise the manuscript to address your concerns and strengthen the overall quality of the work. According to the comments from RC1, we have fully revised the manuscript. You can also check the response to the RC1. Here, it should point out 36 m is not the average height, but the width. Meanwhile, the total effect coefficient value of vegetation (0.21) is relatively small. But in terms of the top ten impact factor rankings, it still holds a leading position. That's why we want to emphasize the role of vegetation on landslide susceptibility.

[Comment 2] The introduction needs significant improvement. It is currently written in a confusing form and lacks a clear structure that would help the reader to follow the study. In my opinion, it would be useful to provide more information about the available literature, rather than just citing studies and quoting short sentences. Also, it is necessary to clarify the research gap by explaining its importance and how this study contributes to bridging it.

Response:

Thank you for this valuable comment. We agree that the previous version of the Introduction required substantial improvement in terms of structure, clarity, and articulation of the research gap.

Accordingly, the Introduction has been thoroughly revised and reorganized to enhance its logical flow and readability. The revised text now provides a more coherent narrative, beginning with the broader context of landslide hazards in vegetated mountainous regions, followed by an integrated discussion of the dual role of vegetation in slope stability. Rather than simply listing prior studies, we expanded the description of existing literature to synthesize current understanding of both the stabilizing and destabilizing effects of vegetation, particularly in relation to rainfall-driven landslide processes.

In addition, the research gap is now clarified in a more explicit and focused manner. The revised introduction emphasizes the limitations of existing studies in fully capturing the complex interactions among vegetation and other environmental controls on landslide susceptibility, as well as the need for approaches that link regional susceptibility patterns with site-specific failure mechanisms. On this basis, the contribution of the present study is clearly positioned as a multi-scale investigation that integrates statistical analysis and geomechanical modeling to better explain vegetation–landslide interactions.

We believe that these revisions significantly improve the clarity, structure, and scientific focus of the Introduction, and more clearly demonstrate the relevance and contribution of this study. We appreciate your insightful suggestions, which have helped strengthen the manuscript. Please check it below and in manuscript in lines 54-116, pages 4-6.

1 Introduction

"*Landslides represent a significant geological hazard in mountainous regions worldwide, causing substantial loss of life, infrastructure damage, and economic disruption (Alvioli et al., 2024; Zhang et al., 2025). In areas with dense vegetation cover, the relationship between vegetation and slope stability is particularly complex* *and non-linear (Deng et al., 2022; Medina et al., 2021). While vegetation is traditionally regarded as a stabilizing agent through root reinforcement, soil moisture regulation, and erosion control (He et al., 2017; Lan et al., 2020; Rey et al., 2019), shallow landslides may occur even in densely vegetated landscapes (Xu et al., 2024). This paradox underscores the dual—and often contradictory—role of vegetation in landslide processes, acting as both a mitigating and a predisposing factor depending on environmental context and trigger conditions.*

The stabilizing function of vegetation is well-documented. Root systems enhance soil cohesion and shear strength, while canopy and litter layers reduce rainfall impact and surface runoff (Gonzalez-Ollauri & Mickovski, 2016; Murgia et al., 2022; Vergani et al., 2017). However, under certain conditions, vegetation can exacerbate slope instability. The added weight of trees, especially on steep slopes, increases gravitational driving forces (Schmaltz & Mergili, 2018). Vegetation can also alter soil hydrological properties, increasing infiltration and soil moisture content, which in turn reduces effective stress and shear resistance during rainfall events (Qin et al., 2022). Furthermore, wind forces acting on tall vegetation can transmit dynamic loads to the slope, while root wedging in thin soils may promote fracture development (Bordoloi & Ng, 2020; Liu et al., 2020). Rainfall remains the primary trigger of landslides in vegetated areas, as it saturates the soil, elevates pore water pressure, and reduces slope stability (Dhanai et al., 2022; Li et al., 2025). Therefore, landslide initiation in vegetated terrain is not governed by vegetation alone but results from the intricate interplay among vegetation characteristics, rainfall intensity, slope gradient, lithology, and other environmental factors.

Substantial efforts have been made to assess landslide susceptibility using various methodologies, including geoscience factor weighting, statistical models, machine learning, and Geographic Information Systems (GIS)-based spatial analysis (Abay et al., 2019; Gebrehiwot et al., 2025; Guo et al., 2023; Pham et al., 2018; Sun et al., 2024; Wang et al., 2024). These approaches have improved our understanding of the spatial distribution of landslides and the relative importance of conditioning factors. However, several critical gaps remain. First, many studies provide qualitative descriptions of factor influences but lack quantitative analysis of spatial correlations and interactive effects among multiple driving factors (Shu et al., 2025; Triplett et al., 2025). Second, while rainfall-landslide relationships have been extensively studied *using spatial autocorrelation and clustering techniques (Chen et al., 2024; Liu et al., 2024; Ortiz-Giraldo et al., 2023; Pokharel et al., 2021; Wang et al., 2020), the moderating role of vegetation in these relationships is poorly quantified. Specifically, how vegetation mediates the effects of rainfall, lithology, slope, and wind on slope stability coefficients remains unclear (Lan et al., 2020). Third, most susceptibility models operate at a single spatial scale, either regional/watershed or site-specific, with limited integration across scales. This hampers a holistic understanding of how macro-scale predisposing factors translate into micro-scale failure mechanisms.*

To address these research gaps, this study investigates the dual-edged role of vegetation in landslide susceptibility by integrating watershed-scale statistical analysis with site-specific geomechanical modeling. We selected the Jinkouhe District in Southwest China—a region with high vegetation cover (⩾65.5%) and frequent landslide activity—as our study area. The research aims to (1) Quantify the individual and interactive effects of key environmental factors (rainfall, vegetation, wind speed, slope, lithology, etc.) on landslide susceptibility at the watershed scale using Geodetector and Structural Equation Modeling (SEM). (2) Analyze the mechanical role of vegetation weight and its coupling with rainfall and anthropogenic loading in triggering a typical shallow landslide through slope stability calculations. (3) Integrate findings from both scales to elucidate how vegetation mediates landslide processes under different environmental conditions, thereby providing a multi-scale perspective on its "double-edged sword" function. By bridging macroscopic susceptibility patterns with microscopic failure mechanisms, this study offers novel insights into the complex vegetation–landslide interplay. The results are expected to enhance the accuracy of landslide risk assessments and inform sustainable slope management strategies in densely vegetated mountainous regions."

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[Comment 3] More attention should also be paid to the language used. For example, what is meant by "good vegetation" (do you mean forest density, or plant species, or plant dimensions?), or "higher vegetation cover" (do you

mean forest horizontal or vertical structure?), or "vegetation-rich region" (do you mean forest density, or plant species?). All this information is key points in this type of analysis, so I would advise the authors to be more precise and technical.

Response:

We sincerely thank you for your constructive comment regarding the terminology used in our manuscript. We fully acknowledge that the original expressions “good vegetation,” “higher vegetation cover,” and “vegetation-rich region” could be ambiguous, potentially leading to misinterpretation. In the manuscript, “good vegetation” is intended to refer to areas with high vegetation cover, indicating regions where vegetation is relatively dense; “higher vegetation cover” specifically refers to higher horizontal vegetation cover, emphasizing the horizontal structure of the vegetation rather than vertical structure or height; and “vegetation-rich region” is used to indicate a region with high vegetation density, reflecting areas where plants are densely distributed. In response to your comments, we have systematically revised these terms throughout the manuscript, replacing ambiguous expressions with more explicit and standardized terminology or removing them where appropriate;

[Comment 4] This section also needs a clear structure_Materials and Methods.

Response:

Thank you for this comment. We agree that a clear and well-organized structure is essential for the Materials and Methods section. Accordingly, the section has been systematically revised and reorganized in the revised manuscript. Following the revisions made in response to the previous comments, the Materials and Methods section is now structured to reflect a clear research logic and multiscale analytical framework.

Specifically, the study is motivated by the observation that landslides and debris flows may still occur in areas with high vegetation density. Therefore, a vegetation-dense region in Southwest China was selected as the study area to investigate the “dual role” of vegetation in landslide processes. Section 2.1 introduces the study area, including its geographical location, elevation, climate, temperature, and vegetation types, followed by the presentation of a representative landslide case to provide field-based context. Section 2.2 describes the data sources and preprocessing procedures. Section 2.3 presents the modeling strategy for landslide susceptibility assessment and the corresponding accuracy evaluation. Section 2.4 introduces the driving factor analysis methods (GD/SEM) applied to the regional-scale susceptibility results. Finally, Section 2.5 focuses on the physical mechanism analysis at the slope scale, incorporating vegetation self-weight into slope stability analysis.

Through this structure, the revised Materials and Methods section explicitly links regional-scale landslide susceptibility assessment with site-scale slope failure mechanisms, providing a coherent methodological framework that integrates susceptibility mapping with process-based interpretation and offers a new perspective on the role of vegetation in landslide occurrence.

[Comment 5] There is no information on the morphology or slope of the study area, or on vegetation cover and soil characteristics.

Response:

We thank you for pointing out this omission. In addition to the spatial distribution maps of topography, slope, vegetation cover, and soil characteristics provided in the supporting information (Figure S1), we have also added a more detailed description of vegetation types and their spatial distribution in the study area. Specifically, to provide a more accurate characterization of vegetation, we obtained the vegetation distribution based on the 1:1,000,000 China Vegetation Type Spatial Distribution vector data, as shown in Figure R6. The vegetation in the study area is mainly classified into shrubland, meadow, broadleaf forest, coniferous forest, and cultivated plants. Among them, shrubland mainly consists of Myrica and Rhododendron; broadleaf forests mainly include Arundinaria-dominated forests, Quercus engleriana forests, and Castanopsis forests; and coniferous forests are primarily composed of Abies forests, Pinus yunnanensis forests, and subalpine Quercus forests. This information has been added to Section 2.1 “Study Area” to provide a clearer and more comprehensive overview of vegetation in the study area.

2.1 Study Area（Revised manuscript line 126 & 134）

"*Detailed spatial distributions of topography and vegetation cover are provided in the supporting information (Supplementary Figure S1).*"

"*Vegetation is classified into shrubland, meadow, broadleaf forest, coniferous forest, and cultivated plants. Shrubland is dominated by Myrica and Rhododendron, broadleaf forests include Arundinaria-dominated forests, Quercus engleriana forests, and Castanopsis forests, and coniferous forests consist mainly of Abies forests, Pinus yunnanensis forests, and subalpine Quercus forests.*"

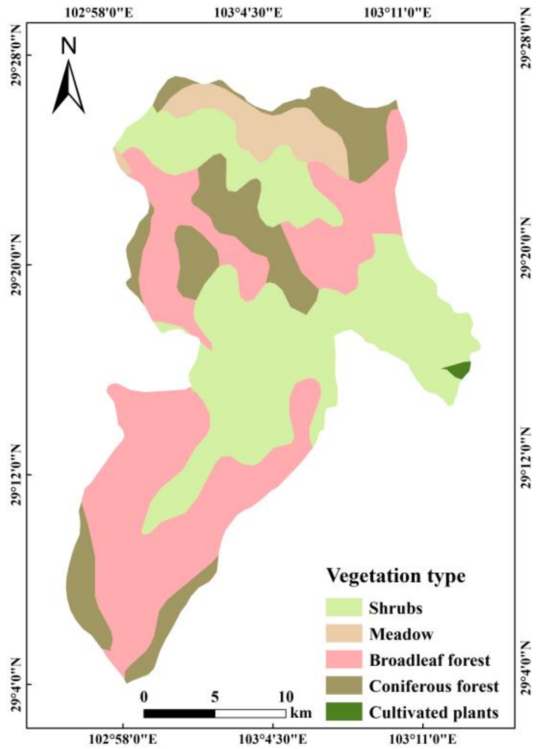

Fig. R1 Vegetation type distribution map

[Comment 6] What are the main plant species, average plant dimensions, the spatial distribution, etc., of your study area?

Response:

We thank you for this comment. The detailed information regarding the main plant species, vegetation types, and their spatial distribution in the study area has already been provided in the previous response and added to Section 2.1 "Study Area" (see also Figure R1).

[Comment 7] How are the main soil types distributed in your study area? Furthermore, why was this parameter not considered in the analysis? Main mechanical and hydrological vegetation effects occur in the soil rather than with the lithological substrate.

Response:

We thank you for highlighting the importance of soil characteristics in mediating the mechanical and hydrological effects of vegetation. Indeed, soil plays a key role in slope stability and landslide susceptibility. However, for the Jinkouhe District study area, we were unable to obtain sufficiently high-resolution soil type data (30 m grid), and the available data were of limited reliability, with some soil types covering up to half of the study area. Therefore, lithology was used instead as a proxy in our analysis. Soil types were not included as an independent factor due to these data limitations and to maintain consistency with the factor selection framework applied to other environmental variables. We acknowledge this limitation and plan to incorporate soil type data in future studies when higher-resolution and more reliable data become available.

[Comment 8] There is insufficient information on the inventory.

Response:

We thank you for pointing out the need for more detailed information regarding the landslide inventory. In this study, the landslide inventory was compiled from two sources: the first source was the landslide inventory of the Jinkouhe area provided by the GeoCloud platform, and the second source consisted of landslides identified through visual interpretation of high-resolution satellite imagery (Sentinel-2) and manual verification. The datasets were integrated, and duplicate or uncertain cases were removed, resulting in a total of 227 landslides, representing the complete landslide distribution within the study area. To address the unclear description in the original manuscript, this section has been revised in # Revised manuscript line 202. Additionally, to visually demonstrate the reliability of some landslide points, Figure R4 shows a subset of landslides identified through visual interpretation, and part of these landslides have been added to Figure 1 in the revised manuscript.

2.2 Data source and preprocessing（Revised manuscript line 197）

“*(8) Landslide hazard point data were obtained from the GeoCloud platform (https://geocloud.cgs.gov.cn/) and through manual interpretation of Sentinel-2 imagery acquired in August 2024. After integrating the sources and removing duplicates and uncertain cases, the final inventory consisted of 227 validated landslides, representing the complete distribution within the study area. Some representative landslides identified through visual interpretation are shown in Figure 1d–h.*”

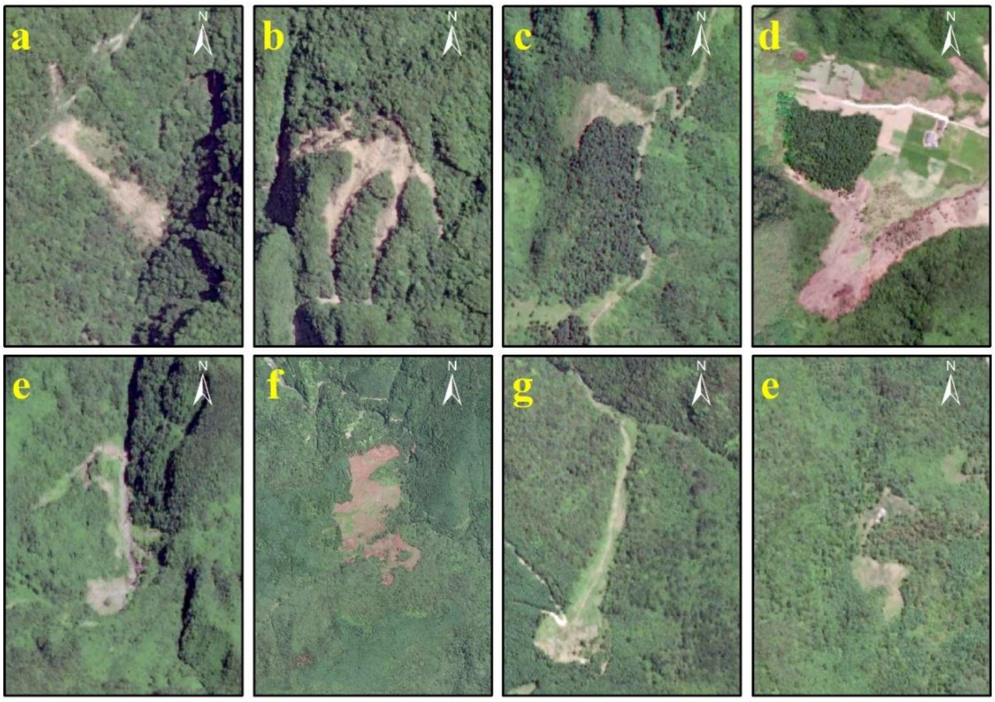

Fig. R2 Visually interpreted subset of landslides

[Comment 9] What is the purpose of reporting the specific case of Figures 2 and 3? Considering that it is not the area of analysis, too much emphasis is placed on it.

Response:

Thank you very much for this valuable comment. We agree that the connection between the major landslide case and the large-scale susceptibility analysis was not clearly presented in the original manuscript. The purpose of introducing this landslide is to use it as a representative case study that links the regional-scale susceptibility assessment with the site-scale mechanisms of slope failure, providing field-based context for subsequent susceptibility analysis and mechanistic interpretation. The landslide was triggered by the combined effects of prolonged rainfall, anthropogenic loading from waste deposits, and the additional weight of dense vegetation. This event highlights the amplifying effect of the interaction between vegetation and rainfall, indicating that local environmental disturbances can significantly increase landslide risk. In other words, vegetation may enhance slope stability under certain conditions but can also aggravate slope failure due to its additional weight and water-retention capacity. Therefore, this case not only provides empirical validation for the regional analysis results but also reveals the amplification of large-scale controlling factors under local conditions, further supporting the “double-edged sword” role of vegetation identified through the GeoDetector and SEM analyses.

[Comment 10] How was the weight of the plants calculated?

Response:

Thank you for your interest in the calculation of vegetation self-weight. Based on field investigations and the post-landslide UAV imagery shown in Figure 3, the vegetation within the landslide-affected area is dominated by mature trees. Owing to the lack of detailed measurements of individual-tree geometric structures and biomass, it is difficult to perform a refined and spatially explicit quantification of vegetation self-weight. Therefore, a simplified parameterization approach was adopted in this study. Specifically, the approximate number of trees within the landslide area was estimated, and their average height and diameter at breast height (DBH) were derived through field observations and image interpretation. By referring to vegetation volume density and related parameters reported in the literature (Lan et al., 2020), the total vegetation self-weight within the landslide area was estimated in terms of magnitude, converted into an equivalent vertical load per unit area, and uniformly applied to the slope surface for slope stability calculations.

It should be emphasized that this study does not aim to precisely quantify the vegetation weight at each spatial location within the landslide body. Instead, from a physical-mechanism perspective, the objective is to evaluate the potential influence of vegetation self-weight as an additional load on slope stability, thereby providing insight into its role in landslide initiation and evolution.

References:

Lan, H., Wang, D., He, S., Fang, Y., Chen, W., Zhao, P., & Qi, Y. (2020). Experimental study on the effects of tree planting on slope stability. *Landslides*, 17(4), 1021-1035. http://doi.org/10.1007/s10346-020-01348-z

[Comment 11] Soil cohesion is strongly influenced by vegetation, as well as plant species, age, and even the type of forest management. Were these aspects considered in the study? Although aware of the difficulty in obtaining certain information, a simpler calibration of parameter c based on species and average forest size would have enabled a better assessment of the forest's effect. How did you consider the areas without forest (the remaining 34% of the area)?

Response:

We appreciate your insightful comments regarding the influence of vegetation on soil cohesion. We fully acknowledge that factors such as vegetation type, species composition, growth stage, and forest management practices can significantly affect soil cohesion through root reinforcement. However, in this study, these factors were not explicitly incorporated into the fine-scale calibration of soil cohesion parameters, primarily due to limitations in both study scale and data availability.

Specifically, the analysis presented in Section 2.5 focuses on a site-scale physical mechanism assessment, aiming to explore the potential role of vegetation-related factors in slope stability rather than precisely inverting soil parameters for different vegetation types or forest structures. Although UAV imagery and field surveys provide general information on vegetation coverage in the study area, critical data on species composition, root depth and density, forest age, and management practices are lacking, which prevents reliable quantitative calibration of the cohesion parameter *c* based on vegetation type or average forest characteristics.

It is important to clarify that the slope stability analysis in Section 2.5 was conducted for a representative single landslide rather than across the entire study area. In this analysis, soil cohesion parameters were combined with available engineering geological data and calculated repeatedly within reasonable ranges to obtain representative stability estimates. Therefore, this procedure does not involve distinguishing between areas with different vegetation cover or forest-free areas, nor does it attempt to generalize the results to the regional scale.

Within the overall study framework, we first conducted regional-scale landslide susceptibility assessment, systematically investigating the mechanisms and interactions of topography, geology, vegetation, rainfall, and wind speed through multiple models and analytical approaches. Subsequently, at the site scale, a representative landslide was selected for slope stability analysis, specifically examining the impact of including vegetation weight on slope stability. Through this multi-scale design, our study aims to elucidate the "dual role" of vegetation in landslide processes: while vegetation may reduce susceptibility at the regional scale, its self-weight under certain conditions can adversely affect local slope stability.

[Comment 12] I do not understand what Class II is intended to observe. If we are talking about rainfall-induced landslides, you should always consider this triggering factor. A better explanation of this choice is necessary.

Response:

We thank you for raising this point. We would like to clarify that our study does not focus solely on rainfall-induced landslides. The landslide inventory used in this study represents historical landslides, and it is not possible to determine the primary triggering factor for each event. To systematically assess the roles of different factors, we combined common factors with vegetation and rainfall/wind speed to create different classes (Class) for analysis. This approach has two main purposes. First, it allows us to examine the effects of each factor from the perspective of factor space heterogeneity and, simultaneously, to systematically investigate interactions among factors and their influence on landslide susceptibility. Second, it enables us to evaluate the impact of adding or omitting certain factors on the spatial distribution of landslide susceptibility. For instance, many previous landslide susceptibility studies did not consider wind speed. By including it in our combinations, we can achieve meaningful comparisons across different classes.

2.3.1 landslide susceptibility based on the analytic hierarchy process （Revised manuscript line 227）

"*To assess how the inclusion or omission of specific factors affects the spatial distribution of landslide susceptibility, and to further explore the effects of each factor from the perspective of factor space heterogeneity and interactions among factors, this study involved altering the influencing factors to examine how environmental variables (rainfall, vegetation, and wind speed) affect landslide susceptibility. Common factors included elevation, slope, aspect, lithology, and distances to faults, rivers, and roads. Vegetation, rainfall, and wind speed were added successively, resulting in five scenarios.*"

[Comment 13] The captions of some figures are not exhaustive.

Response:

We appreciate your comment regarding the figure captions. We have carefully revised and supplemented the captions of the figures with issues throughout the manuscript to make them more detailed and informative. Especially in Figs. 1, 6, 8, 9.

[Comment 14] There is a lot of confusion in these two sections. The discussion section contains part of the results, which are currently rather brief.

Response:

Thank you for this comment. Following a substantial revision of both the Results and Discussion sections, the structure and internal consistency of these sections have been significantly improved. The Results section now presents the findings in a clearer and more systematic manner, while the Discussion section is explicitly organized to correspond to each subsection of the Results, providing more sufficient and coherent interpretation of the reported outcomes. As a result, the linkage between results and their discussion has been clarified, and the issue raised by the reviewer has been fully addressed. The revised manuscript reflects these changes in detail.

[Comment 15] In the discussion section, there are no references to other studies, and subsection 4.4 is inadequate. In fact, written in a way that is disconnected from the results' discussion and reporting only one study, which is moreover not exhaustive, it does not help in understanding the study's novelty.

Response:

Thank you for this constructive comment. We have substantially revised the Discussion section, with particular emphasis on Subsection 4.4, to improve its structure, depth, and linkage to the results. First, additional relevant studies have been incorporated to provide a broader scientific context, especially regarding landslide processes in densely vegetated mountainous regions and the commonly assumed stabilizing role of vegetation.

Second, Subsection 4.4 has been reorganized to explicitly discuss our results at both regional and site scales, clearly distinguishing between susceptibility patterns derived from regional mapping and physical mechanisms revealed by slope stability analysis. This revision ensures that the discussion is directly anchored to the results rather than presenting isolated case descriptions.

Third, the revised discussion explicitly highlights the novelty of this study by emphasizing the limited attention paid in previous research to vegetation as an active influencing factor in high-vegetation areas. By integrating regional-scale susceptibility assessment with site-scale mechanical interpretation, this study demonstrates the dual role of vegetation and clarifies the conditions under which its stabilizing effect may be weakened or reversed.

We believe that these revisions significantly enhance the clarity, completeness, and scientific contribution of the Discussion section. Please check it in lines 593-638, pages 33-35.

4.4 Comparison with previous studies and scope for future research （Revised manuscript line 593）

"*Existing studies on landslides have predominantly focused on rainfall-related triggering mechanisms, such as rainfall intensity, duration, and antecedent moisture conditions (Gatto et al., 2025; Zhang et al., 2025). For example, Cui et al. (2024) analyzed the characteristics and causes of a similar landslide in this area using Massflow V2.8 simulations. They identified rainfall and human activities as key triggers, but insufficiently addressed interactions between soil, moisture, and external forces (such as natural wind and human mining activities) under high vegetation conditions. This limited simulation accuracy. In these studies, vegetation is often treated as a background environmental condition or a stabilizing factor, while its mechanical and hydrological roles are rarely quantified explicitly. As a result, landslides occurring in highly vegetated areas are commonly interpreted primarily as a response to extreme rainfall, with comparatively limited attention paid to vegetation-related processes themselves. Consequently, from the perspective of vegetation as an active influencing factor, research addressing why landslides still occur in areas with dense vegetation coverage remains relatively scarce.*

Furthermore, An et al. (2025) investigated the mechanisms of landslide occurrence in densely vegetated areas by examining the interactions between terrain and lithological properties. They highlighted that in natural forests, landslides tend to initiate along the soil–bedrock interface. Owing to the shallow soil layer and pronounced permeability contrast, perched water readily accumulates above this interface, thereby reducing shear strength and triggering slope failure. Their work underscores the significant role of vegetation as a key intermediary that links various environmental factors in shaping landslide susceptibility. Nevertheless, their study treated terrain and lithology primarily as background environmental conditions and did not account for slope damage induced by wind drag on trees. In contrast, the present study incorporates wind forces both in the macroscopic assessment of landslide susceptibility and in the stability analysis of specific slopes.The results of our study support and extend these findings by demonstrating that high vegetation coverage does not necessarily imply low landslide susceptibility.

Our study integrates regional-scale susceptibility assessment with site-scale mechanical interpretation. This multi-scale framework bridges macroscopic statistical patterns and microscopic physical processes, providing a more comprehensive understanding of vegetation's "double-edged" effect on landslide development. The novelty of this work lies not only in identifying the limitations of vegetation's stabilizing role, but also in clarifying the conditions under which its negative effects may become significant. But research on vegetation types, height, and growth conditions (such as thickness and types of soil and human activity disturbances) in relation to landslide risks remains limited. Future research could apply optical remote sensing image classification and InSAR deformation monitoring to identify potentially unstable slopes and capture temporal deformation characteristics (Li et al., 2025). When combined with interpretable machine learning approaches, such as SHAP-based models, together with analytical tools like GeoDetector and SEM, these methods can quantify nonlinear interactions, threshold effects, and spatial heterogeneity among conditioning factors (Sun et al., 2024; Wen et al., 2025), thereby improving the interpretability of susceptibility evaluation and enhancing the prediction capability for landslides in densely vegetated areas."

References:

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(LSM) based on different boosting and hyperparameter optimization algorithms: A case of Wanzhou District, China. Journal of Rock Mechanics and Geotechnical Engineering, 16(8), 3221-3232. https://doi.org/10.1016/j.jrmge.2023.09.037

Wen, H., Yan, F., Huang, J., & Li, Y. (2025). Interpretable machine learning models and decision-making mechanisms for landslide hazard assessment under different rainfall conditions. Expert Systems with Applications, 270, 126582. https://doi.org/10.1016/j.eswa.2025.126582

Zhang L M, Lü Q, Deng Z H, et al. Probabilistic approach to determine rainfall thresholds for rainstorm-induced shallow landslides using long-term local precipitation records[J]. Engineering Geology, 2025: 108139. https://doi.org/10.1016/j.enggeo.2025.108139

[Comment 16] What is the purpose of calculating the total height of landslides?

Response:

Thank you for your question. In general, landslides with greater total height possess higher gravitational potential energy. The ratio between total height and runout distance can be used to characterize the overall scale of a landslide and to reflect the potential mobility and degree of destruction after failure. This indicator helps to qualitatively assess the impact force and destructive capacity of landslides. Therefore, in this study, the total height of landslides is mainly used as a process-based and explanatory metric to support the interpretation of landslide scale and potential hazard characteristics, rather than as a direct input parameter in the modeling framework.

[Comment 17] "Common factors" instead of "Public factor."

Response:

Thank you for pointing out this inconsistency. This was an oversight on our part. The term "public factors" on line 462 was used in error. Our intended term, as defined in the Methods section (Line 226), is "common factors", which refers to [elevation, slope, aspect, lithology, and distances to faults, rivers, and roads.] the factors that are shared across different factor combinations in our analysis. We have corrected "public factors" to "common factors" on line 504 in the revised manuscript to maintain terminological consistency throughout the paper.

[Comment 18] Regarding subsection 4.3, I completely agree with RC1's comment that "several statements about the 'ambiguous role' of vegetation are speculative and not sufficiently substantiated by quantitative evidence."

Response:

We thank you for highlighting the need for stronger quantitative support in Section 4.3 regarding the “ambiguous role” of vegetation. We agree that some statements in this subsection were more speculative and have now revised this section 4.3 better integrate our empirical findings and quantitative results. Specifically, we have:

1.Explicitly linked the discussion to our quantitative results from GeoDetector and SEM (e.g., NDVI’s interaction effects, total effect coefficients), as well as slope stability calculations under saturated vs. natural conditions.

2.Replaced speculative statements with evidence-based interpretations, using data from our susceptibility scenarios (Categories I–V) and stability factor (Fs) values to explain how vegetation’s role shifts with rainfall and slope conditions.

3.Clarified that the “ambiguity” is not merely hypothetical, but is demonstrated through: The bifactor enhancement between NDVI and rainfall (Fig. 8), showing that vegetation can amplify rainfall’s impact in certain contexts; The decrease in slope stability (Fs) from 1.13 to 0.89 under saturated conditions when vegetation weight is considered (Table 3), providing direct mechanical evidence of its potential destabilizing effect; The shifts in susceptibility zoning when vegetation is added to the model (Table 6), illustrating its spatially varying influence.

We believe these revisions strengthen the subsection by grounding the discussion in our own analytical results, thereby providing a more substantiated explanation of vegetation’s dual role.

#4.3 Mechanisms of landslides in areas with high vegetation coverage （Revised manuscript line 543）

"*The mechanisms underlying landslide initiation in densely vegetated areas are complex and context-dependent, as evidenced by the contrasting effects of vegetation revealed in our multi-scale analysis. Our findings demonstrate that vegetation does not act uniformly as a stabilizer; rather, its role is modulated by hydrological conditions, slope gradient, and external loading.*

At the watershed scale, the GeoDetector results indicate that NDVI alone exhibits limited independent explanatory power (q = 0.27, Table 4). However, its interaction with rainfall significantly enhances landslide susceptibility (e.g., NDVI × rainfall q = 0.67, Fig. 8), suggesting that vegetation can amplify the destabilizing effects of precipitation under certain conditions. While vegetation intercepts rainfall and promotes evapotranspiration, it can also alter soil moisture distribution via stemflow, root-induced preferential flow, and reduced surface runoff. Under prolonged rainfall, these processes may lead to localized saturation, thereby exacerbating landslide and debris flow risks in vegetated slopes. This aligns with the SEM results, which attribute a total indirect effect of 0.21 to NDVI, mediated largely through soil moisture dynamics and interactions with rainfall and slope (Fig. 9, Table 5). The susceptibility scenario analysis further illustrates this duality: adding vegetation alone (Class II) slightly reduced the extent of very high susceptibility zones, yet when combined with rainfall (Class IV) and wind (Class V), it led to a notable expansion of high-susceptibility areas and an increase in landslide counts (Table 6, Fig. 10). This suggests that vegetation's protective capacity may be offset or reversed under prolonged rainfall, especially on steeper slopes.

At the site-specific scale, the stability calculations provide direct mechanical insight into how vegetation can transition from a stabilizing to a destabilizing factor. Under natural (unsaturated) conditions, the slope remained stable even with the added weight of vegetation and waste material (Fs = 1.02). However, under saturated conditions, the same additional loads—particularly the self-weight of trees—reduced the stability coefficient to 0.89, triggering failure (Table 3). This demonstrates that the mechanical reinforcement from roots can be outweighed by the gravitational load of *vegetation when soil strength is reduced by saturation, a shift that is quantitatively captured by our modeling.*

These findings help explain why landslides may occur unexpectedly in densely vegetated areas. Vegetation can create a false sense of stability by masking early signs of movement (e.g., surface cracking, minor slumping) and by being traditionally associated with slope protection. Moreover, the same root networks that enhance soil cohesion also facilitate preferential infiltration, potentially accelerating soil saturation during heavy rainfall—a process reflected in the strong interaction between NDVI and rainfall in our spatial analysis. In terrain with high lateral variability in slope, lithology, or soil depth, vegetation may thus contribute to highly localized and concealed instability, as exemplified by the 2023 Jinkouhe landslide.

In summary, our integrated analysis provides quantitative evidence that vegetation's role is not merely "ambiguous" in a speculative sense, but is quantifiably dual: it stabilizes slopes through root reinforcement under moderate conditions, yet can promote instability through added weight, enhanced infiltration, and synergistic interactions with rainfall when critical thresholds are exceeded. This duality underscores the importance of considering vegetation not as a static stabilizing factor, but as a dynamic component of the hillslope system in landslide susceptibility assessments."

[Comment 19] What do the authors mean by "Good vegetation"? It is not an adequate technical term.

Response:

We thank you for pointing out that the term "Good vegetation" is not sufficiently technical. We agree that precise terminology is important for clarity and reproducibility. In the revised manuscript, all instances of "Good vegetation" have been replaced with "areas with high vegetation cover" to more accurately describe locations with dense vegetation. This change ensures that the description is technically precise and consistent throughout the manuscript. The specific modifications can be found in Response Letter Comment #3.

[Comment 20] In addition, how is it possible that "Vegetation's absorption of part of the rainfall also increases soil saturation, further exacerbating the risks of landslides and debris flows."?

Response:

Thank you for this important question. The statement reflects the nuanced and context-dependent role of vegetation in hillslope hydrology. We acknowledge that the phrasing may appear contradictory at first glance, as vegetation is widely known to intercept rainfall and promote evapotranspiration, which generally reduce soil moisture. However, under certain conditions—particularly in densely vegetated, humid environments—vegetation can indeed contribute to localized increases in soil saturation through the following mechanisms, thereby exacerbating landslide susceptibility:

1 Canopy Drip and Stemflow Concentration: Vegetation intercepts rainfall, which is then redistributed as canopy drip and stemflow. This concentrated water delivery can lead to preferential infiltration near tree bases and along root channels, creating localized zones of higher soil moisture than in open areas. In some cases, stemflow can funnel large volumes of water directly into the root zone, accelerating pore-pressure buildup during prolonged rainfall.

2 Root-Induced Preferential Flow Paths: Dense root networks create macropores and channels that facilitate preferential flow, allowing rainwater to bypass the soil matrix and rapidly percolate to deeper layers. This can lead to quicker saturation of the critical shear zone, especially in shallow soils, even if the total rainfall volume is reduced by interception.

3 Reduced Surface Runoff and Increased Infiltration: Vegetation and litter layers reduce surface runoff, thereby increasing the total infiltration volume into the soil profile. While this generally enhances slope stability by reducing erosion, during intense or prolonged rainfall it can lead to soil saturation from below, particularly if the substrate has low permeability or if a perched water table develops.

4 Shade and Reduced Evapotranspiration in Understory Layers: In dense forests,

the understory and soil surface may receive limited sunlight and air circulation, which can suppress evaporation. Combined with continuous litterfall that retains moisture, this microclimate can maintain higher soil moisture levels for longer periods, prolonging the window of susceptibility after rainfall.

5 Synergistic Effect with Rainfall Characteristics: In our study area (subtropical monsoon climate), rainfall events are often prolonged and of high intensity. Under such conditions, interception storage may become saturated early in the event, after which vegetation plays a minimal role in reducing net rainfall. Meanwhile, the mechanisms above continue to facilitate infiltration and moisture retention, effectively amplifying the wetting process during extended rainfall.

In summary, vegetation does not simply “absorb” rainfall in a way that reduces landslide risk uniformly. Instead, it modifies the hydrological pathways and temporal–spatial distribution of soil moisture. In certain settings, these modifications can lead to accelerated or concentrated saturation in susceptible zones, thereby increasing landslide potential. This aligns with our findings that the combination of high NDVI, rainfall, and slope gradient resulted in the highest landslide susceptibility in our study area.

We have totally rewritten section 4.3; please check it in lines 543-591. For example:

“*While vegetation intercepts rainfall and promotes evapotranspiration, it can also alter soil moisture distribution via stemflow, root-induced preferential flow, and reduced surface runoff. Under prolonged rainfall, these processes may lead to localized saturation, thereby exacerbating landslide and debris flow risks in vegetated slopes.*”

Please let us know if further clarification or references are needed.

We sincerely appreciate your constructive feedback. We hope the revisions and responses provided will ensure our manuscript meets the standards for publication in ***Natural Hazards and Earth System Sciences***.