Author Response to Referee #1

Soil quality dynamics across a landslide profile from intact slopes to displaced material and bedrock

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RC: Reviewer Comment   **AR:** Author Response

General comments
The manuscript presents an interesting characterization of landslide effects on soil properties.

RC: The limitations of the study are clearly and appropriately described in the methodology section.
Regarding the methodology, I suggest including data from forested or protected areas as reference sites to compare soil quality against a more stable and well-defined reference condition, or alternatively, using appropriate reference data from the literature.

AR: We thank the reviewer for this valuable suggestion. We agree that forested or protected areas can provide a well-defined reference condition for soil quality assessment. However, the present study was specifically designed to evaluate relative soil degradation along a geomorphological transect crossing intact slopes, landslide material, and parent substrate within the same lithological and land-use context, in order to isolate the effects of landsliding. The inclusion of forested or protected reference sites would have introduced additional variability related to vegetation cover and land-use history. To address this limitation, we have clarified in the manuscript that the intact slopes represent a local reference condition, and we addressed this aspect in Section 4.1 by comparing our results with data reported in previous studies from similar areas and for the same soil quality parameters.

Into the Section 2.2. we added the following sentence (Line 145-148): '*These sites share the same lithology, topographic setting, and land-use history as the landslide-affected soils, allowing the isolation of landslide-induced effects. Although forested or protected areas can represent more stable reference conditions, such sites were not included in the present study to avoid confounding effects related to contrasting vegetation cover and land-use regimes.*'

In addition, several changes were applied in Section 4.1 (Line 380-493).

RC: The statistical analysis is very basic, relying solely on a one-factor ANOVA. Given the limited number of soil properties, applying multivariate analyses such as PCA or clustering may be challenging; however, the authors could explore alternative statistical approaches to strengthen the interpretation of the results.

AR: Thank you very much for your observations and suggestions. The statistical analysis has been substantially revised and expanded to provide a more robust and comprehensive assessment of soil variability and landslide effects.

First, given the relatively small sample size and the non-normal distribution of several variables, we replaced the one-factor ANOVA with appropriate nonparametric methods. Specifically, the Mann–Whitney U test was applied to compare soil properties between landslide-affected and unaffected areas, while the Kruskal–Wallis test with Bonferroni-adjusted post hoc comparisons was used to evaluate differences among depth intervals. In addition, comparisons between longitudinal and transversal transects within the landslide area were performed to evaluate lateral variability and internal heterogeneity.

Second, Spearman rank correlation analysis was introduced to investigate relationships among soil physico-chemical and magnetic properties. This approach provided important insights into the structure of pedogenic relationships and their disruption within the landslide area, thereby strengthening the interpretation of landslide-induced changes.

Regarding multivariate analyses such as PCA or discriminant analysis, we carefully evaluated their applicability. However, these methods rely on assumptions and sample size requirements that are difficult to satisfy in the present dataset, particularly due to the limited number of independent sampling locations in the reference (unaffected) area and the hierarchical structure of the data (multiple depths sampled within the same points). In particular, discriminant analysis requires multivariate normality and homogeneity of covariance matrices, which could not be reliably ensured. Similarly, PCA is primarily an exploratory dimensionality-reduction technique and does not directly address the study's primary objective of testing differences between landslide-affected and unaffected soils.

Therefore, we focused on robust nonparametric univariate and correlation-based analyses that are better suited to the sample size and data structure, while still providing clear and statistically supported evidence of landslide-induced changes in soil properties. These revisions substantially strengthen the statistical rigor and interpretability of the results.

The revised statistical methods and results are described in detail in the Statistical analysis section (Section 2.3: Line 205-222) and throughout the Results section (Section 3: Line 234-375).

RC: The discussion section requires revision, as it is currently more theoretical than directly supported by the presented data. For example, in the statement *"Bulk density emerged as a particularly robust indicator, with higher values consistently recorded in degraded or landslide-affected areas. High values of bulk density indicate compaction due to mechanical disturbance, sediment displacement, or livestock trampling."* contribution of livestock trampling is introduced without supporting evidence from this study. The authors should clarify whether animal-induced compaction can reasonably be considered comparable to landslide-induced compaction in this context, or restrict the interpretation to processes directly supported by their data.

AR: We thank the reviewer for this comment. We are agree that the reference to livestock trampling was not directly supported by our analysis and weaken the interpretation. The discussion has been revised to restrict the interpretation of elevated bulk density to geomorphic processes directly evidenced in our study area, namely sediment displacement, topsoil removal, and mechanical compression associated with landslide activity. References to animal-induced compaction have been removed to avoid overinterpretation beyond the scope of the dataset. We replaced the initial discussion with the following one (Section 4.3: Line 529-538): "*Bulk density emerged as a particularly robust indicator, with higher values consistently recorded in degraded or landslide-affected areas. In the current study, the higher values of BD could reflect soil compaction and structural disturbance and restructure caused by mass movement processes, includingHigh values of bulk density indicate compaction due to mechanical disturbance, sediment displacement, topsoil removal, and mechanical compression during landslide activity.or livestock trampling, leading to reduced porosity, infiltration capacity, and root penetration These processes determine the reduction in total porosity, water infiltration capacity, and root penetration potential (Hamza and Anderson, 2005; De Rosa et al., 2020). Compaction has been widely recognized as a key physical degradation mechanism that limits soil aeration and water movement, accelerating surface runoff and erosion (Zhang et al., 2006). In addition, the increase in BD is consistent with the observed reduction in organic matter content and the homogenization of clay distribution within landslide-affected profiles, supporting the interpretation of a structurally degraded soil system. Therefore, bulk density can effectively capture the mechanical imprint of both anthropogenic and geomorphic stressors, making it a reliable early-warning indicator in vulnerable landscapes.*"

Specific comments

RC: Figure 1 and Figure 2: The resolution needs to be improved.
AR: Thank you for your observation. We replaced the figures with new, improved ones.

RC: Line 135: The geological information is well detailed; however, additional pedological and soil mineralogical information is needed to better understand soil pedogenesis in the region.
AR: Thank you for your suggestion. Whitin the subchapter 2.1. (Line 105-112) we inserted the following paragraph: "*The pedogenesis process took place on Sarmatian rocks (marls and clays) rich in expandable clay minerals (montmorillonite, illite, beidellite), which, under the conditions of the temperate-continental climate of the Transylvanian Basin, favoured the formation of a Haplic Chernozem (Acree et al., 2020). The soil is poorly debased, saturated in bases (especially Ca^{2+}) and characterized by a well-developed mollic horizon. The relatively low permeability of the parent rock determined a moderate alteration of the mineral substrate, with in situ argillization (Acree et al., 2020) and the formation of clay minerals (Ianoș, 2004). The grassy vegetation contributed to the accumulation of organic matter (Blaga et al., 2005), and the thermal and rainfall variations favored the formation and stabilization of humus rich in calcium-saturated humic acids (Pendea et al., 2002), which explains its accumulation in the upper part of the profile and the pedogenetic specificity of the soils in the region.*"

RC: Line 160: Please provide references for each method used to determine bulk density.

AR: The method is already given, as it is described in ISO 11272:2017 – Core Method: …' *where ρb is in g m^{-3}, md is the mass of the sample dried at 105°C in grams g, and Vs is the volume of the steel cylinder in cubic centimetres cm^3 (ISO 11272:2017).*' In addition, we also mentioned this method at Line 192.

RC: Line 183: The authors need to be consistent in the use of abbreviations for bulk density (ρ).
AR: Thank you for your comment. We corrected the abbreviations (Line 192)

RC: Lines 204–211: NDVI is described in the methodology, but the results related to this variable are not presented in the Results section, nor is its specific use sufficiently explained.
AR: At the beginning of the Results chapter (Line 234-242), we added the following paragraph: '*The NDVI analysis indicates that vegetation cover within the landslide perimeter is predominantly sparse to moderate, with 93% of pixel values below 0.40. Around 24% of the area falls within the stressed or sparse vegetation class (NDVI 0.11–0.30), while 7% is characterized by nearly bare surfaces (0.00–0.10), indicating an exposed soil and a reduced protective cover. Only 0.3% of the landslide surface is covered by dense vegetation (NDVI > 0.60), and areas potentially associated with stable woody cover remain below 1%. This analysis reflects an unstable terrain characterized by scarce vegetation, with limited root development and reduced soil cohesion. The dominance of low NDVI values indicate that post-failure vegetation recovery is in an early successional stage, reflecting recent or ongoing slope reactivation processes. To support the observations derived from the NDVI analysis, the following section presents the results of the soil physicochemical parameters, which contribute to the detailed characterization of the studied slope.*'

RC: Line 206: Present the NDVI formula in the same way as the other formulas included in the manuscript.
AR: We inserted the formula in the same way as the other formulas were included in the manuscript (Line 226)

RC: Line 235: Add a table clearly indicating the type of sites (reference sites, within landslide, outside landslide).
AR: Tables (1 and 3) were added to summarize the soil properties for landslide-affected sites, unaffected reference sites, and parent material samples, including minimum, median, and maximum values for each parameter across the investigated depth intervals. These tables provide a clear overview of the dataset and explicitly distinguish between the different site categories.

RC: Line 235: Table 1 should be summarized and complemented with the results of the ANOVA tests.
AR: To improve clarity and readability, statistically significant differences are now directly indicated in the multi-panel boxplot figure (Figure 3) using significance brackets. This graphical representation allows readers to easily identify statistically significant differences

both between landslide-affected and unaffected soils at the same depth and between depth intervals within each zone. We believe that presenting statistical significance in graphical form improves interpretability and avoids redundancy with the descriptive statistics provided in the tables.

The following references were added to the References list:

Acree, A., Weindorf, D.C., Paulette, L., Van Gestle, N., Chakraborty, S., Man, T., Jordan, C., Prieto, J.L.: Soil classification in Romanian catenas via advanced proximal sensors, Geoderma, 377, 114587, https://doi.org/10.1016/j.geoderma.2020.114587, 2020.

Blaga, Gh., Filipov, F., Paulette, L., Rusu, I., Udrescu, S., Vasile, D.: Pedology (in Romanian), Editura Mega, Cluj-Napoca, 449 pp., 2008.

Dearing, J.A.: Environmental magnetic susceptibility using the Bartington MS2 system, Chi Publishing, England, 2nd edition, 52 pp., 1999.

Ianoş, Gh.: Geography of soils (in Romanian), Editura Mirton, Timişoara, 319 pp., 2004.

Panagos, P., De Rosa, D., Liakos, L., Labouyrie, M., Borrelli, P., Ballabio, C.: Soil bulk density assessment in Europe, Agriculture, Ecosystems and Environment, 364, 10897, https://doi.org/10.1016/j.agee.2024.108907, 2024.

Pendea, I.F., Szanto, Zs., Bădărău, Al.S., Dezsi, S.: Age and pedogenic reconstruction of a paleo-relict chernozem soil from Central Transylvanian Basin, Geologica Carpathica, 53, 37-38, 2002.

The following reference was deleted from the References list:

Boushane, N. and Bouhlassa, S.: Assessing magnetic susceptibility profiles of topsoils under different occupations, International Journal of Geophysics, 2018, 1-8, https://doi.org/10.1155/2018/9481405, 2018.