Inventory mapping of forest-covered landslides using Geographic Object-Based Image Analysis (GEOBIA), Jena region, Germany

Authors' response

Anonymous Referee #1

Comment:

This study presents a semiautomatic method for landslide identification in Germany. I find the topic relevant and promising; however, improvements are necessary, particularly in the methodology section, which requires a more detailed description. Additional comments and suggestions are outlined below:

1. The authors use the term "landslides" in the introduction. In English, this is a general term encompassing all types of mass movements (e.g., shallow landslides, debris flows, rockfalls, etc.). Did your analysis identify all these types? If not, I recommend using a more precise term to reflect the specific process addressed in the study.

Response:

Thank you for the comment. In this study, we did not map all types of mass movements, but primarily focused on deep-seated (rotational) landslides, along with a few old shallow landslides. However, we did not differentiate between landslide types in our analysis, basically, the focus was on forest-covered landslides in general. Unfortunately, using LiDAR DTM, we do not have any information on their age. However, assuming that features are well preserved under forest cover, they might be quite old (Bell et al., 2012). We agree that clarification is helpful, and we have added a brief explanation regarding the mass movements we study in the last paragraph (revised manuscript, at line 83) of the Introduction.

2. **Study Area section**: Please provide information on recorded damage and economic losses in the region, if available. What is the primary triggering factor for landslides in Thuringia? Is it related to tectonic activity, climatic conditions, or other factors?

Response:

Thank you for this valuable comment. Unfortunately, specific information on recorded damage and economic losses in the region is not available, and we have included this information in the revised manuscript, at line 115-116.

To address the second concern, we have expanded the 'Study Area' section to clarify the main triggering factors. The updated text explains that landslides in this region are primarily caused by geological and structural conditions, particularly where limestone (Muschelkalk) overlies sandstone (Buntsandstein), and by steep slopes along the cuesta scarp. We also acknowledge that permafrost thawing at the end of the last glaciation may have played a significant role in triggering many of the older, deep-seated landslides (Achilles et al., 2016). These clarifications have now been incorporated into the revised manuscript, at lines 105-111.

3. **Line 98**: The manuscript states that "the area has experienced periods of landslide activity." Please specify which periods are being referred to.

Response:

Thank you for pointing this out. In our study, we focus on old, forest-covered landslides identified through DTM-based mapping and semi-automatic analysis. The study by Achilles et al. (2016) assumes that the landslides may have occurred during the Holocene, possibly beginning at the end of the last glaciation. Although the DEM, as our primary data source, does not provide explicit temporal information, the presence of large landslide features beneath dense forest cover suggests that there may have been a period of increased landslide activity in the past. While we are unable to determine the precise timing of these events, this interpretation aligns with the assumptions discussed in the above mentioned research. This information has been incorporated into the revised manuscript, at lines 109-114.

4. **Data section**: What criteria were used for visual landslide mapping? Which types of landslides were identified and mapped? This information is essential and should be included.

Response:

Thanks for this comment. In the revised manuscript, at lines 132-143, we have clarified the criteria used for visual landslide mapping, as well as the types of landslides identified. The landslide inventory map (reference map) was produced through manual visual mapping in ArcMap 10.7, primarily based on traditional and multi-directional hillshade derived from 1m LiDAR–DTM data. This method follows the procedure described by Schulz (2004), which is already cited.

Although hillshade was the only data type directly used to create the inventory, additional land-surface variables (LSVs), such as slope, curvature (plan and profile), topographic openness, topographic position index (TPI) and terrain ruggedness index (TRI), were employed to assist with on-screen interpretation. These LSVs were particularly useful for improving the delineation of landslide boundaries where hillshade alone did not provide sufficient contrast. In most cases, the landslide scarp and body were mapped separately if they could be visually distinguished; however, in a few instances, identification of the scarp was not possible.

The inventory mainly consists of deep-seated (rotational) landslides, with some shallow features also present. However, the study does not explicitly classify landslide types, as the objective is to detect medium to large forest-covered historical landslides.

5. **GEOBIA-based landslide inventory mapping section**: Please specify the versions of the GIS software used (e.g., eCognition, ArcGIS).

Response:

Agree, and we have specified them in the revised manuscript, at line 145 and 148.

6. **Figure 1**: I suggest incorporating the symbol for landslide features (currently shown in white) into the **map legend** itself rather than only in the figure caption. This will enhance immediate understanding, as the current legend indicates landslides in green, which is confusing.

Response:

Thanks for pointing this out. We totally agree. Therefore, the map legend revised to insure consistency between the legend and the figure caption.

7. **Line 126 – Step 1**: What were the specific criteria applied for visual landslide mapping? This information is crucial. Please also state the total number of landslides identified and the total mapped area.

Response:

Thank you for pointing this out. The first part of your comment appears to overlap with point 4 of your earlier comments, which we have already addressed. The second part of your concern has been addressed in Section 4.3, which contains all the relevant information. Specifically, Table 4 in the revised manuscript shows the number of mapped landslides, note the last rows marked "**Inventory** = **38**" and "**40**" for scarps and bodies, respectively. Table 5 (in the revised manuscript, at the last row) presents the total mapped area (the inventory) in hectares: **20 ha** for scarps and **243 ha** for bodies. This information was used to evaluate and compare the results of our method with those from manual mapping. To avoid redundancy, we have not repeated these details elsewhere in the manuscript. We hope this clarification adequately addresses your concerns.

8. **Line 136**: Indicate the software versions used for ArcGIS and R.

Response: Thank you, we agree and have incorporated it in the revised manuscript at line 153.

9. **Lines 145–150**: What were the proportions of the samples used for landslide scarps, landslide bodies, and non-landslide areas? Please include this breakdown.

Response:

Thanks for this comment. We agree with you and have made the necessary revisions. The proportions of each sample are included in the revised manuscript, at lines 158-159. It is also important to note that the non-landslide areas have been divided into two categories: non-scarp and non-body areas. This means that they are not treated as a single, non-landslide class.

10. **STAGE II – Segmentation and Classification**: Include the segmentation parameters such as **shape** and **compactness**.

Response: Done.

Suggestion: A figure illustrating the mapped landslide scarps and bodies would enhance clarity.

Response:

Thank you for your suggestion. Although the specific concern was not entirely clear to us at first, we decided to revise Figures 4, 5, and 7 (Fig 7 renumbered to Fig 8 in the updated version) to further improve clarity. In the updated figures, landslide scarps and bodies from the inventory and the GEOBIA results are represented using distinct colors, which we believe enhances visual interpretation and facilitates a clearer comparison. We hope these revisions address your point effectively.

11. **Line 162**: Please elaborate on the "refinement process." What specific criteria were used to determine when the result was satisfactory?
12. **Lines 162–166**: Provide the threshold values used in the ruleset applied during the classification (e.g. shape and compactness).

Response:

Thank you for these valuable comments on related issues (comments #11 and 12). As they both relate to the classification and refinement process, we have decided to respond to them together.

In the original manuscript (lines 162–164), we mention the general classification criteria used: '*In this phase, we utilised morphometric parameters of the LSVs and classified objects, including their mean values, standard deviations, length-to-width ratios, areas, relative borders, and distances to specific objects*.'

While this description outlines the general approach, we agree that a more specific and detailed explanation is necessary. Therefore, in the revised version of manuscript, we have expanded the explanation by include a comprehensive set of rule-set parameters in the **Appendices** (**Table A1-B2**). These clarify the exact criteria and thresholds applied during the classification process for both scarps and landslide bodies.

The iterative refinement process was guided by a combination of visual inspection and comparison against the manually mapped landslide inventory. At each step of the refinement process, we evaluated the outputs by analysing the number of true positives, false positives and false negatives, adjusting the threshold values accordingly in order to strike a balance between accuracy and minimising misclassifications, this already explained in other way in the Result and Discussion as well.

13. **Line 194**: (Dias et al., 2023). Ensure proper in-text citation formatting and consistency.

Response: Thanks for this comment. We agree and have checked through the manuscript.

14. **Figures**: Improve the resolution and overall size for better readability and visual interpretation.

Response:

Thanks for you for your comment. We agree that the figures should be clearly readable across all file types. Accordingly, we have modified the study area figure (Fig. 1), as already recommended, and we have also revised Figures 4, 5, and 7 (Fig 7 renumbered as Fig. 8 in the revised manuscript) to further improve clarity. In the updated figures, landslide scarps and bodies from the inventory and the GEOBIA results are depicted using distinct colors, which we believe improves visual interpretation and facilitates clearer comparison. Additionally, we have split the original Figure 6 into two separate figures (now Figures 6 and 7 in the revised manuscript) and revised them with higher resolution, larger dimensions, and improved layout. We have also updated the figure captions to be more detailed and descriptive. We hope these revisions effectively address your concerns (see the revised manuscript).

15. **Section 4.2 – GEOBIA-based landslide modeling results**: Include the total area identified for landslide features by both Method I and Method II for comparison.

Response:

We addressed this point in our response to comment 7, which we hope clarifies your concern. Please let us know if any further details are still required.

16. The **Results** section needs to be more comprehensive. Please include more descriptive analysis and interpretation of the findings.

Response:

Thank you for your comment. Following your recommendation, we have added two tables to **Section 4.2** ('GEOBIA-based landslide modelling results') to clarify the findings. The tables (Tables 2 and 3, revised manuscript) present morphological parameters for GEOBIA-based mapping results, including scarps and bodies, for both models. Brief interpretations of these results have also been integrated into the revised manuscript to enhance understanding, at lines 262 and 271.

17. There are two references listed for **Dias et al. (2023)**, labeled “a” and “b” in the references. However, only **Dias et al. (2023)** is cited in the main text. Please ensure that the correct designation (**a** or **b**) is used consistently in both the text and the reference list.

Response:

Thank you for your observation. For the record, I only intended to reference **the second article, or 'b'**, in the original version. Consequently, you will now see a single citation for **Dias et al. (2023)** in both the text and the reference list, **with no 'a'** or **'b'** designation.

References:

Achilles, F., Danigel, M., Frey, V. S., Voigt, T., and Büchel, G.: Massenbewegungen am Übergang des Oberen Buntsandstein in den Unteren Muschelkalk im Jenaer Gembdental, Beitr. Geol. Thüringen, NF.23, 103–114, 2016.

Bell, R., Petschko, H., Röhrs, M., and Dix, A.: Assessment of landslide age, landslide persistence and human impact using airborne laser scanning digital terrain models, Geogr. Ann. Ser. A Phys. Geogr., 94, 135–156, https://doi.org/10.1111/j.1468-0459.2012.00454.x, 2012.

Dias, H. C., Hölbling, D., and Grohmann, and C. H.: Rainfall-Induced Shallow Landslide Recognition and Transferability Using Object-Based Image Analysis in Brazil, Remote Sens., 1–16, 2023.

Schulz, W. H.: Landslides mapped using LIDAR imagery, U.S. Geol. Surv. Open-File Rep., Seattle, W, 1396, 2004.