USGS Cooperative Landslide Hazard Mapping and Assessment Program Final Technical Report

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Title: Event-based landslide inventory mapping: Comparisons with the past and advancing hazard assessment in the Appalachian Plateau, Kentucky, USA

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Abstract

Convective storms on 26–30 July 2022 triggered widespread landsliding in eastern Kentucky. Using lidar change detection, we mapped 6,457 landslides across 525 km^2, producing a near-complete inventory for landslides ≥ 150 m^2. Extending mapped densities to the entire storm area, we estimate that tens of thousands of landslides were initiated during this storm, making this one of the largest published events in eastern North America. Landslides smaller than 1,000 m^2 contributed 44% of total landslide-event erosion, highlighting the significance of smaller landslides. About half of event landslides initiated >100 m from historical polygons (direct reactivations are a minority), and landslides preferentially occurred on N–NE–E-facing slopes, the inverse of the historical inventory. Over 50% of the event inventory landslides intersect with moderate to high classed area of landslide susceptibility, an established statistics-based model developed using historic landslides. These results show that event-specific forcings can rival topographic predisposition and that inventories omitting small slides understate event magnitude and sediment contributions. Event-specific considerations, including mapping limitations, are essential to understanding future rainfall-triggered landslide hazard.

Goals and Objectives

This study contributed our understanding of a significant landslide event that occurred in July 2022 in eastern Kentucky. We combined traditional landslide inventory mapping of historical landslides with rapid, lidar-derived elevation differencing (lidar change detection, LCD) to detect and characterize landslide activity. We focused on landslide inventory comparisons that allow the hazard to be addressed in a sharper geologic context (specifically, by evaluating historical landslides compared to those of the July 2022 event), as well as addressing the extent and style of landslide movement. We analyzed a major landslide event triggered by a convective storm in the Appalachian Plateau (Kentucky, USA); as convective storms are recurrent triggers in soil-mantled uplands worldwide, we expect our findings to have global relevance. **The main objectives included:**

1) Using LCD, constrain a landslide event scale for a convective storm
2) Evaluate how including small landslides (<1,000 m^2) influence event metrics
3) Compare event and historical landslide patterns, including aspect preferences and reactivation metrics

4) Evaluate the effectiveness of using a landslide susceptibility model trained on historical landsides for informing hazard from single modern-day large convective storms

Guidance Criteria Funded

This study contributed to Four Strategic Actions from the U.S. Geological Survey (USGS) Landslide Hazards Program (LHP) National Strategy for Landslide Loss Reduction

- *Strategic Action 1.1: Characterize the societal risks posed by landslide hazards*
- *Strategic Action 1.2: Expand research and development to assess the where,when, and why of landslide hazards*
- *Strategic Action 1.3: Develop a publicly accessible national landslide hazard and risk database*
- *Strategic Action 1.4: Provide publicly available reports of significant landslide events.*

Three risk reduction priority areas (Guidance Criteria) from the full funding program announcement include:

- *Landslide hazard mapping and assessment*
- *Planning and coordination*
- *Education and outreach*

Accomplishments

Introduction

Between July 25 and July 30, 2022, a series of convective storms produced approximately 350 to 400 mm of rainfall across parts of eastern Kentucky, bringing catastrophic flash flooding and triggering landslides and debris flows. Using LCD, we mapped of 6,457 landslides in a 525 km^2 section of the 5,800 km^2 area impacted by the storm (Fig. 1).

Our results show that event-specific forcings can rival topographic predisposition and that inventories omitting small slides understate event magnitude and sediment contributions. Event-specific considerations, including mapping limitations, are essential to understanding future rainfall-triggered landslide hazard.

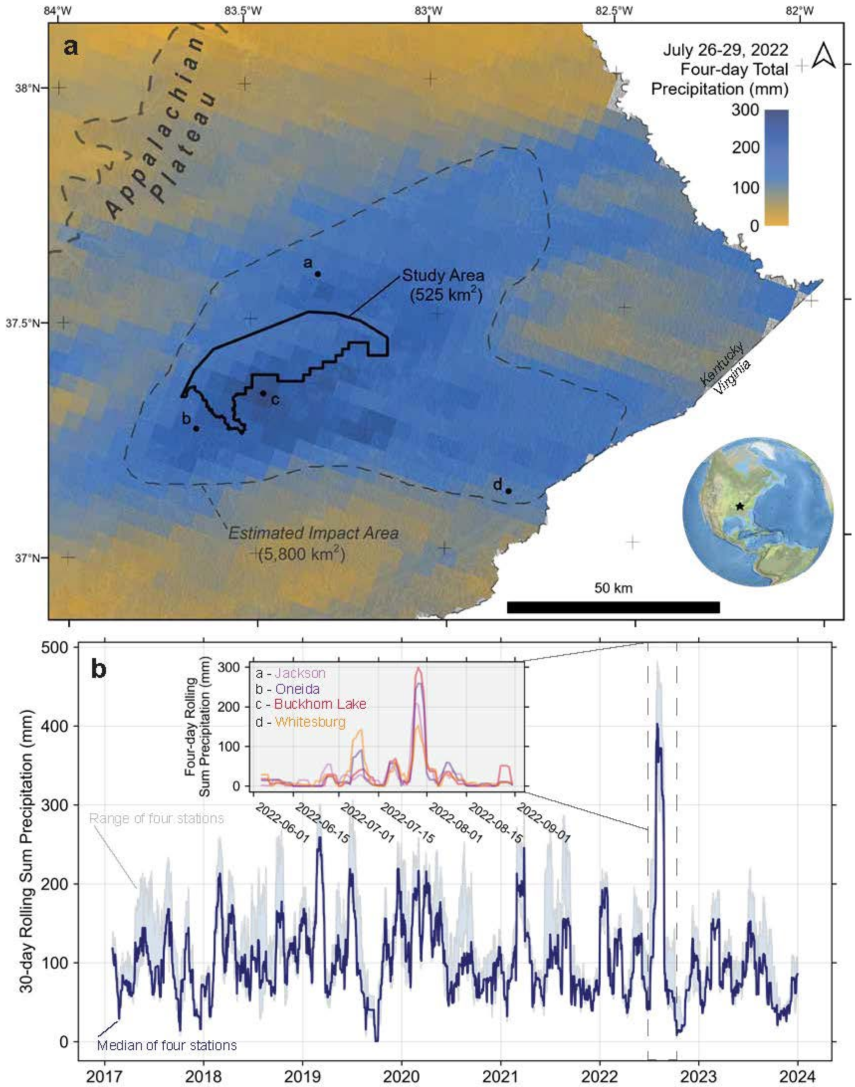

Figure 1. Map of four-day total precipitation during the July 2022 storm event (a). 30-day total rainfall data from four gages in the vicinity covering 2017–2023. Dark blue line indicates the mean of all stations (b). Inset graph details individual gages with four-day rolling sum rainfall centered around the 2022 storm.

Guidance Criteria 1 – Landslide Hazard Mapping and Assessment

We mapped two distinct landslide inventories: (1) an event inventory mapping landslides active between the 2017 and 2023 lidar acquisitions, extensively using LCD results and (2) a historical inventory documenting landslides predating the 2017 lidar acquisition (Fig. 2). To assess landslide reactivation, we compared the two inventories using the framework from Temme et al. (2020), which introduces three styles of reactivation (direct, local, and remote) related to the distance from historical landslides (0–1 m, 1–10 m, and 10–1000 m, respectively). **We mapped 6,457 landslides across our 525 km^2 study area using LCD between 2017 and 2023 acquisitions.** We estimate that most landslides in our inventory occurred during the July 2022 event with few exceptions.

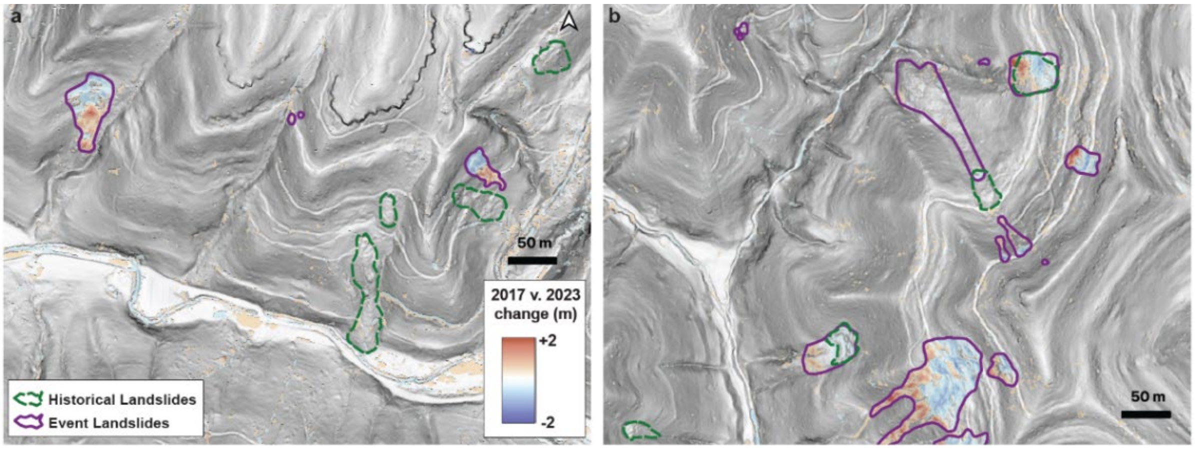

Figure 2. Examples of landslides mapped by lidar change detection (LCD) methods, highlighting areas with and without direct landslide reactivations (a–b).

The event inventory yielded a mean landslide density of 12 landslides/km^2 and a median of 9 landsides/km^2. The highest localized density exceeded 130 landslides/km^2 in an area with significant surface mining and slopes likely covered with modified soils.

Of the landslides mapped in the event inventory, we classified 6,325 earth or debris slides, 121 earth or debris flows, and 10 rockfalls. Of the event landslides, 45% were classified as modified slopes (primarily construction activity, mining, and road building). Of these, 88% were related to roads, 9% were related of mining activity, and 3% were classified as "other."

The inventory is complete for landslides with areas >150 m^2, with a rollover near 43 m^2 (Fig. 3). We define rollover as the modal area of the inverse-gamma fit and the completeness threshold as the minimum area above which the tail follows a power law (also termed "cutoff").

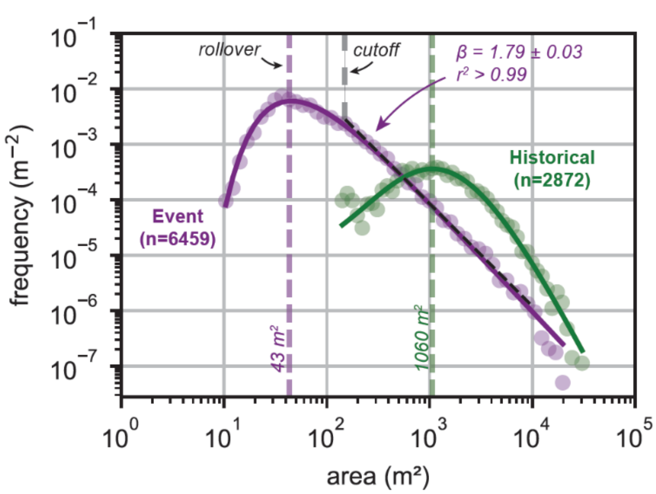

Figure 3. Frequency-area distributions of the event and historical landslide inventories. Dashed vertical lines represent the most frequent landslide sizes in the inventories.

And slides from the July 2022 event showed a strong aspect preference: aspect-frequency ratios were >1 for N, NE, and E bins and <1 for all others (Fig. 4). In contrast, the historical inventory exhibited the opposite pattern, with FR > 1 only for S, SW, W, and NW bins.

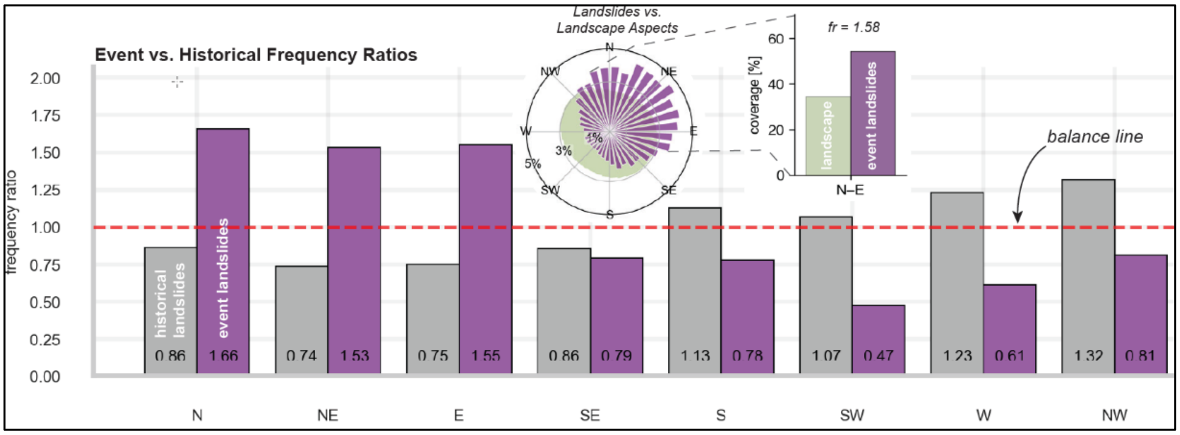

Figure 4. Bars show frequency ratio (FR) by 45° aspect sector (purple: July 2022; gray: historical). Dashed line marks FR = 1 (no enrichment). Numbers on bars give FR values.

During mapping, we identified 534 event landslides that directly overlapped with historical landslides. We attributed the reactivation status of 270 event landslides as “ambiguous,” as these slides did not directly overlap with historical slides, but the 2017 lidar data suggested previous landslide activity. Among the historical landslides, 18% exhibited direct reactivation, 3% exhibited local reactivation (within 1 to 10 m), and all remaining historical landslides exhibited remote reactivation (within 10 to 1000 m; Fig. 5). For half of the historical landslides, the nearest event landslides were >100 m away. Further, we found that historical landslide size decreased with increasing distance to the nearest 2022 event landslide (Spearman $\rho = -0.144$, $p < 1\times10^{-14}$). Of the historical landslides >2,500 m^2, approximately 25% were direct reactivations, leaving over 700 historical landslides that did not move during the July 2022 storm.

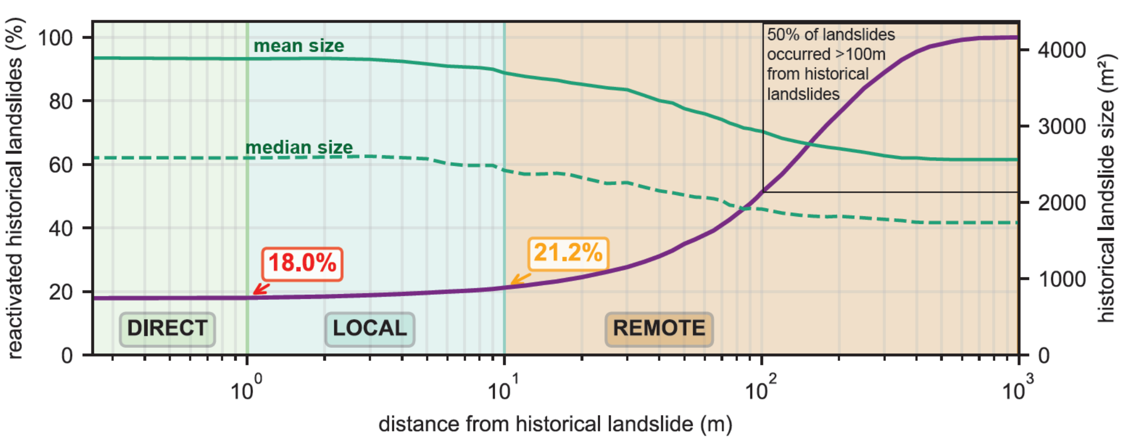

Figure 5. Historic landslide reactivation analysis and cumulative density function of distances from historical landslides to event landslides.

We intersected the LCD with existing landslide susceptibility models for the region developed by researchers at the Kentucky Geological Survey to assess the success/prediction rate of these models with the event inventory (https://kgs.uky.edu/kgsmap/helpfiles/landslidesusc_help.shtm) (Table 1).

Table 1. Lidar change detection (LCD) derived landslide inventory intersected with a regional landslide susceptibility model.

Susceptibility Class	**Percent Area of LCD Inventory**
Low	9.76%
Low-Moderate	33.72%
Moderate	37.89%
Moderate-High	17.59%
High	0.47%

The landslide susceptibility models are data-driven dual-machine learning approaches and were generated using historic landslide inventory. We plan on future work that will evaluate this susceptibility modeling with event inventories.

The accomplishments within this Guidance Criteria also include establishing a protocol for evaluating rainfall-triggered events that is critical for evaluating recurrence and hazard assessment. Typically, these events are significantly underestimated. Our work challenges existing landslide event magnitude scales, which rely on the total count, area, or volume of mapped landslides. Our finding related to event completeness, area-volume relationships, erosion analysis, reactivation, and connection to existing landslide susceptibility are all data that can inform future detailed hazard and risk assessments. The findings can support stakeholder situational awareness, emphasizing the idea that convective storms can produce similar numbers and frequencies of landslides as tropical storms but with much less warning.

Guidance Criteria 2 – Planning and Coordination

The findings in this study can directly influence improvement related to planning and coordination among research, private industry, land management, and emergency management communities, as well as across various levels of government. Landslide inventories are critical, foundational, components for addressing landslide hazards. The Kentucky Geological Survey and BGC Engineering both have a long history of supporting the implementation of reliable landslide hazard management data.

All datasets used in this study are or will be publicly available:

- The project participants have submitted a manuscript to the American Geophysical Union's (AGU) journal *Geophysical Research Letters*.

- Lidar change detection rasters are available on Zenodo (https://zenodo.org/records/16813914).
- The event landslide inventory is provisionally hosted on OSF (https://osf.io/tuvqw/overview?view_only=79501ea561984e198188d3cf4dd7f1c7) for peer review; the final, curated dataset will be published by the Kentucky Geological Survey.
- The current Kentucky Geological Survey historic inventory can be accessed here https://kgs.uky.edu/kgsmap/helpfiles/landslide_help.shtm and downloaded here https://uknowledge.uky.edu/kgs_data/7/
- Code to reproduce analyses, figures, and tables from the released datasets is archived on Zenodo (https://doi.org/10.5281/zenodo.17551099).

Details regarding LCD workflow, rainfall data processing, landslide mapping and attribution, landslide volume estimation, volume scaling, reactivation assessment, slope modification attribution, and aspect control can be found in a supplemental document submitted to *Geophysical Research Letters*.

The work has resulted or will result in the following external facing presentations:

- **U.S. Geological Survey National Landslide Hazard Risk Reduction Working Group meeting** : On January 8th, 2026, Matt Crawford plans to discuss the project findings and implications.
- **U.S. Geological Survey Landslide Hazards Seminar**: Corey Scheip plans to discuss the project findings and implications of this work in early 2026.

Guidance Criteria 3 – Landslide Education, Engagement, and Outreach

This study supports the National Landslide Preparedness Act and National Strategy for Landslide Loss Reduction Risk Reduction priority area of education and outreach. The Kentucky Geological Survey strives to implement measures of outreach and education as part of the mission, particularly regarding sponsored projects related to geologic hazards. Several examples are listed in the Related Efforts component of this study's proposal.

Active engagement with the user community in the application and interpretation of landslide hazard information is needed for effective risk reduction. Stakeholder buy-in is a critical step in information acceptance, adoption, and use. The use of landslide inventories and landslide susceptibility maps are reduced when: (a) the users don't know the products exist; (b) users don't understand the underlying data; and (c) the users were not provided the opportunity for input into the development of products.

Project participants in this study contributed to the following outreach activities. These activities were either directly related to the study or tangentially, depending on the event, but were related to landslide inventory mapping, hazard planning and coordination, and outreach nonetheless.

Matt Crawford

Workshops

Co-organized and taught a short course titled *Landslide Mapping Using Lidar and Ortho-Imagery in a GIS–Building Fundamental Mapping Skills for the Next Generation of Landslide Scientists*, Geological Society of America Connects 2025 (co-led with William Burns (Oregon Dept. of Geology and Mineral Industries) and Stephen Slaughter (U.S. Geological Survey), 10/18/2025. Lidar-based landslide mapping techniques were a significant part of this workshop, training a range of participants from students to mid-career geologists and engineers.

Organized and taught a short course titled: *Understanding and Using KGS Landslide Data*, Kentucky Geological Survey Annual Meeting, 6/10/2025.

Professional Talks

Data for a Hazard Ready Nation, Natural Hazards Research and Applications Workshop (Panelist) Broomfield, CO, 7/14/2025

Comparisons of Historical and Event Landslide Inventories Using Lidar Change Detection: Rethinking Landslide Activity in Big Storms, Geological Society of America Annual Meeting (GSA Connects), San Antonio, TX, 10/20/2025

Landslides in Kentucky: Hazard, Risk, and Response, Kentucky Emergency Services Conference, Louisville, KY, 9/4/2025

Landslide Susceptibility and Risk through FEMA Hazard Mitigation Grants: Tips and Guidelines for Use, Kentucky Association of Mitigation Managers Annual Conference, Corbin, KY, 9/17/2024

Corey Scheip

Professional Talks

Improving Landslide-Event Inventories Using High-Fidelity Lidar Change Detection in Eastern Kentucky, European Geoscience Union General Assembly, Vienna, Austria, April 2025 (https://doi.org/10.5194/egusphere-egu25-10018)

Hudson Koch

Professional Talks

Kentucky Geological Survey Website Tools (for evaluating landslides), presentation for Kentucky Geotechnical Engineering Group, Frankfort, KY, 6/8/2025

Evelyn Bibbins

Professional Talks

The Kentucky Geological Survey Landslide Inventory Database: Updates and Improvements, Geological Society of America Annual Meeting (GSA Connects), San Antonio, TX, 10/20/2025.

Unmet Results

This study achieved the stated objectives. There are some content areas addressed in the study proposal where future work would be beneficial to the overall Guidance Criteria and Strategic Actions from the U.S. Geological Survey (USGS) Landslide Hazards Program National Strategy for Landslide Loss Reduction. One example is further analysis with event inventories and established, statistics-based, landslide susceptibility. Constraining the ages of landslides through LCD (and having two ages of lidar digital elevation models) allows for model validation but also opportunities to develop new models differentiating pre- and post-failure topography. A second example is aiming to understand landslide path dependency. Our findings related to event landslides and reactivated historic landslides begins to shed light on this, but more can be done identifying the spatial overlap between landslide data sets and determining landslides path dependency and its relation to broader landscape evolution.

Summary

Analysis of landslide occurrence is challenging due to meteorological characteristics, such as banded precipitation. Here, we present the most detailed landslide event inventory yet produced for the Appalachian region. We mapped 6,457 landslides across our 525 km^2 study area using LCD between 2017 and 2023 acquisitions. We demonstrate that landslides smaller than 1,000 m^2 contributed 44% of total erosion from this event, highlighting that traditional methodologies potentially underestimate landslide erosion by nearly a factor of two. We found that approximately half of the 2022 landslides initiated more than 100 meters away from historically mapped landslides. This finding emphasizes that sole reliance on historical inventories may underestimate hazard areas and fail to capture the complexities of landslide triggering processes.

Landslide events punctuate the longer-term background rates of erosion within a region, and these events often serve as case studies to understand landslide dynamics and impacts, as well as to inform future hazard planning. Understanding the frequency and magnitude of landslide events is of paramount interest to a wide variety of stakeholders, including the emergency and municipal planning communities, local government officials,

private industry, and researchers. Event-aware mapping and regularly updated inventories can better guide emergency response and future planning after major storms.

The information provided here directly contributes to strategies of the USGS Cooperative Landslide Hazard Mapping Program. Our findings (1) show detailed and contextually relevant information on landslide hazards and risk (2) provide data that support landslide hazard mitigation, preparedness, response, and risk reduction and (3) support communities who plan for landslide hazards, improving public knowledge, and protect those at risk of landslide hazards.

Bibliography

Scheip, C., Crawford, M., Koch, H., Bibbins, E. (Submitted). Reconsidering the magnitude of convective storms in triggering landslide events in the Appalachian Plateau, USA. Submitted to *Geophysical Research Letters*.

> ***Disclaimer.*** *This technical report is a non–peer-reviewed summary of work supported by the USGS Landslide Hazard Risk Reduction Program G*rant # G24AP00425-00. *Portions of the text, figures, and tables overlap with a manuscript submitted to Geophysical Research Letters; duplication is provided only to the document grant-funded sponsor. This report should* ***not*** *be considered a formal scientific publication. If the journal article is accepted, please cite the final published version; until then, do not cite this report except as a programmatic deliverable.*

Crawford, M.M., Scheip, C.M., Koch, H.J., and Bibbins E.M, 2025, Comparisons of Historical and Event Landslide Inventories Using Lidar Change Detection: Rethinking Landslide Activity in Big Storms, Geological Society of America Abstracts with Program, vol. 57, no. 6, doi: 10.1130/abs/2025AM-7884.

Scheip, C., Crawford, M., Bibbins, E., Koch, H., Graham, A., Winters, S., Hsiao, V., Weidner, L., Zellman, M., and Anderson, S.: Improving Landslide-Event Inventories Using High-Fidelity Lidar Change Detection in Eastern Kentucky, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-10018, https://doi.org/10.5194/egusphere-egu25-10018, 2025.