DETECTING AVALANCHE PATH GROUND COVER AND VEGETATION CHANGE ACROSS MULTIPLE SCALES THROUGH TIME USING REMOTE SENSING TOOLS

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ABSTRACT: Large-magnitude avalanches often alter vegetation composition, avalanche path dimensions, and subsequent avalanche return periods. Understanding temporal changes in individual avalanche path trimlines, runout zones, and geomorphic characteristics helps forecasters, planners, and engineers estimate potential avalanche destructive size and impact on infrastructure or settlements in the runout zone. Understanding these changes on a large scale also provides information on post-cycle avalanche distribution. Here, we use remote sensing platforms and change detection techniques to examine vegetation change in avalanche paths in Montana and Colorado. In northwest Montana, we implemented a novel approach using lidar, aerial imagery, and a random forest model to classify imagery-observed vegetation within avalanche paths. We calculated spatially explicit avalanche return periods using a physically based spatial interpolation method and characterized the vegetation within those return period zones. In Colorado, we investigated changes in avalanche path vegetation characteristics prior to and after a widespread large-magnitude avalanche cycle. The highest frequency of avalanche return periods was broadly characterized by grassland and shrubland, but topography greatly influences vegetation classes and return periods. Furthermore, statistically significant differences in lidar-derived vegetation canopy height exist between categorical return periods. We used optical sensors from satellite imagery to analyze changes in Normalized Difference Vegetation Index (NDVI) to calculate ground cover change over time. NDVI, a measure of near-infrared and red bands within the imagery, allowed us to distinguish between green vegetation (e.g., trees and shrubs) and non-vegetated ground cover (e.g., dead and downed trees, rocks, and dirt) within avalanche paths. For this study, we calculated changes in NDVI values by comparing imagery from 2018 to imagery from 2019 after a widespread large magnitude avalanche cycle occurred in March 2019 in Colorado, United States. We applied a filtering process to reduce error, classified NDVI change based on the value distribution, and then calculated area change of all areas within each avalanche path. We completed this process for 1633 avalanche paths throughout Colorado. We found that using NDVI difference values pre- and post-avalanche cycle allowed us to identify ground cover change in avalanche paths throughout Colorado. These changes span from a slight expansion of existing avalanche paths to substantial landscape disturbance. For example, a size D5 avalanche caused severe ground cover change in 18% of one single path near Aspen, Colorado. This suggests that large magnitude avalanches can redefine avalanche path dimensions and could impact subsequent avalanche size and frequency. Using NDVI from satellite imagery is a simple way to detect ground cover changes in avalanche paths on a large scale or in remote areas. In general, remote sensing products to detect and examine vegetation and ground cover change in avalanche paths can help inform avalanche distribution and benefit planning efforts.

KEYWORDS: Land change, remote sensing, NDVI, avalanche runout

1. INTRODUCTION

Large-magnitude avalanches can significantly alter vegetation composition, reshape avalanche path dimensions, and influence the frequency of future avalanches. By studying the temporal changes in individual avalanche path trimlines, runout zones, and geomorphic characteristics, forecasters, planners, and engineers can better estimate the potential destructive size of avalanches and their impact on infrastructure or settlements within the runout zone. On a broader scale, understanding these changes also provides valuable insights into post-cycle avalanche distribution. Forests protect settlements and infrastructure against avalanches by influencing runout extent and avalanche velocity (Teich et al., 2012;Takeuchi et al., 2018). Thus, changes in existing vegetation

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structure in an avalanche path can influence subsequent impact of avalanches (Peitzsch et al., 2024). A mutual relationship exists between avalanches and forest structure and function. Avalanches shape vegetation patterns and forest structure, but forests can also influence the release and runout extent of avalanches.

In northwest Montana, we implemented a novel approach using lidar, aerial imagery, and a random forest model to classify vegetation within avalanche paths. We then used dendrochronological techniques, and a twenty-year historical avalanche occurrence data set combined with spatial interpolation to calculate and map avalanche return periods and characterize the vegetation within those return period zones. We focused on two specific avalanche paths that experience frequent small to medium avalanches each winter, sub-decadal larger magnitude avalanches, and have extensive observational records from the late 1990s to present. Understanding local vegetation evolution and forest characteristics within avalanche paths helps inform larger landscape scale analysis.

In March 2019, a large and extensive state-wide avalanche cycle occurred throughout Colorado. The Colorado Avalanche Information Center (CAIC) recorded over 200 avalanches size D4 or larger during the early March cycle. For reference, the CAIC only recorded 25 D4 or larger avalanches over the previous nine winters. The March 2019 avalanche cycle impacted transportation and commerce across the state. Avalanches buried several vehicles along State Highway 91 and forced closures along Interstate 70 and U.S. Highway 550. The latter was closed for 18 days. Over the duration of the event, 23 people were caught in avalanches, resulting in two fatalities and four severe injuries. Avalanches damaged powerlines in at least five counties and impacted ten other structures. The CAIC found no historical evidence of an avalanche cycle as destructive and widespread as the March 2019 cycle through observational records, historical publications, and interviews with longtime avalanche workers. This event provided an opportunity to investigate major landscape changes due to widespread large-magnitude avalanching. To examine ground cover changes over time, we used Normalized Difference Vegetation Index (NDVI) (Huang et al., 2020) values from satellite imagery to examine ground cover change in over 1600 avalanche paths in Colorado prior to and after the March 2019 avalanche cycle.

2. METHODS

In this study, we manually classified a limited sample of vegetation types within two avalanche paths using high-resolution imagery in southern Glacier National Park, Montana, United States. Following this, we employed an automated classification procedure combining lidar and high-resolution aerial imagery to characterized and quantify vegetation types across the entire extent of both avalanche paths. We mapped avalanche return periods using dendrochronology records and historical observations and characterized the vegetation composition within those reconstructed return periods. Finally, we compared lidar-derived canopy height (data set: USGS, 2017) in each avalanche path for three categorical return periods: one to three years, four to ten years, and eleven to twenty years. See Peitzsch et al. (2024) for a full description of methods and USGS (2017) for specifics related to lidar data collection specifications.

In Colorado, we used Sentinal-2 optical satellite imagery to analyze changes in NDVI. NDVI, a measure of near-infrared and red bands within the imagery, allowed us to distinguish between green vegetation (e.g., trees and shrubs) and non-vegetated ground cover (e.g., dead and downed trees, rocks, and dirt) within avalanche paths. For this study, we calculated changes in NDVI values by comparing mean NDVI values derived from snow-off imagery from 2018 to imagery from 2019 after a widespread large-magnitude avalanche cycle occurred in March 2019 in Colorado, United States. We applied a filtering process to reduce error, masked out negative NDVI values associated with water and cloud features, classified NDVI change based on the value distribution, and then calculated the area change of all areas within each avalanche path. We completed this process for 1633 pre-defined avalanche paths throughout Colorado.

3. RESULTS

Using lidar and satellite imagery, we classified the vegetation and ground cover in two avalanche paths in northwest Montana—Shed 7 (S7) and Path 1163 (1163). We then analyzed the proportion of each vegetation type within the mapped return periods for each avalanche path. In Path 1163, shrubland and grassland were more prevalent in areas with higher frequency avalanche activity, while forested areas dominated lower frequency zones (Figure 1). However, in Path 1163, high-frequency avalanche intervals contained more forest than similar intervals in Shed 7. Additionally, Shed 7 had significantly more shrubland and grassland than Path 1163, particularly in the longer return intervals, specifically the eleven- to thirty-year interval.

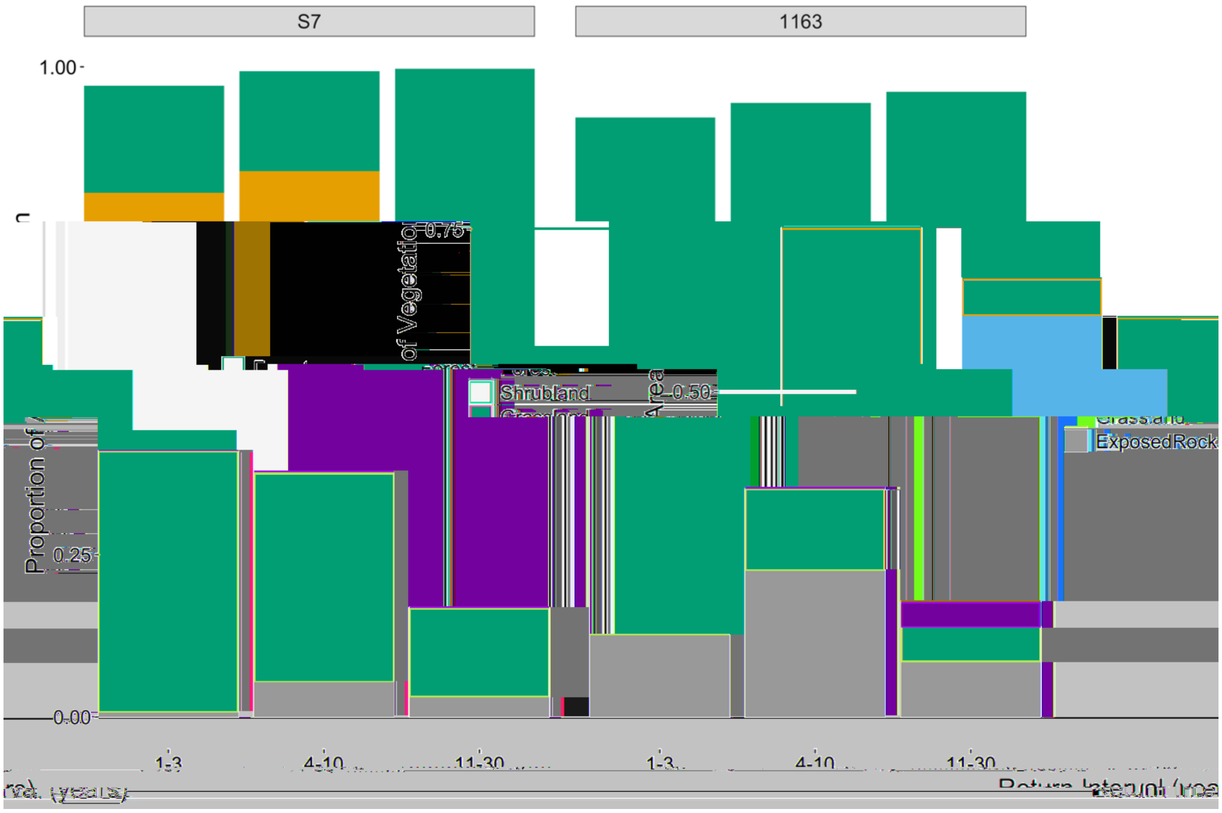

Figure 1: Proportions of each vegetation class for Shed 7 (left) and Path 1163 (right) in northwest Montana. Return interval years are on the x-axis. Vegetation classes are represented by colors (legend on the right). Note that columns do not necessarily sum to 1.0 because of classification of perennial snow in the data set. Figure from Peitzsch et al., (2024).

Next, we investigated the relationship between lidar-derived vegetation height and categorical return periods. An analysis of variance revealed a statistically significant difference in mean tree height across return period intervals for both Shed 7, $F(2) = 171.3$, $p < .001$, and Path 1163, $F(2) = 1518$, $p < .001$ (Figure 2). Tukey's post hoc test showed that, in Shed 7, the mean tree height was greatest in the eleven- to thirty-year return interval category (4.06 m) but slightly and significantly lower in the four- to ten-year interval category (3.10 m) when compared to the one- to three-year return interval (3.27 m; $p = .01$; Figure 2b). In Path 1163, tree height increased progressively with each longer return period category: 2.40 m in the one- to three-year interval, 7.30 m in the four- to ten-year interval, and 10.10 m in the eleven- to thirty-year interval (Figure 2d).

The return periods depicted here are likely underestimations given the limitation of dendrochronological techniques in developing an avalanche chronology (Corona et al., 2012), particularly in locations where few samples exist (e.g., the incised channel on the avalanche paths), as well as an incomplete observational record further back in time. Therefore, the absolute values of the return periods should be used with caution, and the patterns of return periods are the more critical component to this analysis.

Differences in vegetation within the specific return periods for Path 1163 and Shed 7 are due to the geomorphology of each slope. Path 1163 has a smaller and narrower starting zone and is further constrained by the narrow, incised channel of the track. This causes all of the return periods within the path to be laterally narrower when compared to Shed 7, with potentially more overlap. Shed 7, on the other hand, has a wide starting zone and track and is, overall, less steep than Path 1163. This allows avalanches to disperse more easily, thereby causing a greater proportion of each return period to harbor grassland and shrubland vegetation classes and a greater proportion of forest in the eleven- to thirty-year return interval in Path 1163 (Peitzsch et al., 2024).

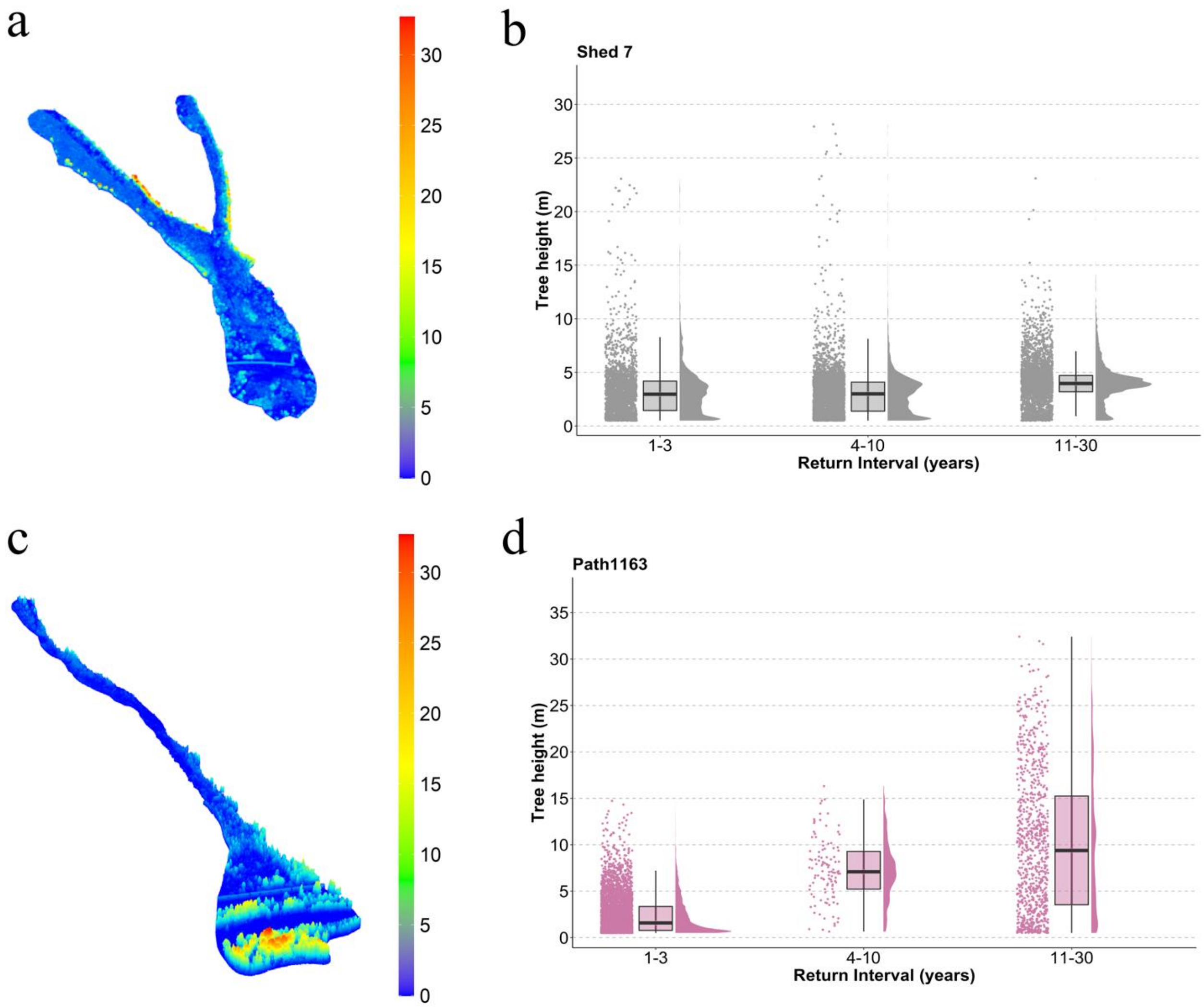

Figure 2: (a,c) Lidar-derived heights of vegetation and (b,d) raincloud plots (b,d) of tree height (m) for return intervals for (a,b) Shed 7 and (c, d) Path 1163. Raincloud plots show the individual return intervals (years) and associated tree height for each tree (points on left), box plots (center) showing the median (black horizontal line) and interquartile ranges for heights for each return interval bin, and the distribution of tree heights for each bin (shaded distribution on right). All pairwise comparisons of return intervals are significantly different in both Shed 7 and Path 1163. Figure from Peitzsch et al. (2024)

Examining vegetation characteristics using temporally static data within return periods of avalanche paths is important for planning. However, investigating changes in ground cover over time and space allows planners and forecasters insight into the impact and spatial extent of specific avalanche cycles. Thus, we tested the efficacy of using satellite imagery data to examine changes in ground cover over time and space, specifically before and after a widespread large-magnitude avalanche cycle. We found that using NDVI difference values pre- and post-avalanche cycle allowed us to identify ground cover change in avalanche paths throughout Colorado. These changes span from a slight expansion of existing avalanche trim lines to substantial landscape disturbance (Figure 3). Unsurprisingly, the greatest changes in NDVI occurred in the track and runout zones. For example, a size D5 avalanche caused severe ground cover change in 18% of one single avalanche path (Conundrum) near Aspen, Colorado (Figure 4). Slight changes in NDVI from pre-2019 avalanche cycle imagery to post-2019 imagery occurred near the ridgelines. This is likely due to snow patches present in the early imagery and absent in later images. We intend to further filter noise and will consider additional sources of uncertainty, such as commercial logging and wildfire impacts on NDVI differences, in future change detection efforts.

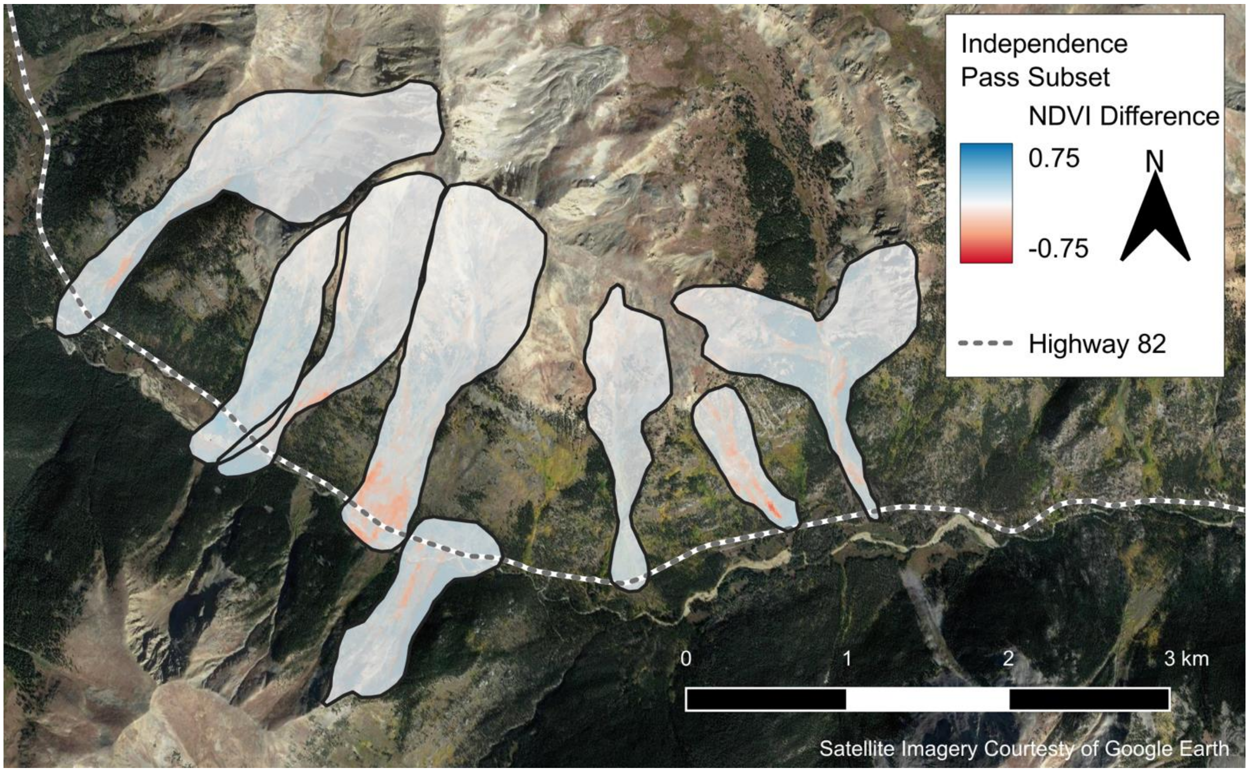

Figure 3: NDVI differences from pre-2019 imagery compared to post-2019 imagery of a subset of avalanche paths near Independence Pass, Colorado. A negative NDVI difference value (the red portion of the difference scale) indicates a reduction in vegetation after the 2019 avalanche cycle. The white color represents zero or near zero values suggesting no or minimal change between time periods. The changes are cropped to known and mapped avalanche paths by the Colorado Avalanche Information Center. Background satellite imagery is provided by Google Earth (2024).

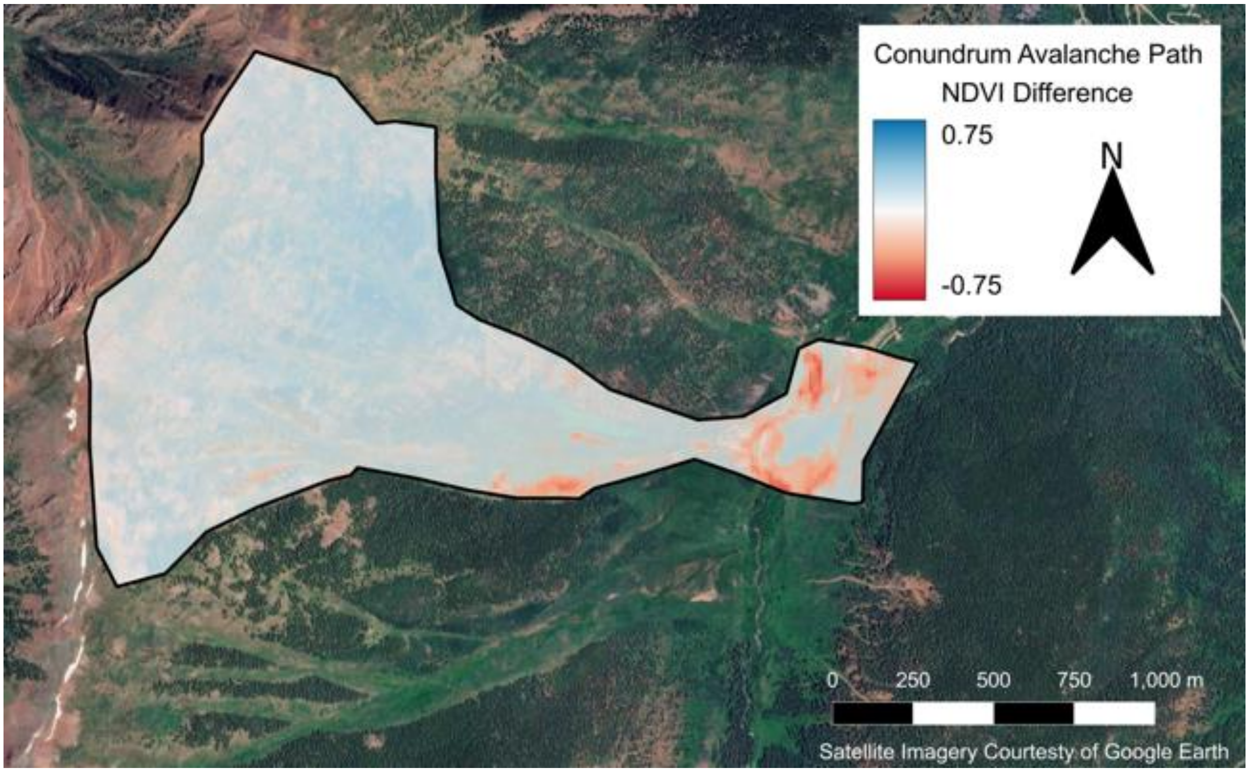

Figure 4: Change in NDVI pre-2019 and post-2019 in the Conundrum avalanche path near Aspen, Colorado. A size D5 avalanche occurred in this path during the March 2019 avalanche cycle. The pink represents changes in NDVI of 3 standard deviations or greater than the mean change within this path. Background satellite imagery is provided by Google Earth (2024).

4. DISCUSSION

Training a vegetation model on one or several avalanche paths could be useful in predicting other paths where return period data are nonexistent. However, our results suggest that doing so would be potentially inaccurate because of the variable vegetation classes and patterns across any given path. The increasingly greater proportion of forests in larger return interval categories across paths suggests that using evidence of more forested terrain to categorize less frequent categorical return intervals is feasible. Therefore, to extrapolate specific return period intervals based on all vegetation classes across a large area using a lidar- and spectrally derived vegetation model would require a larger training data set from a wide variety of heterogenous avalanche paths and a very large tree ring to reconstruct a return period interval data set or a long observational record.

As expected, the lowest frequency return period zones in both avalanche paths are characterized by the greatest vegetation height but are still prone to impact from larger avalanches (Teich et al., 2012). Therefore, investigating patterns in canopy height alone was useful in examining return interval categories. However, our results suggest that vegetation height does not necessarily increase linearly with return intervals. This suggests that lidar-derived canopy height can be used to identify return period categories commonly used in planning and to examine stand age as a proxy for categorical return intervals in areas with distinct vegetation height differences. However, caution should be used when evaluating this metric for detailed infrastructure planning purposes, and the metric should be used in combination with other tools.

Our exploratory analysis suggests that large-magnitude avalanches can redefine avalanche path dimensions and could impact subsequent avalanche size and frequency. Using NDVI from satellite imagery is a simple way to detect ground cover changes in avalanche paths on large spatial and temporal scales and in remote inaccessible areas. However, this single metric alone is insufficient for avalanche dynamic simulations where high resolution parameters, including surface roughness, are important for modeling avalanche runout (Brožová et al., 2020). With further refinement, we intend to examine changes in ground cover over larger spatial extents and over a longer temporal scale. This would provide insight into the frequency and full spatial extent of large magnitude avalanche cycles.

We recognize that the vegetation composition of the avalanche paths is only representative of the time when data were collected. Timing of data acquisition, often a factor of data availability, can impact classification accuracy in the event of disturbances such as avalanches around the time of data collection. In this study, lidar data were collected in July to August 2016. In the absence of NAIP imagery collected in 2016, we chose to work with 2017 NAIP imagery due to its unusually late collection date (September/October) and therefore unique ability to aid in differentiating between species groups that at other times of the year would have similar spectral signatures. Additionally, we show that vegetation composition exerts a substantial effect on being able to classify return intervals across multiple avalanche paths even in our study area with similar aspect and elevation. Therefore, extrapolating return intervals based on vegetation or ground cover characteristics may only be appropriate in other regions if vegetation patterns are similar across avalanche paths. Therefore, examining ground cover changes over specific time intervals as we did in Colorado requires imagery from similar times within each given year for accurate comparisons. Further work could examine a time series of change using imagery further back in time. Limitations to this include using coarser imagery, but a general characterization of change would still be useful to examine the spatial extent of any given avalanche cycle and how that compared to forecasted or observed extent.

5. CONCLUSION

Here, we demonstrated the utility of using remote sensing products to characterize vegetation and quantify ground cover change over time in avalanche paths in different regions and at different complimentary scales. In northwest Montana, we quantified the proportion of vegetation within avalanche path return periods using lidar and satellite imagery data and an automated vegetation classification technique at the slope scale. We also examined lidar-derived canopy height within those categorical return periods. In general, we found a greater canopy height and grass and shrub-type vegetation in less frequent return intervals in the avalanche paths we investigated in this study. When examining changes in ground cover over specific time intervals at the landscape scale, we used satellite imagery based NDVI values differenced from a pre- and post-avalanche cycle. We found substantial ground cover changes in many of the track and runout zones throughout Colorado, and, in one path, changes in 18% of the avalanche path area. These results suggest that remote sensing platforms are a useful tool in assessing avalanche path ground cover change over space and time and provide insight into the distribution and spatial extent of specific avalanche cycles.

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DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This work was supported by the U.S. Geological Survey Climate R&D/Land Change Science Program.

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