SPATIAL EXTENT OF FORESTED AVALANCHE TERRAIN IMPACTED BY WILDFIRE ACROSS THE SAWTOOTH NATIONAL FOREST

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ABSTRACT: Forest structure is a major driver of mountain snowpacks and avalanche occurrence. Healthy forests can reduce the incidence of dangerous slab avalanches, slow avalanches when in motion, shorten their runout distances, and act as a safety buffer for backcountry users, infrastructure, and transportation corridors. Since 1984, wildfire area in the seasonal snow zone of the western United States has increased by 70% throughout the seasonal snow zone, creating significant changes to avalanche prone mountains and their connected communities. A major unknown is the impact a reduction of forested area due to forest fires will have on avalanche occurrence. We hypothesize increased potential for avalanching in forested areas impacted by wildfire. Reduced tree cover may make previously heavily forested terrain more susceptible to avalanching. Increases in the size of avalanche start zones, paths, and runouts due to forest fires may increase the destructive size of avalanches and create cascading ecological effects within the adjacent forested terrain. Forest fires may therefore increase the likelihood of avalanche release, resulting in further loss of tree cover and increased avalanche area as well as decreased protection for human infrastructure. In this study, we quantify avalanche area changes before and after the Ross Fork wildfire (2022) in Sawtooth National Forest, Idaho, USA. We utilized satellite imagery, a digital elevation model and historical fire spatial data to quantify and characterize avalanche area changes within the fire perimeter using the Auto-ATES workflow (Sykes et al., 2022). We found decreases in forest coverage that contributed to widespread increases in potential avalanche release areas, avalanche tracks, and potential runout zones throughout the study area as well as the creation of new potential avalanche release areas and a substantial decrease in non-avalanche connected terrain within the fire perimeter. These preliminary findings help inform avalanche and snow safety professionals as well as land managers working in wildfire-prone forested areas about potential post-wildfire changes in avalanche terrain.

KEYWORDS: avalanche and wildfire, avalanche mapping, avalanche-forest

1. INTRODUCTION

Wildfires continue to increase in intensity, extent, frequency, and duration across the western United States (Littell et al. 2009; Westerling 2016; Westerling et al. 2006), having a significant influence on the mountains they burn over. Overlap in geography between forest fire and snow has accelerated by 9% per year between 1984 to 2017 and currently over 60% of wildfires burn in the seasonal snow zone (Gleason & Nolin 2016; Gleason et al. 2019). Wildfire increase is most prominent in the snow dominated mountains of the northern Rocky Mountains and Pacific Northwest, where more than a 3000% and 5000% increase in wildfire area has accrued since 2003, respectively (Westerling, 2016). Forests within the seasonal snow zone can influence snowpack stratigraphy and avalanche release and dynamics (Berger et al. 2013; Teich et al. 2012; Vigletti et al., 2009, Brang et al., 2006). Forest gap density and distribution over steep slopes can influence avalanche occurrence, directly influencing slope stability and protection provided to people, settlements, and infrastructure (Brang et al., 2006; Sakals et al., 2006; Schönenberger & Brang, 2001). Wildfire modifies forest distribution and structure and transforms the snowpack energy balance (Vilà-Vilardell et al., 2023). Previous research highlights the hydrologic impact of forest fire effects on snow, with enhanced snow melt rates associated with disruption to runoff and water availability (Gleason et al. 2019, Gleason et al. 2013; Harpold et al. 2014; McGrath et al. 2023; Smoot & Gleason, 2021; Westerling et al. 2006).

1.1 Background

Wildfires influence forest structure and consequently the mountain snowpack. A 300 % reduction in forest canopy and 500 % reduction in stem density associated with fire activity (Gleason et al., 2013) alters the distribution of forest cover over mountainous terrain (Brang et al., 2006). Healthy forest canopy intercepts 60% of snow (Roth & Nolin, 2017; Storck et al., 2002) and reduces 40% of overall snow accumulation (Harpold et al. 2014; Lundquist and Dickerson-Lange 2013; Varhola et al. 2010), which affects the stratigraphy of seasonal snowpack and associated slope stability (Oven et al., 2020). On the other hand, the presence of dead wood, which continues to shed up to a decade following fire (Bond-Lamberty & Gower, 2008; Gersh et al., 2022), increases the surface roughness and prevents snow gliding (Feistl et al., 2013).

A 60% increase of snow surface exposed to solar radiation through a decrease of forest canopy and a 40% decrease in the surface albedo through the shedding of light absorbing particles (LAPs) and black carbon increase net shortwave radiation to the snowpack surface by 200% (Gleason et al. 2013; Uecker et al., 2020). LAPs concentrated within the snowpack increase radiative heating and melt of the snowpack, alter temperature and vapor pressure gradients, and can influence wet snow stability, cold snow metamorphism, and melt freeze processes (Birkeland, 1998; Landry, 2014) even when buried by 30 cm or more of snow (Guy & Deems 2016; Landry 2014).

Wildfire increase is most prominent in the snow dominated mountains of the northern Rocky Mountains and Pacific Northwest. Wildfires in mountainous terrain impact settlements and infrastructure causing substantial safety and economic consequences (Moritz et al. 2014) (Figure 1).

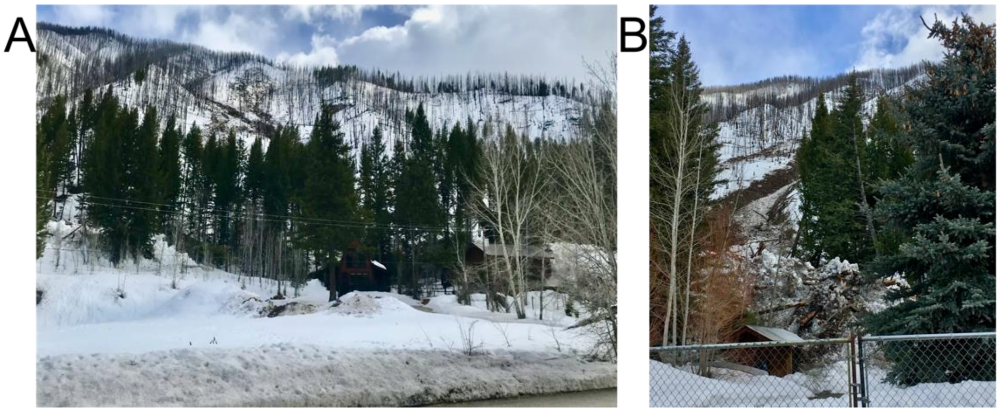

Figure 1: Example of a recent wildfire area in Warm Springs, Idaho. (A) Wet slab avalanche in a recently burned forest above a residential area. (B) Avalanche track and debris impacted several structures in the residential area.

In this study, we aim to quantify the potential increase in avalanche area immediately following a major wildfire in an intermountain snow zone. Through broad-scale observation of forest modifications, these preliminary findings will inform avalanche practitioners and snow safety professionals working in wildfire prone forested areas on potential changes to avalanche terrain post wildfire.

1.2 <u>Study Region</u>

The Ross Fork fire in the Sawtooth National Forest of central Idaho, United States, was discovered on 14.8.2022 and burned approximately 37,928 acres (153.49 km^2) before being declared out on 16.11.2022 (Figure 2). The fire burned 14.25% of the 1078.25 km^2 total watershed area (defined by HUC12 boundaries).

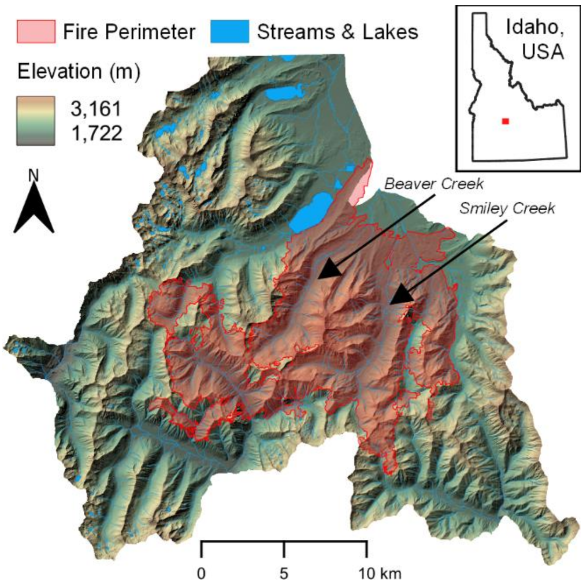

Figure 2: Overview of Ross Fork wildfire area in central Idaho, USA. Elevation data are shown within the affected HUC12 drainages, with the two primary case study drainages labeled.

2. METHODS

We utilized the AutoATES workflow (Sykes et al., 2023, Toft et al., 2023) to model pre- and post-fire avalanche terrain characteristics (*Sec 2.1*) then calculated basic comparative statistics to identify changes within the Ross Fork fire perimeter (*Sec 2.2*) between pre- and post-fire periods. We define pre-fire as any period prior to 14.8.2022 and post-fire as any period after 16.11.2022.

2.1 <u>Auto-ATES</u>

To assess the impacts of the Ross Fork Fire on the distribution of avalanche release areas and runout zones, we utilized three different geospatial modeling techniques which are part of the AutoATES workflow; 1) Change detection of forest canopy cover density pre- and post-fire based on Sentinel 2 satellite remote sensing classification, 2) Estimation of potential avalanche release areas (PRA) using a fuzzy membership approach (Toft et al. 2023; Veitinger et al. 2016), and 3) Avalanche runout simulation using *FlowPy* gravitational mass flow tool (D'Amboise et al., 2022).

Classifying forest land cover using Sentinel 2 imagery has several advantages: access to imagery is free, revisit times are frequent (5 days), and the spatial resolution is moderate for spatial products from all platforms (10 m for blue, green, red, near infrared bands). To perform the canopy cover change detection, we selected pre-fire imagery from 22 July 2022 and post-fire imagery from 25 September 2022 as these are the highest quality images pre- and post-fire. We used a random forest algorithm on the 10 m Sentinel 2 bands to create a landcover classification to identify forested and non-forested pixels (Sykes et al., 2022). We estimated canopy cover by calculating the number of forested pixels within a 5-cell neighborhood, centered on the pixel. We used the resulting pre- and post-fire canopy cover layers as inputs for both the PRA model and runout simulation tool *FlowPy*.

Identifying potential avalanche release area is the most important step in automated avalanche terrain modeling. Using a fuzzy membership based model allows for fine tuning of model parameters to improve accuracy based on local feedback and to accommodate different types of input data. We chose to use the 10 m resolution National Elevation Dataset from the USGS as our input digital elevation model (DEM) along with the Sentinel 2 based canopy cover data. The PRA model identifies avalanche release areas based on slope angle, forest density, and wind shelter. The resulting continuous raster layer ranges from 0 to 1, indicating the likelihood of the pixel being an avalanche release area. In order to use the PRA layer as input for the runout simulation tool we need to apply a threshold to create a binary PRA or non-PRA dataset. We used the value 0.15 to convert the continuous output to a binary raster (Toft et al., 2023).

FlowPy gravitational mass flow simulation tool uses a DEM and optional forest layer to estimate the runout path and intensity of snow avalanches. The simulation relies heavily on the user defined maximum alpha angle parameter which we set at 20°. Tuning this parameter based on local geography and historical avalanche observations is key for accurate results. We used field observation and images and calculated best estimates in GIS based on these images. When a forest density input layer is defined it is also important to define the max forest friction and max forest detrainment parameters, which we set to 270 for both (Toft et al., 2023). This controls how much forest cover can modify mass and add friction to the flowing avalanche which results in decreasing the maximum alpha angle in forested areas. The outputs that we utilized from *FlowPy* and subsequently used as inputs to Auto-ATES are the maximum alpha angle along the flow path and the maximum energy line height, or z-delta (zΔ), for each cell.

2.2 Comparison Calculations

We quantified change in each of the Auto-ATES output variables by calculating categorized areas pre- and post-fire within the Ross Fork fire perimeter. First, we calculated forest cover loss by classifying post-fire forest cover difference values below 0 as "forest loss." Next, we examined pre- and post-fire possible release areas (PRA) by using a binary classification of "avalanche release areas" or "non-avalanche release areas" spatially across the study area. We then used a continuous scale between 0 and 1 (0 = unlikely possible release area, 1 = mostly likely possible release area) to identify changes pre- and post-fire along this scale. Similarly, we used a continuous scale to quantify changes in pre- and post-fire runout zone area (0-100; 0 = non-runout zone,100 = most likely runout zone). Finally, we used the zΔ metric (Sykes, 2022) to quantify changes in the relative avalanche size potential between pre- and post-fire periods. This scale (values from 0 to 270) can be used as a relative measure of "overhead hazard." We classified values on a relative hazard scale in the exploration of this variable defined as:

- "no hazard" = zΔ values of < 1
- "low hazard" = zΔ values of 1 – 50
- "mod hazard" = zΔ values of 50 – 100
- "high hazard" = zΔ values of > 100

To assess whether changes in PRAs pre- and post-fire consist of newly created PRAs or an increase in existing pre-fire PRAs, we used four terms to classify PRA:

- *pre-existing* is defined as PRAs pre-fire,
- *post-fire growth* is defined as the combined PRAs of new terrain connected to "pre-existing" PRAs,
- *post-fire new* is defined as PRAs of new terrain completely disconnected from "pre-existing" PRAs, and
- *post-fire growth partitioned* is defined as only the area of additional growth in PRA terrain connected to pre-existing PRAs.

We then quantified area changes in each of these four categories between pre- and post-fire periods.

3. RESULTS

The Ross Fork Fire caused a 94.75 km^2 loss of forest cover (Figure 3) and a 3.6 km^2 increase in PRAs within the fire perimeter.

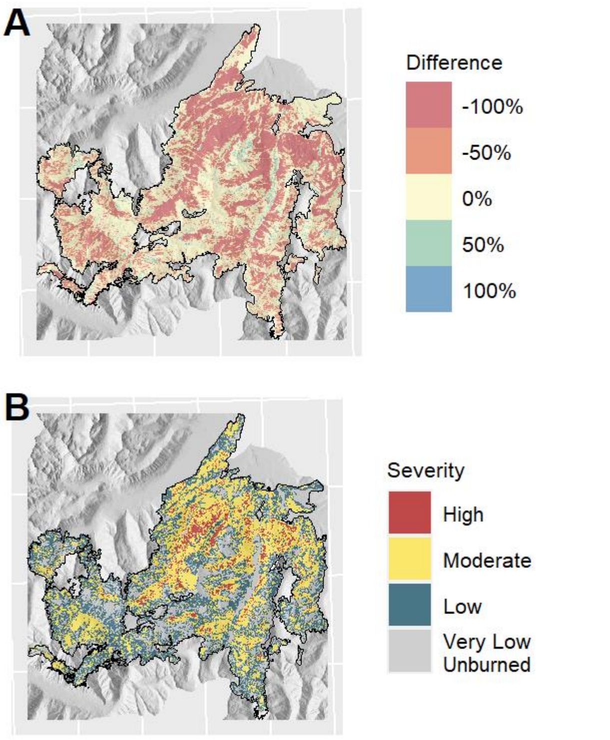

Figure 3: Maps of (A) post-fire forest cover change and (B) burn severity within the Ross Fork wildfire perimeter. The black polygon represents the perimeter of the Ross Fork Fire.

We filtered PRA values < 0.15 to show where the change occurred. PRA values (a measure of release area likelihood) throughout the fire perimeter increased post-fire by a mean of 0.01. These increases predominantly occurred between 0.4 and 0.7 (Figure 4A). We filtered out PRA values below the 0.15 threshold to focus solely on possible (rather than unlikely) avalanche release areas. By doing so, we found an increase in mean PRA values of 0.02 across the study area (Figure 4B).

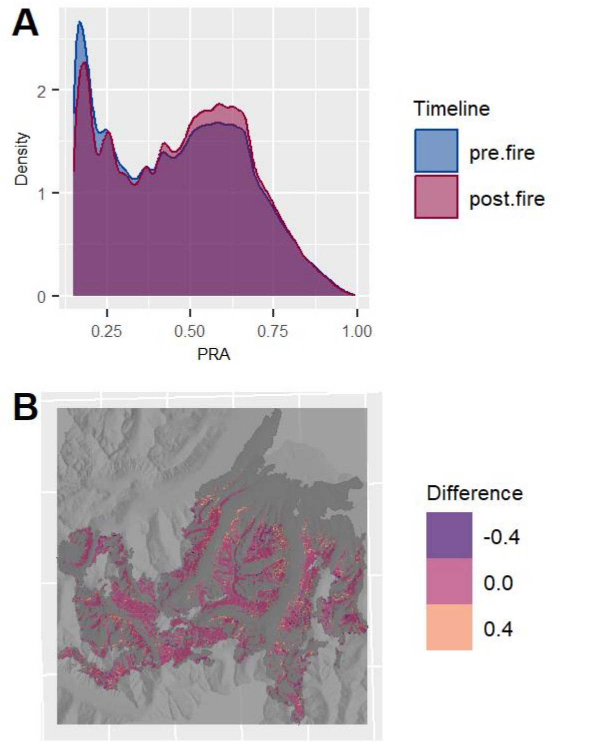

Figure 4: PRA density and spatial distributions. (A) Relative density of PRA values pre- and post-fire with values < 0.15 filtered out. (B) Spatial distribution of the change in PRA values post-fire.

Potential runout area increased 26.63 km^2 between pre- and post-fire periods; a 17% area increase within the fire perimeter that was previously classified as non-runout area (Figure 5A). The majority of the increase in potential runout area is between runout values of 20 and 39 (13 and 4%, respectively) (Figure 5B).

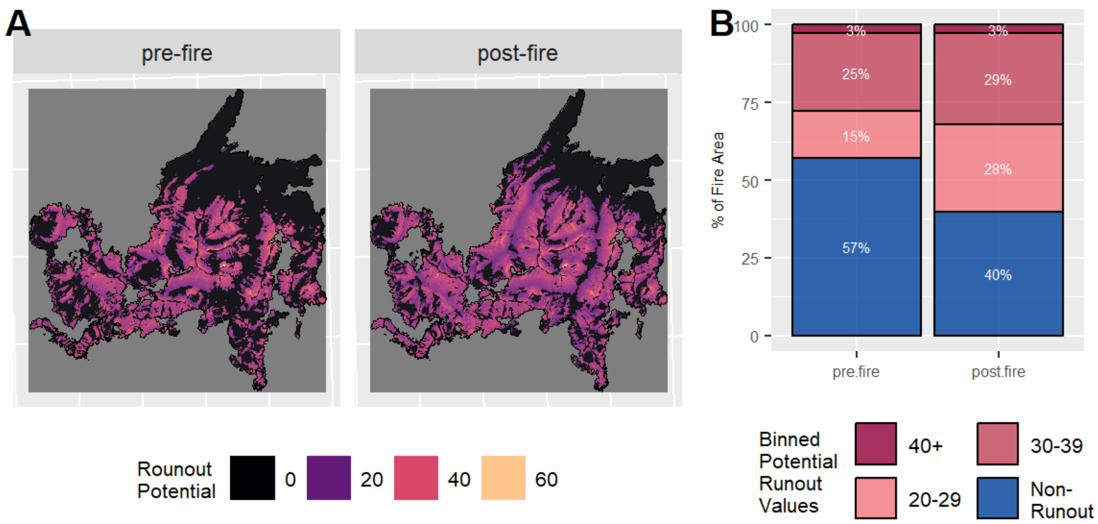

Figure 5: (A) Runout potential maps pre- and post-fire and (B) binned distributions of potential runout values within the Ross Fork wildfire perimeter.

We calculate a 26.7 km^2 decrease in no-hazard area, where $z\Delta < 1$ (from 89.2 km^2 pre-fire to 62.5 km^2 post-fire), and a mean $z\Delta$ value increase of 8.3 within the fire perimeter. Areas of $z\Delta$ increase across all overhead hazard categories except "No Hazard" where a 17% decrease exists (Figure 6).

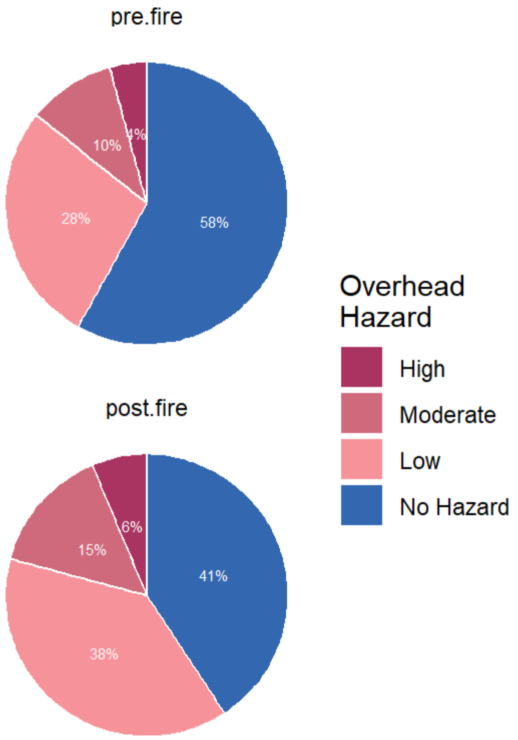

Figure 6: Pre- and post-fire distributions of classified overhead hazard expressed as a percent of total Ross Fork wildfire area.

Further analysis shows a variable pattern of growth in pre-existing PRAs (*pre-existing* vs. *post-fire growth*). Post-fire growth tended to occur in larger existing PRAs while new PRAs created by the fire (*post-fire new*) tended to be smaller in size (Figure 7A). Additionally, while the number of PRAs increased post-fire, the growth of existing PRAs was a more frequent occurrence (Figure 7B).

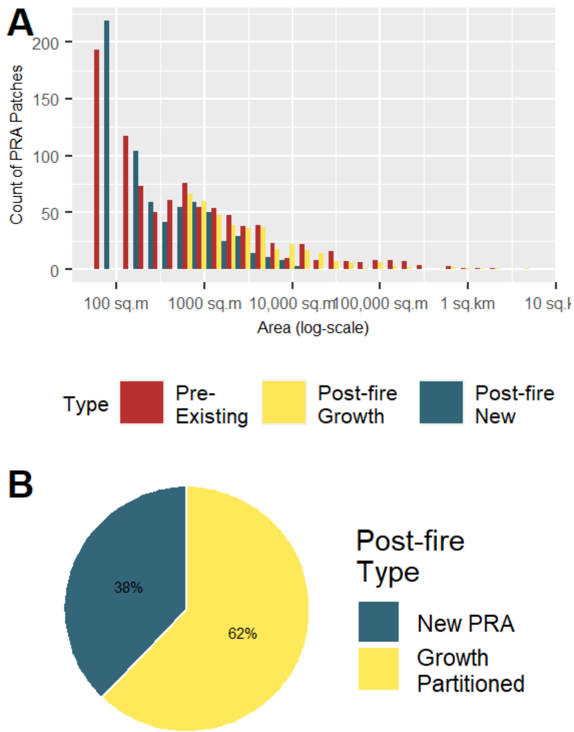

Figure 7: PRA area distributions as shown in (A) cumulative counts of *pre-existing*, *post-fire growth*, and *post-fire new* PRAs grouped by total size patch (B) and the relative growth of post-fire PRA areas.

4. DISCUSSION

A substantial change in forest cover in this study area caused notable increases in existing avalanche terrain in both the release areas and runout zones, but also caused areas previously classified as non-avalanche terrain to become avalanche terrain.

The absolute increase in PRA within the fire perimeter is equivalent to approximately 673 American football fields (109 m (360 feet) in length by 48 m (160 feet) wide). While this is not a large proportion of the total fire area, it is substantial in the context of an increase in areas where avalanches have the potential to release. Distribution of PRA values shifts from smaller values pre-fire to the 0.4 to 0.7 range post-fire. This suggests an overall increase in PRAs from less likely to more likely due to fire effects. Similarly, a 17% increase in avalanche runout area in terrain that was previously classified as non-runout area can have severe consequences. While most of the overhead hazard change shifted from "No Hazard" to "Low Hazard," some terrain shifted to "High Hazard," indicating changes with major potential consequences in avalanche release and runout probability. This implies that we expect to see larger avalanches affecting more terrain within the fire perimeter post-fire. Specifically, the greatest change in $z\Delta$ values occurred in the Beaver and Smiley Creek drainages, two areas popular with motorized and non-motorized users. These changes in avalanche terrain can have serious implications for backcountry travelers, avalanche forecasters, and infrastructure planners. For example, a backcountry recreationalist may be accustomed to traveling in a specific area under pre-fire conditions where the probability of release was unlikely. Post-fire conditions, however, may be dramatically different with increased probability of avalanche release. Similarly, avalanche forecasters and infrastructure planners now need to consider changes in release area probability and runout zone extension when assigning a hazard rating or planning for new construction or maintenance in recently burned areas.

The overall increase in potential avalanche affected area (both PRA and runout zones) within the fire perimeter is important, but understanding the character of those changes can help with planning and messaging the avalanche danger. The changes in pre- and post-fire PRAs illustrates that newly formed PRAs (*post-fire new*) are primarily smaller in size than new growth areas of pre-existing PRAs (*post-fire growth partitioned*) and that there was 1.6 times as much total PRA growth terrain (*post-fire growth partitioned*) as there was new PRA (*post-fire new*) formed post-fire. This suggests that if avalanche starting zones already existed in our study area, the fire caused an increase in starting zone size almost twice as frequently as it created new starting zones. These results also demonstrate that forecasters and managers of areas with substantial forested avalanche terrain should consider mapping and assessing wildfire impacted areas. This would help with messaging and education of backcountry audiences, planning for changes in avalanche mitigation procedures at ski areas or transportation corridors, and infrastructure planning.

The geospatial modeling tools used in this analysis capture areas where the terrain has the potential for avalanche release and runout. However, the real-world frequency of avalanche release is also strongly influenced by snowpack characteristics such as weak layer stratigraphy and local loading patterns. Therefore, the output of these models quantifies the maximum potential terrain that could contain avalanche hazard, independent of snowpack conditions. Another limitation of this method is that the sun angle and reflectance intensity is different for September versus July. In future work, we intend to use imagery from the same time of year to create a more consistent and accurate classification.

This case study generates numerous questions and further work will include completing this analysis on other wildfire areas in different climate types and geographic regions for comparison. We also plan to examine wildfire impacts to snowpack structure and its effects on slope stability.

5. CONCLUSION

In this study we show how wildfire modifies existing and creates new avalanche terrain. Using a robust high-resolution PRA modeling workflow in forested terrain (Sykes et al., 2022), we quantified changes in forest cover, potential avalanche release areas, runout area, and overhead hazard within the perimeter of the 2022 Ross Fork Fire, Sawtooth National Forest, Idaho, United States. Overall, we found a 2.3% increase in potential avalanche release areas and a 17% increase in avalanche runout area in terrain that was previously classified as non-runout area. We also found a larger increase in existing release areas than formation of new release area, but the overhead hazard also increased. Our results suggest that avalanche forecasters, land managers, and infrastructure planners should consider changes in release area probability and runout zone extension when assigning a hazard rating or planning for new construction or maintenance in recently burned areas.

DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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REFERENCES

Berger, Frédéric, Luuk Dorren, Karl Kleemayr, Bernhard Maier, Špela Planinšek, Christophe Bigot, Franck Bourrier, Oliver Jancke, David Toe, and Gillian Cerbu.: Eco-Engineering and Protection Forests Against Rockfalls and Snow Avalanches., Intech, 191-210, https://doi.org/10.5772/56275, 2013.

Birkeland, Karl W., Ron F. Johnson, and D. Scott Schmidt. 1998.: Near-Surface Faceted Crystals Formed by Diurnal Recrystallization: A Case Study of Weak Layer Formation in the Mountain Snowpack and Its Contribution to Snow Avalanches. Arctic and Alpine Research 30 (2): 200–204. https://doi.org/10.2307/1552135.

Bond-Lamberty, Ben, and Stith Gower.: Decomposition and Fragmentation of Coarse Woody Debris: Re-Visiting a Boreal Black Spruce Chronosequence. Ecosystems 11 (September): 831–40. https://doi.org/10.1007/s10021-008-9163-y, 2008.

Brang, Peter, Walter Schönenberger, Monika Frehner, Raphael Schwitter, Jean-Jacques Thormann, and Berchthold Wasser.: Management of Protection Forests in the European Alps: An Overview. Forest Snow and Landscape Research 80 (January), 2006.

D'Amboise, Christopher J. L., Michael Neuhauser, Michaela Teich, Andreas Huber, Andreas Kofler, Frank Perzl, Reinhard Fromm, Karl Kleemayr, and Jan-Thomas Fischer.: Flow-Py v1.0: A Customizable, Open-Source Simulation Tool to Estimate Runout and Intensity of Gravitational Mass Flows. Geoscientific Model Development 15 (6): 2423–39. https://doi.org/10.5194/gmd-15-2423-2022, 2022.

Feistl, T., Peter Bebi, Marc Hanewinkel, and Perry Bartelt.: The Role of Slope Angle, Ground Roughness and Stauchwall Strength in the Formation of Glide-Snow Avalanches in Forest Gaps. International Snow Science Workshop at Grenoble, 2013.

Gersh, Max, Kelly E. Gleason, and Anton Surunis.: Forest Fire Effects on Landscape Snow Albedo Recovery and Decay. Remote Sensing 14 (16): 4079. https://doi.org/10.3390/rs14164079., 2022.

Gleason, Kelly E., Joseph R. McConnell, Monica M. Arienzo, Nathan Chellman, and Wendy M. Calvin.: Four-Fold Increase in Solar Forcing on Snow in Western U.S. Burned Forests since 1999. Nature Communications 10 (1): 2026. https://doi.org/10.1038/s41467-019-09935-y., 2019.

Gleason, Kelly E., and Anne W. Nolin: Charred Forests Accelerate Snow Albedo Decay: Parameterizing the Post-fire Radiative Forcing on Snow for Three Years Following Fire. Hydrological Processes 30 (21): 3855–70. https://doi.org/10.1002/hyp.10897, 2016.

Gleason, Kelly E., Anne W. Nolin, and Travis R. Roth: Charred Forests Increase Snowmelt: Effects of Burned Woody Debris and Incoming Solar Radiation on Snow Ablation. Geophysical Research Letters 40 (17): 4654–61. https://doi.org/10.1002/grl.50896, 2013.

Guy, Zach M, and Jeffrey S Deems: Unusual Dry Slab Avalanche Releases Involving Dust-on-Snow Layers in Colorado. Proceedings, International Snow Science Workshop, Breckenridge, Colorado, 74-81, 2016.

Harpold, Adrian A., Joel A. Biederman, Katherine Condon, Manuel Merino, Yoganand Korgaonkar, Tongchao Nan, Lindsey L. Sloat, Morgan Ross, and Paul D. Brooks: Changes in Snow Accumulation and Ablation Following the Las Conchas Forest Fire, New Mexico, USA. Ecohydrology 7 (2): 440–52. https://doi.org/10.1002/eco.1363, 2016.

Landry, Christopher C: “Desert Dust and Snow Stability.” Proceedings, International Snow Science Workshop, Banff, 557 - 563, 2014.

Littell, J., Donald McKenzie, David Peterson, and A. Westerling: Climate and Wildfire Area Burned in Western U.S. Ecoprovinces, 1916–2003. Ecological Applications : A Publication of the Ecological Society of America 19 (July): 1003–21. https://doi.org/10.1890/07-1183.1, 2009.

Lundquist, Jessica D., Susan E. Dickerson-Lange, James A. Lutz, and Nicoleta C. Cristea: Lower Forest Density Enhances Snow Retention in Regions with Warmer Winters: A Global Framework Developed from Plot-Scale Observations and Modeling. Water Resources Research 49 (10): 6356–70. https://doi.org/10.1002/wrcr.20504, 2013.

McGrath, Daniel, Lucas Zeller, Randall Bonnell, Wyatt Reis, Stephanie Kampf, Keith Williams, Marianne Okal: Declines in Peak Snow Water Equivalent and Elevated Snowmelt Rates Following the 2020 Cameron Peak Wildfire in Northern Colorado. Geophysical Research Letters 50 (6): e2022GL101294. https://doi.org/10.1029/2022GL101294, 2023.

Moritz, Max, Enric Batllori, Ross Bradstock, Malcolm Gill, John Handmer, Paul Hessburg, Justin Leonard: Learning to Coexist with Wildfire. Nature 515 (November): 58–66. https://doi.org/10.1038/nature13946, 2014.

Oven, Domen, Barbara Žabota, and Milan Kobal: The Influence of Abiotic and Biotic Disturbances on the Protective Effect of Alpine Forests against Avalanches and Rockfalls. Acta Silvae et Ligni 121 (January): 1–18. https://doi.org/10.20315/ASetL.121.1, 2020.

Roth, T. R., and A. W. Nolin: Characterizing Maritime Snow Canopy Interception in Forested Mountains. Water Resources Research 55 (6): 5464-81. https://onlinelibrary.wiley.com/doi/abs/10.1029/2018WR024089, 2019.

Sakals, Matthew, John Innes, David Wilford, Roy Sidle, and Gordon Grant: The Role of Forests in Reducing Hydrogeomorphic Hazards. Forest Snow and Landscape Research 80 (January): 11–22, 2006.

Schönenberger, Walter, and Peter Brang: Structure of Mountain Forests: Assessment, Impacts, Management, Modelling. Forest Ecology and Management 145 (May): 1–2. https://doi.org/10.1016/S0378-1127(00)00569-7, 2001.

Smoot, Emily E., and Kelly E. Gleason: Forest Fires Reduce Snow-Water Storage and Advance the Timing of Snowmelt across the Western U.S. Water 13 (24): 3533. https://doi.org/10.3390/w13243533, 2021.

Storck, Pascal, Dennis P. Lettenmaier, and Susan M. Bolton: Measurement of Snow Interception and Canopy Effects on Snow Accumulation and Melt in a Mountainous Maritime Climate, Oregon, United States. Water Resources Research 38 (11): 5-1-5–16. https://doi.org/10.1029/2002WR001281, 2002.

Sykes, John, Pascal Haegeli, and Yves Bühler: Automated Snow Avalanche Release Area Delineation in Data-Sparse, Remote, and Forested Regions. Natural Hazards and Earth System Sciences 22 (10): 3247–70. https://doi.org/10.5194/nhess-22-3247-2022, 2022.

Sykes, J., Toft, H., Haegeli, P., Statham, G. (2023). Automated Avalanche Terrain Exposure Scale (ATES) mapping - Local validation and optimization in Western Canada. Natural Hazards and Earth System Sciences - In Review

Teich, Michaela, Perry Bartelt, Adrienne Grêt-Regamey, and Peter Bebi: Snow Avalanches in Forested Terrain: Influence of Forest Parameters, Topography, and Avalanche Characteristics on Runout Distance. Arctic, Antarctic, and Alpine Research 44 (4): 509–19. https://doi.org/10.1657/1938-4246-44.4.509, 2012.

Toft, H., Sykes, J., Schauer, A., Hendrikx, J., Hetland, A., (2023) AutoATES v2.0: Automated avalanche terrain exposure scale mapping. Natural Hazards and Earth System Sciences - In Review

Uecker, Ted M., Susan D. Kaspari, Keith N. Musselman, and S. McKenzie Skiles: The Post-Wildfire Impact of Burn Severity and Age on Black Carbon Snow Deposition and Implications for Snow Water Resources, Cascade Range, Washington. Journal of Hydrometeorology 21 (8): 1777–92. https://doi.org/10.1175/JHM-D-20-0010.1, 2020.

Varhola, Andrés, Nicholas C. Coops, Markus Weiler, and R. Dan Moore: Forest Canopy Effects on Snow Accumulation and Ablation: An Integrative Review of Empirical Results. Journal of Hydrology 392 (3–4): 219–33. https://doi.org/10.1016/j.jhydrol.2010.08.009, 2010.

Veitinger, Jochen, Ross Purves, and Betty Sovilla. Potential Slab Avalanche Release Area Identification from Estimated Winter Terrain: A Multi-Scale, Fuzzy Logic Approach. Natural Hazards and Earth System Sciences 16 (October): 2211–25. https://doi.org/10.5194/nhess-16-2211, 2016.

Viglietti, D, S Letey, R Motta, M Maggioni, and M Freppaz: Snow and Avalanche: The Influence of Forest on Snowpack Stability. International Snow Science Workshop Davos, Proceedings, 323 - 327, 2009.

Vilà-Vilardell, Lena, Miquel De Cáceres, Míriam Piqué, and Pere Casals: Prescribed Fire after Thinning Increased Resistance of Sub-Mediterranean Pine Forests to Drought Events and Wildfires. Forest Ecology and Management 527 (January): 120602. https://doi.org/10.1016/j.foreco.2022.120602, 2023.

Warren, S. and Wiscombe W., A Model for the SPectral Albedo of Snow. II: Snow Containing Atmospheric Aerosols. Journal of the Atmospheric Sciences 37: 2734-45., 1980.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam: Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science 313 (5789): 940–43. https://doi.org/10.1126/science.1128834, 2006.

Westerling, A. L: Increasing Western US Forest Wildfire Activity: Sensitivity to Changes in the Timing of Spring. Philosophical Transactions of the Royal Society B: Biological Sciences 371 (1696): 20150178. https://doi.org/10.1098/rstb.2015.0178, 2016.