University of Nevada, Reno

Changes in Snow Hydrology After a Severe Wildfire

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by

Arielle L. Koshkin

Dr. Anne Nolin/Thesis Advisor

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We recommend that the thesis
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Arielle L. Koshkin

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MASTER OF SCIENCE

Anne Nolin, Ph.D.
Advisor

Scott Tyler, Ph.D.
Committee Member

Kat Bormann, Ph.D.
Committee Member

Benjamin Hatchett, Ph.D.
Graduate School Representative

David W. Zeh, Ph.D., Dean
Graduate School

May 2022

ABSTRACT

Most freshwater in the western United States used for agriculture, municipalities, and industrial consumption originates from headwaters in snow-dominated watersheds. During the winter months, snowpacks serve as natural water towers providing flood control, and during the spring snowmelt is a major contributor to reservoirs for agricultural and municipal water supplies, and hydroelectric power generation. However, wildfires are increasing in intensity, size, frequency, and duration in snow-dominated watersheds and are burning higher in elevation, well into the seasonal snow zone. After a wildfire, the burned trees shed black carbon and charred woody debris which decreases the snow albedo and increases snowmelt rates resulting in an earlier snow disappearance date. The loss of canopy cover causes an increase in solar radiation reaching the snow surface and together these effects lead to an increase in net shortwave radiation. The increase in the geographical overlap between fire and snow poses unique and emerging challenges for managing snow-dominated watersheds.

This study investigates the post-wildfire impacts of the Creek Fire that burned nearly 44% of the Upper San Joaquin Watershed (USJW) in the south-central Sierra Nevada in 2020. The goal of this research is to quantify and understand post-fire impacts on snowpack ablation as a function of burn severity in a snow-dominated watershed. Using three spatial scales, ground-based, airborne, and satellite data, we measured a diverse set of snowpack properties along a burn severity gradient (unburned forest, moderate burn severity, and high burn severity). Snow depth was derived from lidar from multiple overflights of the Airborne Snow Observatory (ASO). Concurrent with the ASO overflights, we collected ground-based measurements of snow depth, SWE, snow albedo, and black carbon concentrations. Burn severity was computed from Landsat 8 data using the Differenced Normalized Burn Ratio.

Results highlight that the nuance of burn severity matters when understanding the impacts of fire on snow. Higher burn severity is associated with higher black carbon concentrations, lower albedo, increased net shortwave radiation, and subsequently, lower snow depths during ablation and earlier snow disappearance compared to moderate burn severity and unburned areas. These impacts are seen most notably at mid-elevations (1500 -2500 m). To understand the impacts of wildfires on snow hydrology and water resources, regional and broad-scale variability of these impacts on snow-water storage and snowmelt timing needs to be taken into account to improve water resource management and forecasting models. As fires become more prevalent, water resources from snowpacks will become more threatened, especially in high severity burned areas. It is important that runoff forecast models reflect the post-fire changes in alpine watersheds.

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TABLE OF CONTENTS

Abstract. i

Acknowledgements iii

Table of Contents iv

List of Tables vi

List of Figures vii

1. Introduction 1

2. Mini-Review: Wildfire Impacts on Western U.S. Snowpack 4

2.1 Abstract. 4

2.2 Introduction. 6

2.3 Snow Albedo and Snowpack Energy Balance 9

2.4 Forest-Snow-Fire Interactions. 12

2.5 Burn Severity. 13

2.6 Timing of snowmelt. 15

2.7 Land Surface and Snowpack Models. 17

2.8 Conclusion. 18

2.9 References 19

3. Journal Article: Impacts of Burn Severities on Watershed-Scale Hydrology. 31

3.1 Abstract. 31

3.2 Introduction. 32

3.3 Study Area. 36

3.4 Methods 38

3.5 Results. 47

3.6 Discussion. 55

3.7 Conclusion. 58

3.8 References 62

4. Conclusion and Recommendations for Future Research **74**

Appendices and Supplemental Materials **77**

A. Supplemental Figures **77**

LIST OF TABLES

CHAPTER 3:

3. 1. Relevant remote sensing products used in this study……………………………….42

3.2. A table of average snow disappearance date (SDD) for the water year 2021 for each burn severity. Positive numbers indicate earlier melt while negative numbers indicate later snowmelt. ……...……………………………. .………………………………………52

LIST OF FIGURES

CHAPTER 2:

2.1. Schematic drawings of (a) unburned forest, (b) moderate severity burned forest, and (c) high severity burned forest paired with photos from the Creek Fire in winter of 2021……………………………………… ………………………………..………10

2.2. Synthesis of four snow metrics after a wildfire delineated by burn severity including peak snow water equivalent (peak SWE), peak SWE date, Snow Disappearance date (SDD) and snow melt rates. Figure adapted from (Smoot and Gleason, 2021)………………..…17

CHAPTER 3:

3. 1. Maps of the Upper San Joaquin Watershed (USJW) located in the south-central Sierra Nevada, California. (a) Digital elevation and hydrography of the USJW (data source: USGS); (b) average snow cover frequency derived from MODIS from 2000-2020; (c) burn severity map (data source: BAER, USDA Forest Service); (d) previously burned area from 2000-2019 in the USJW (data source: MTBS). ………… ……………….…………...37

3.2. ASO lidar-derived snow depth at 3-meter resolution (a) 26 February 2021, (b) 1 April 2021, (c) on 3 May 2021. ASO modeled SWE at 50-meter resolution (e) 26 February 2021, (f) 1 April 2021, (g) 3 May 2021. Density plot comparing elevation and SWE on (h) 26 February 2021, (f) 1 April 2021, (g) 3 May 2021. ……………………………………39

3.3. Photos from three field sites in the Creek Fire near Huntington Lake, Calif. (a) High burn severity, (b) moderate burn severity, and (c) unburned on 27 February 2021. (d) Snow depth measurements in an unburned forest using a MagnaProbe and (e) Albedo measurements in a high burn severity forest using the Spectral Evolution RS-3500 Portable Spectroradiometer™) ..……………………...……… ……………………..................43

3. 4. (a) Snow depths derived from three overflights, 26 February 2021, 01 April 2021, and 03 May 2021 categorized by burn severity and separated by elevation bands. (b) Density of burn severity pixels by elevation. (c) Density of snow depths for each overflight by elevation. Red dotted lines represent the largest overlap between burned pixels and snow depth at 1500-2500 m. Note: These measurements only capture the ablation period………………...……………………...…… ……………….................................48

3. 5. (a) Black carbon concentrations for high burn severity, moderate burn severity, and unburned snow samples collected on 27 February 2021 (green) and 1 April 2021 (blue) from the Creek Fire. Photos depict the snow surface for each burn severity taken on 27 February 2021. Mean spectral albedo measurements of high burn severity, moderate burn severity, and unburned areas were measured during spectrometer surveys on (b) 27 February 2021 and (c) 1 April 2021. ..……….……………...………………..................50

3.6. A map of snow disappearance date (SDD) for the USJW and Creek Fire derived from MODIS/MOD10A1. ………………...……………………..…………………….……...52

3.7. Range of net shortwave radiation (Q_{ns}) value displaying the sensitivity of the calculations for each burn severity from January to April under different snow conditions (accumulation, mid-winter dry spells, and ablation). Starting values for Leaf Area Index (LAI), and albedo (α) are noted above. Calculations are based on empirical data from the field. Values are reported in Wm^{-2}….……………………..……………………………53

3. 8. Fires across California for MTBS dataset for 2000-2019. (a) Burn severity for all fires from 2000-2019. (b) Fire perimeters delineated by snow zone. The snow zone is defined as the average snow cover frequency from 2000-2021 derived from MODIS/MOD10A1 with greater than 20% snow cove (Crumley et al. 2020)………….55

SUPPLEMENTARY FIGURES:

A.1 Random Forest classification algorithm assessing importance scores for four variables to predict snow depth broken down by elevation for both February and April..…………..75

A.2 Burn severity map generated using dNBR for July 2019 to July 2020 in Google Earth Engine. This map did not match the forest service map, so the study was performed using the published dataset. ……………………………………………………… ...…………76

A.3 (A) Snow depth station and (B) SWE data obtain from the California Department of Water Resources for two elevations (Kaiser Point at 9200 ft and Huntington Lake at 7000 ft) in the USJW. ………………………………………..………… ....……………77

CHAPTER 1

INTRODUCTION

Most freshwater in the western United States originates as snow in mountain watersheds (Barnett et al., 2005; Li et al., 2017; Musselman et al., 2021). Mountain snowpacks are vital for recharging aquifers and sustaining streamflow into the drier summer months (Barnett et al., 2005, 2008; Hunsaker et al., 2012; Tague & Grant, 2009). Serving as reservoirs during the winter months, snowmelt runoff affects the timing and magnitude of spring streamflow and is a major control on reservoir storage for agricultural and municipal water supplies, hydroelectric power generation, and flood control (Kang et al., 2016; Kormos et al., 2016; Molotch et al., 2005; Yan et al., 2021). With climate change, snowpacks are declining and disappearing earlier (Mote et al., 2005, 2018) while water demands are increasing with increased populations and urbanization (Boretti & Rosa, 2019).

Simultaneously, wildfires have increased in frequency, size, intensity, and duration across the American West (Dennison et al., 2014; Hallema et al., 2018; Williams et al., 2022) in large part because of reduced snowpacks, earlier melt rates, and more prolonged dry periods (Abatzoglou et al., 2021; Abatzoglou & Kolden, 2013; Semmens & Ramage, 2012; Westerling et al., 2006; Westerling, 2016). These fires are also burning in more snow-dominated watersheds and higher into the seasonal snow zone (Hallema et al., 2018; Kinoshita & Hogue, 2015; Stevens, 2017, Abatzoglou & Kolden, 2013; Dennison et al., 2014; Moritz et al., 2012). Most large-scale wildfires are not currently accounted for in snowmelt runoff or land-surface models and can considerably alter runoff predictions and forecasting. The increase in the geographical overlap between snow and fire poses a notable and emerging challenge to managing snow as a water resource. With increased wildfire, a decline in winter snowpacks, and an increase in demand for water, the ability to accurately predict snowmelt runoff for water usage is more critical than ever. This accuracy cannot be achieved without considering newly burned forests.

Consequently, burn severity maps demonstrate that fires burn unevenly across a landscape due to fuels, weather, and topography. High burn severity fires remove the entire canopy while low burn severity only affects the ground vegetation. Because of these discrepancies, it is important to understand the nuance of the impacts of burn severity on snowpacks after a wildfire. When modeling fire impacts on snow and snowmelt runoff, an entire burn scar cannot be assumed to have the same effects across the landscape. Little research has been done to fully understand the differences between burn severity impacts on snow. The goal of this research is to examine the differences in post-fire impacts on snowpacks across a burn severity gradient. This work seeks to synthesize the changes in snow hydrology after a wildfire and provide further understanding of the role burn serveries play in post-fire snowpack changes. Here, I provide a roadmap for the rest of the thesis.

Chapter 2 is a review of the impacts of wildfires on snowpacks in the western United States. This review paper will be submitted to the Journal of Frontiers in Water to their call for Advances in Observations and Modeling of Snow, Forest-Snow Processes and Snow Hydrology. To date, no review paper exists of this scope and this paper summarizes current research and provides context for the physical properties that link wildfire effects to declining snowpacks. This review highlights the importance of incorporating wildfires into land-surface and snowpack runoff models as well as spatially-explicit snow-water equivalent (SWE) reanalyses products. In addition, it highlights the need for more observations to understand the impacts of wildfires on a regional scale. Understanding these important impacts of wildfire on snow can help push the conversation forward on how water managers plan to mitigate these impacts on downstream water availability.

In Chapter 3, the Upper San Joaquin Watershed (USJW) was used as a case study to understand burn severities influences on mountain snowpacks. Using three different spatial scales, ground-based, airborne, and satellite data, we measured a diverse set of snowpack properties across the USJW along a burn severity gradient (unburned forest, moderate burn severity, and high burn severity). We used in situ measurements of snow albedo, laboratory analyses of black carbon concentrations in snow samples, lidar-derived snow depths, and satellite-derived burn severity maps to address the following questions: 1) What is the relationship between snow depth and burn severity; 2) How do different burn severities impact spectral snow albedo and black carbon concentrations in the snow? 3) How does burn severity affect snow disappearance dates? 4) Is there a significant difference in snowpack net shortwave radiation across burn severities? 5) What percent of burned areas across California fall into high, moderate, and low burn severity classes. This thesis chapter will be submitted to the Journal of Hydrology and Earth System Science (HESS). We expect these results to spark a conversation on where efforts should lie in assessing damages caused by wildfires on water supply and motivate other researchers to look more closely at the nuance of burn severity rather than treating an entire burn scar as homogeneous. In addition, we hope this research can also motivate the incorporation of wildfire and burn severity into runoff and land surface models, and reanalysis of SWE datasets.

Together Chapter 2-3 represents a step forward in our understanding of fire and snow interactions and provides a nuanced understanding of how different burn severities have varying impacts on snow ablation and retention. Incorporating these findings into runoff forecast models and spatially-explicit SWE reanalyses is imperative for understanding the impacts of wildfire on water resources and accounting for these major landscape disturbances in runoff predictions. In addition, these findings suggest careful consideration of the nuance of burn severity when assessing the impacts of fire on snowpacks. Chapter 4 summarizes the advancements offered by this thesis, notes the limitations of the work, and provides recommendations for future research.

CHAPTER 2

WILDFIRE IMPACTS ON WESTERN UNITED STATES SNOWPACKS

1. Abstract

Across the western United States, most water used for irrigation, municipalities, and industrial consumption originates from mountain snowpack. Snowpacks serve as natural reservoirs during the winter months, playing important roles in water storage for agricultural and municipal water use, hydroelectric power generation, and flood control. In these same watersheds, wildfires are increasing in intensity, size, frequency, and duration. These fires are burning higher in elevation into the seasonal snow zone. In burned areas, snow disappears 4-23 days earlier, and melt rates increase by 57%. The black carbon and charred woody debris shed from burned trees onto the snowpack decreases the snow albedo by 40%. The loss of canopy cover causes a 60% increase in solar radiation reaching the snow surface. Together these effects lead to a 200% increase in net shortwave radiation absorbed by the snowpack. The increase in the geographical overlap between fire and snow poses unique and emerging challenges for managing snow-dominated watersheds. This review seeks to synthesize the implications of severe wildfire for snow hydrology in mountainous watersheds and the subsequent influence on the volume and timing of water resources. To understand the impacts of wildfires on snow hydrology and water resources, we need to consider the regional and broad-scale variability of these effects on snow-water storage and snowmelt timing to better inform streamflow forecast models and improve water resource management across time scales from daily to decadal.

2. Introduction

In the western U.S., snow is the primary source of water and streamflow (Li et al., 2017). Mountain snowpacks accumulate during the winter months and release meltwater in spring and summer when water demands are generally the greatest (Church, 1932; Garen, 1992). For decades, snowpack observations have been used to forecast spring and summer streamflow, which helps farmers, reservoir operators, and communities plan irrigation, flood control, hydropower, and water consumption (Anghileri et al., 2016; Pagano et al., 2004). With climate change, snowpacks are predicted to continue to decline by 40-75% by the end of the century (Mote et al., 2018, Siirila-Woodburn et al. 2021). At the same time, water demands are increasing with increasing population and urbanization (Boretti & Rosa, 2019). Snowpacks are vital to recharging downstream reservoirs that capture and store winter precipitation and release that water during the dry summer months (Mote et al., 2005, 2018). In snow-dominated watersheds, snowmelt runoff can contribute up to 80% of the total annual flow (Stewart et al., 2004). Understanding the timing and quantity of accumulation and melt are integral to effectively managing water resources to meet both consumptive and ecosystem needs.

Concurrent with declining snowpacks, the characteristics of western U.S. wildfires are changing. From 1984 to 2020, there was a 1,150% increase in area burned, and in 2020 alone, nearly 6% of California’s forested area burned (Williams et al., 2022). From 1984 to 2011, the top 10% of fires by size in California increased by a significant trend of more than 2 km^2 per year without a significant increase in the number of fires occurring (Dennison et al., 2014). Especially in years with earlier snowmelt, wildfires are burning higher in the snow zone (Alizadeh et al., 2021) and in more snow-dominated watersheds affecting the headwaters of the western water supply (Hallema et al., 2018; Kinoshita & Hogue, 2015; Stevens, 2017).

Climatic conditions conducive to wildfire including vapor pressure deficit, fuel aridity (Seager et al., 2015), and climatic water deficit (Dobrowski et al., 2013) have coincided with an increase in fire across the West (Abatzoglou & Kolden, 2013; Dennison et al., 2014; Westerling et al., 2006; Williams & Abatzoglou, 2016). Dry fuels resulting from climate warming, and the associated atmospheric drying potential increase the susceptibility of a landscape to wildfire (Alizadeh et al., 2021). This trend is predicted to increase across the western U.S. enhanced by the effects of anthropogenic climate change causing declining snowpacks, longer dry periods, an increasingly dry atmosphere, and earlier snow disappearance (Abatzoglou et al., 2021; Abatzoglou & Kolden, 2013; Dennison et al., 2014; Moritz et al., 2012; Semmens & Ramage, 2012; Westerling et al., 2006; Westerling, 2016; Williams & Abatzoglou, 2016).

The increase in the geographical overlap between fire and snow poses unique challenges for managing snow-dominated watersheds. In the western U.S., between 1984 and 2017, Gleason et al. (2019) found a 9% increase per year in area burned within the seasonal snow zone. Seasonal snow zones are areas that have a persistent snowpack throughout the winter compared to ephemeral snow zones that have intermittent snowpacks (Hammond et al., 2018; Sturm & Liston, 2021). Fires in the seasonal snow zone account for 4.4 times more area than fires outside the seasonal snow zone (Gleason et al., 2013). Since 1984, the greatest increase in burned area has occurred above 2500 m

(Alizadeh et al., 2021), which is well into the seasonal snow zone. The size of the fire is potentially misleading as fire suppression and management occur more frequently in lowlands where more values-at-risk are threatened. Alizaadeh et al. (2021) has shown an increase in mean wildfire elevation of 7.6 m yr^{-1}. Wildfires occurring in the seasonal snow zone pose a significant threat to the capabilities of mountain snowpacks to act as natural water towers and require a comprehensive bedrock through an atmosphere perspective to quantify their current and future impacts in a warming world (Siirila-Woodburn et al., 2021).

These massive landscape changes caused by wildfire are not currently accounted for in either snowmelt runoff models (e.g., iSNOBAL, Alpine3D, and SnowModel) or land surface models (e.g., NOAH, CLM, ISBA) posing a unique challenge to understanding impacts of fires on seasonal snow. Neither model type accurately parameterizes post-fire snow albedo nor effectively characterizes burned landscapes (Lehning et al., 2006; Liston & Elder, 2006; Marks et al., 1999). Therefore, these models may not adequately account for the effects of wildfire on snow including an increase in net shortwave radiation. Spatially-explicit snow reanalyses also do not directly account for landscape alterations due to wildfire (Broxton et al., 2016; Margulis et al., 2016), and therefore time-series analyses based on these data products may not adequately represent changes in snow hydrology and canopy structure in burned watersheds.

This mini-review aims to synthesize peer-reviewed literature discussing the impacts of wildfires on mountain snowpacks and water resource availability. It provides an overview of the post-fire impacts of fire on snow including (1) decreasing snow albedo altering the energy balance of the snowpack; (2) changing forest canopy that alters accumulation and shading patterns; (3) nuances of burn severity in assessing the impacts of fire on snow; and (4) altered timing of snow disappearance and peak snow-water equivalent (SWE). Finally, this review summarizes current knowledge gaps and concludes with recommendations for future measurements and model improvements.

3. Snow Albedo and Snowpack Energy Balance

The high albedo (0.9-0.95) of clean snow (Warren, 1982) influences snowpack energy balance from the snow's surface to climatological global scales (Skiles et al., 2018). Burned forests decrease snow albedo by shedding black carbon and burned woody debris onto the snowpack (Gleason et al., 2013; Gleason & Nolin, 2016). Fires do not burn evenly across a landscape because of variations in fuel loading, fire weather, and topography. As a result, fire impacts vary widely across the mosaic of a post-fire landscape resulting in different burn severities classifications. At the high-severity end of the burn spectrum, wildfires remove the forest canopy, which increases light transmission through the canopy, and decreases longwave radiation emission from once healthy photosynthesizing trees. These processes contribute to an increase in the net shortwave radiation affecting the snowpack energy balance (Burles & Boon, 2011; Gleason et al., 2013; Pomeroy & Dion, 1996; Winkler, 2011). In a moderately burned forest, some canopy remains and not all trees are dead while in a low burn severity, the entire forest canopy could still be in tack altering the effects on the underlying snowpack (Figure 1).

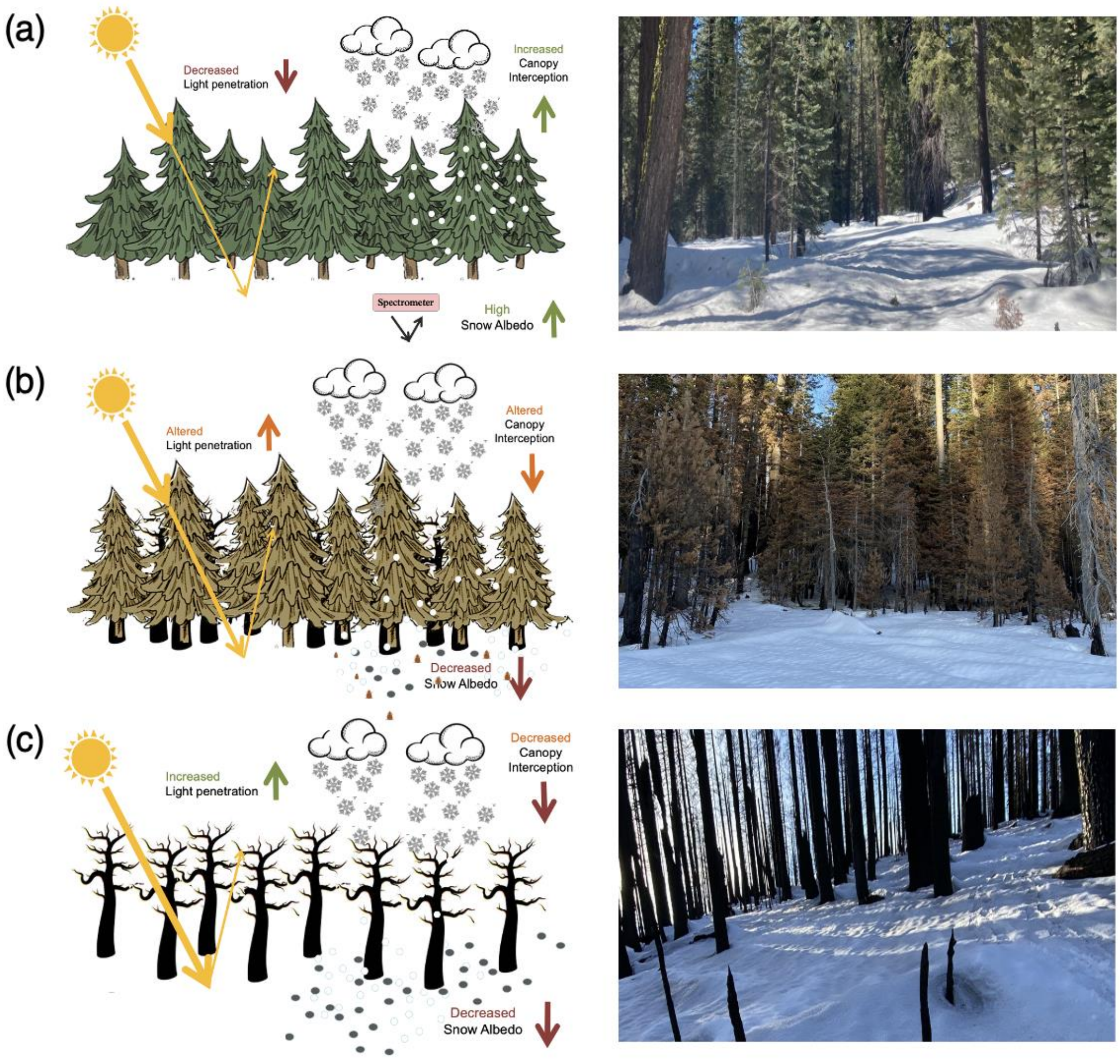

Figure 1. Schematic drawings of (a) unburned forest, (b) moderate severity burned forest, and (c) high severity burned forest paired with photos from the Creek Fire in winter of 2021

Shortwave albedo is tightly coupled with the energy and mass balance of the snowpack (Dozier et al., 1981, 2009; Skiles et al., 2012). As snow albedo decreases, the snowpack absorbs more solar energy accelerating the rates of warming and melt, and shifting the date of snow disappearance earlier (Gleason et al., 2013; Molotch et al., 2005; Wiscombe & Warren, 1980). Since snow is highly reflective in the visible wavelengths (400-700 nm), even small changes in visible albedo due to light-absorbing particles (LAPs) will significantly increase net shortwave radiation and accelerate snowmelt (Dozier et al., 2009; Gleason & Nolin, 2016; Painter et al., 2007; Warren & Wiscombe, 1980). In January, when the snow cover extent is the greatest, Gleason et al. (2019) calculated the radiative forcing from albedo changes to be 32 and 101 Wm^{-2} one year after a severe fire for the SNICAR model and measured albedo values respectively. After 15 years post-fire, the radiative forcing declined to 23 and 44 Wm^{-2} (Gleason et al., 2019). Generally, snow albedo changes in two fundamental ways from alteration in the snow's surface characteristics. First, LAPs decrease snow albedo in the visible wavelengths (Painter et al., 2007; Warren & Wiscombe, 1980), and secondly, snow grain size decreases in the near-infrared wavelength (Nolin et al., 1993; Nolin & Dozier, 2000; Skiles et al., 2012).

Although previous studies have shown that LAPs, such as dust, soot, and charred woody debris in the snow all increase radiative heating and faster rates of snowmelt (Flanner et al., 2009; Gleason et al., 2013; Painter et al., 2007; Skiles et al., 2012, 2018), black carbon and charred woody debris are an order of magnitude more effective at absorbing solar energy in the visible spectrum compared to mineral dust (Gleason et al., 2019; Thomas et al., 2017; Warren & Wiscombe, 1980). Black carbon has been shown to decrease snow albedo by 40% in burned forests, an effect that is most significant during periods of high insolation (Gleason et al., 2013). In high severity burns, forest canopy removal increases incoming solar radiation by 60% (Gleason et al., 2013). Together, the albedo decrease combined with canopy removal was shown to increase snowpack net shortwave radiation by 200% (Gleason et al., 2013). Decreased snow albedo and increased insolation can reduce maximum snow water storage in burned forests (Musselman et al., 2018) because mid-winter melt events mimic the process of "slower melt in a warmer world" (Smoot & Gleason, 2021). As winter snowpacks continue to decline, lower snow albedo and increased net shortwave radiation will amplify ongoing declines in SWE (Burles & Boon, 2011; Skiles et al., 2012; Thackeray et al., 2014; Warren, 1982).

4. Forest-Snow-Fire Interactions

Snowpack mass balance in burned areas is affected by tradeoffs between increased net shortwave and decreased canopy interception (Varhola et al., 2010). A healthy forest canopy intercepts up to 60% of snowfall (Roth & Nolin, 2017; Storck et al., 2002) which can reduce snow accumulation by up to 40% (Harpold et al., 2014; Lundquist et al., 2013; Varhola et al., 2010). Initially, post-fire canopy loss increases the snow accumulation in burned areas (Burles & Boon, 2011; Gleason et al., 2013, 2019; Gleason & Nolin, 2016). On the plot scale, burned areas see a significant increase in snow depth during the accumulation season compared to nearby control plots after a fire (Burles & Boon, 2011; Harpold et al., 2014). On a watershed scale, Micheletty et al., (2014) showed a significant increase in basin-average snow cover fraction (fSCA) and the total number of high snow-covered (fSCA) days after a fire due to the canopy reduction.

In an unburned forest, the canopy both shades the snow and is a source of longwave radiation, influencing the timing of snowmelt in the forest (Lundquist et al., 2013; Roth & Nolin, 2017). Consequently, removing the forest canopy increases solar radiation transmitted to the snow, increasing solar forcing, and altering the sublimation of the underlying snowpack (Faria et al., 2000; Harpold et al., 2014; Varhola et al., 2010). Without tree cover, the combination of solar forcing and sublimation can result in vapor loss of up to 50% (Molotch et al., 2007; Musselman et al., 2008; Reba et al., 2012). Eddy-covariance measurements demonstrate that sublimation rates in open areas are 3 to 10 times higher than in forests areas (Reba et al., 2012). As a result, Harpold et al. (2014), showed that in New Mexico, there was a 50% reduction in snow depth in burned forests during winter ablation. A decrease in net longwave radiation (Burles & Boon, 2011) and an increase in snow sublimation can partially offset and balance the increase in net shortwave radiation (Harpold et al., 2014). Increased solar radiation and radiative heating in combination with decreased albedo from LAPs have amplifying effects on water retention in post-fire snowpacks in forested regions.

5. Burn Severity

Fires do not burn uniformly across a landscape, and variation in burn severity can be assessed using remotely sense satellite data and ground observations. Burn severity is commonly evaluated by the Difference Normalized Burned Ratio (dNBR) using Landsat satellite images from pre-and post-fire dates. The dNBR normalizes the reflectance in the near-infrared (NIR) (0.85-0.88 µm) and shortwave-infrared (SWIR) (2.11-2.29 µm) wavelengths to differentiate between burned and unburned vegetation. Burned woody vegetation and bare earth have high reflectance in the SWIR compared with NIR, while healthy vegetation has high reflectance in the NIR and lower in the SWIR.

$$\text{NBR} = \frac{\text{R}_{\text{NIR}} - \text{R}_{\text{SWIR}}}{\text{R}_{\text{NIR}} + \text{R}_{\text{SWIR}}} \tag{1}$$

(2) $$\mathrm{dNBR} = \Delta\mathrm{NBR} = \mathrm{NBR}_{\mathrm{Pre-fire}} - \mathrm{NBR}_{\mathrm{Post-fire}}$$

where R_{NIR} is near-infrared reflectance, R_{SWIR} is shortwave-infrared reflectance and dNBR is the change in NBR from pre- to post-fire (Cardil et al., 2019; Eidenshink et al., 2007; Key & Benson, 2006; Miller & Thode, 2007). The Monitoring Trends in Burn Severity (MTBS) program maintains a large database of burn severities (Eidenshink et al., 2007). The USDA Forest Service performs on-the-ground assessments for large fires producing the Burned Area Emergency Rehabilitation (BAER) soil burn severity maps.

To fully understand the impacts of wildfires on a watershed scale, it is important to understand how the variability in burn severity alters the snowpack characteristics and snowmelt rates (Figure 1). For every 20% increase in overstory mortality used as a proxy for burn severity, Maxwell et al. (2019) found that in south-central Utah, peak SWE increased by 15%, and snow depth increased by 17% across burn severity gradients. Even with a 114% increase in snow in 2015 compared to 2016, the effects of burn severity on the snowpack remained consistent each year (Maxwell et al., 2019). Burn severity can alter peak SWE and accumulation by reducing forest canopy density and changing the amount of snowfall that reaches the forest floor (D'Eon, 2004; Maxwell et al., 2019). However, this impact is less severe at higher elevations where storm intensity and snowfall are greater and forest density is thinner, overcoming the impacts of change in canopy structure (D'Eon, 2004). Regardless of elevation, high burn severity demonstrates the largest decrease in post-fire snow-water storage and snow metrics (Smoot & Gleason, 2021). The two orders of magnitude difference in black carbon concentration between high burn severity and low burn severity partially explain this discrepancy (Uecker et al.,

2020) but the effects of altered canopy density also alter energy balance of the snowpack. Previous studies are a small body of research focused on case studies of specific fires demonstrating the need for more research to fully understand the nuance between burn severities across different forest types and snowpacks. Conceptualizing the effects of fire on snow by burn severity could help understand the large-scale (watershed or mountain range) impacts of wildfires on water resource retention in snowpacks. Eventually, models need to take into account large, burned landscapes and ideally also capture the varying effects of burn severity to understand post-fire changes in runoff and flood forecasting.

6. Timing of Snowmelt

The impacts of decreased albedo, increased accumulation and solar radiation accelerate snow snowmelt after a fire (Figure 2). In burned forests, snow disappears 4-23 days earlier, and snowmelt rates increase as much as 57% during ablation (Burles & Boon, 2011; Gleason et al., 2013; Uecker et al., 2020; Winkler, 2011). Smoot and Gleason (2021) assessed 78 burned SNOTEL sites across the western U.S. and found, that in high severity burned areas, maximum snow-water storage decreased by 30 mm and snowmelt rates increased by 3 mm/day compared to unburned areas. In the Washington Cascades, Uecker et al. (2020) showed that in burned areas, 84% of seasonal snow melted out before 1 May compared to only 56% in the pre-fire forested areas. The effects of reduced water storage and earlier snowmelt can be observed for at least 10 years following a fire (Burles & Boon, 2011; Gleason et al., 2013, 2019; Uecker et al., 2020; Williams et al., 2022; Smoot and Gleason, 2021).

Lower latitude and characteristically warmer maritime climate snowpacks undergo larger post-fire shifts in snow disappearance date, peak SWE and as a result, decreased volume of snow-water storage (Serreze et al., 1999; Sun et al., 2019) (Figure 2). Already more vulnerable to climate warming, warmer snowpacks are persistently near 0℃ indicating a slight change in the energy balance due to increased solar forcing from wildfires will likely have a large-scale impact on the persistence of the snowpack (Smoot and Gleason, 2021). Continental climates, which are colder and drier, yield shallower snowpacks with higher cold content (Sturm et al., 1995; Sturm & Liston, 2021), but are still susceptible to severe wildfire and therefore susceptible to alterations in the timing of peak SWE and snow disappearance (Smoot & Gleason, 2021). The shift in the timing of snowmelt, snow disappearance date, and peak SWE, especially in high burn severity areas, decreases late spring runoff (Figure 2). Snowmelt is a significant contributor to mountain headwater runoff, thus shifts in snowmelt may have serious consequences on the patterns and magnitudes of late season stream temperatures and discharge (Smoot & Gleason, 2021).

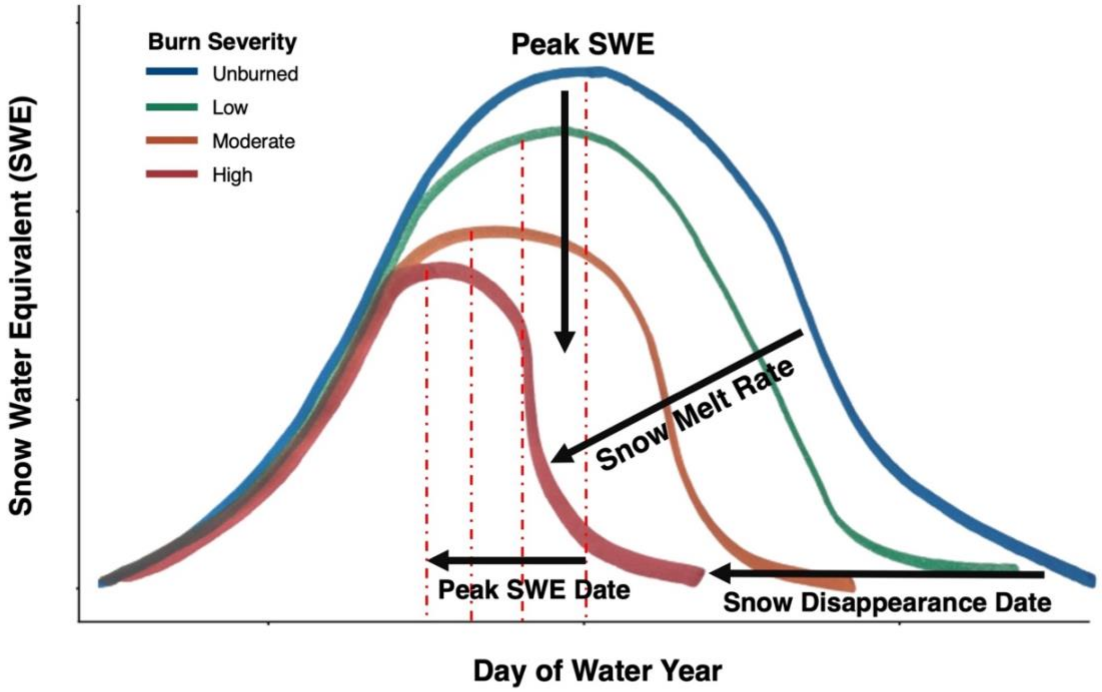

Figure 2. Synthesis of four snow metrics after a wildfire delineated by burn severity including peak snow water equivalent (peak SWE), peak SWE date, Snow Disappearance date (SDD) and snowmelt rates. Figure adapted from (Smoot and Gleason, 2021).

7. Land Surface and Snowpack Models

Wildfires significantly alter the energy balance of the snowpack and changes in albedo and canopy structures are the dominant contributors. However, most snow and land surface models are not accurately accounting for these changes in net shortwave radiation. The lack of albedo parameterization and incorporation of LAPs in climate and energy balance models provides high uncertainties in snowmelt quantity and timing (Hedrick et al., 2018; Skiles et al., 2018). Some models rely on end-member values of albedo and input an exponential decay to model the decline in albedo (Lehning et al., 2006; Liston & Elder, 2006; Marks et al., 1999). Using two seasons of snow albedo measurements in a burned forest, Gleason and Nolin (2016) developed an albedo decay function that takes into account black carbon. Although implemented into SnowModel, this parameterization has not yet been incorporated into a distributed watershed model. Currently, most research and operational models do not account for the amplified effects of black carbon and post-fire canopy loss. As more forests burn throughout the seasonal snow zone, it is imperative that models account for these post-fire effects on snow. Without this incorporation, there are large uncertainties in snowmelt timing and runoff after a fire. This advancement is critical for operational managers to effectively manage reservoir storage after a major wildfire.

8. Conclusion

Across the western U.S., wildfires have persistent and widespread effects on snow hydrology. As fires continue to burn larger, more frequently, more severely, higher in the snow zone, and over an extending fire season, mountain snowpacks are increasingly vulnerable. Researchers and operational managers need to consider the impacts of fire on snowpack in operational and research-focused models to gain a more complete picture of how fires will influence snow hydrology and subsequent water availability. It is critical we understand the sensitivity of snow-dominated watersheds to the impacts of wildfire to evaluate how the extent these disturbances directly impact the water availability derived from the snowpacks. Incorporating these impacts into reanalysis SWE datasets and parameterizing these effects in snowmelt and land surface models is a first step towards understanding these impacts on water resources. The overlap of fire and snow is only going to increase in a warming climate. This creates an imminent need to continue observing the physical processes that come with these landscape-altering events. To mitigate wildfire impacts on snow-water resources, we need to prioritize more albedo and canopy density field observations to help parameterize these values to accurately account for changes in net shortwave radiation in burned areas in research and operational models. The shift in the post-fire snowpack energy balance is critical to accurately model the quantity and timing of runoff. Further research is needed to understand the uncertainties associated with regional and broad-scale variability in wildfire impacts on snowmelt timing and snow-water storage. This accuracy hinges on adequate and representative data to provide a more complete understanding to improve hydrologic and climate models.

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CHAPTER 3

IMPACTS OF BURN SEVERITY ON WATERSHED-SCALE SNOW HYDROLOGY

1. Abstract

Most freshwater in the western United States used for irrigation, industrial consumption, and municipalities originates from headwaters in snow-dominated watersheds. During the winter months, snowpacks serve as natural water towers and are a major contributor to reservoirs for agricultural and municipal water supplies, hydroelectric power generation, and flood control. Wildfires are increasing in frequency, intensity, duration, and size in snow-dominated watersheds and are burning higher in elevation, well into the seasonal snow zone. Using three spatial scales, ground-based, airborne, and satellite data, we assessed post-fire black carbon concentrations, snow albedo, net shortwave radiation, lidar-derived snow depth, and snow disappearance date along a burn severity gradient. Black carbon concentrations increased an order of magnitude in high burn severity compared to unburn causing a decrease in snow albedo. Net shortwave radiation increased by up to 2217% from unburned to high burn severity depending on the month resulting in snow disappearing 19 days earlier in high burn severities compared to unburned. Moderate burn severity followed similar patterns with smaller magnitudes of change. Although the most dramatic impacts occur in high burn severity, only 18% of burned areas in California in the snow zone are classified as high burn severity. The increase in the geographical overlap between fire and snow poses unique and emerging challenges for managing snow-dominated watersheds.

2. Introduction

Wildfires have increased in frequency, extent, intensity, and duration across the western United States (Dennison et al., 2014; Hallema et al., 2018; Williams et al., 2022). In large part because of reduced snowpacks, earlier snow disappearance dates, increased temperatures, and more prolonged dry periods (Abatzoglou et al., 2021; Abatzoglou & Kolden, 2013; Semmens & Ramage, 2012; Westerling et al., 2006; Westerling, 2016), wildfires are predicted to continue increasing in frequency, size, and severity. Wildfires are burning higher in elevation resulting in more fires in watersheds that are in the seasonal snow zone (Hallema et al., 2018; Kinoshita & Hogue, 2015; Stevens, 2017, Abatzoglou & Kolden, 2013; Dennison et al., 2014; Moritz et al., 2012). Wildfire disturbance affects the distribution and magnitude of snow accumulation and ablation. Precise accuracy of snowmelt runoff cannot be achieved without taking into account newly burned forests that alter the landscape of a watershed (Boon, 2009; Burles & Boon, 2011; Gleason et al., 2013; Liu, 2005). Although wildfires can considerably alter runoff (Lanini et al., 2009; Shakesby et al., 2016), their effects are not currently accounted for in most streamflow runoff models. Most managed reservoirs assume stationarity and do not account for large landscape changes (Milly et al., 2008). With increased wildfire, a decline in winter snowpacks (Mote et al., 2018), and an increase in demand for water in the western US as population and urbanization increase (Boretti & Rosa, 2019), it is more critical than ever to be able to accurately predict snowmelt runoff for water consumption.

The majority of the freshwater in the western US that is used for municipal, irrigation, and industrial use originates in montane watersheds (Barnett et al., 2005; Li et al., 2017; Musselman et al., 2021; Serreze et al., 1999). Mountain snowpacks are vital for recharging groundwater and sustaining streamflow into the drier summer months (Barnett et al., 2005, 2008; Hunsaker et al., 2012; Tague & Grant, 2009). Snowmelt runoff is a major source of reservoir storage for agricultural and municipal water supplies, hydroelectric power generation, and flood control because snowpacks provide natural water storage during the winter months (Kang et al., 2016; Kormos et al., 2016; Molotch et al., 2005; Yan et al., 2021). However, burned forests can heavily influence patterns of snow accumulation and ablation by increasing light transmission, altering surface energy balance, and decreasing canopy interception (Gleason et al., 2013; Gleason & Nolin, 2016; Harpold et al., 2012; Harpold et al., 2014). While patterns of snow accumulation in a burned forest can vary based on canopy density and variability in winter conditions, the shift to earlier and faster snowmelt is a persistent trend in burned forests, which affects the timing and quantity of water availability (Burles & Boon, 2011; Maxwell et al., 2019; Stevens, 2017). These landscape changes can pose challenges for water managers in the western US who are dependent on mountain snowpack for the vast majority of the annual water supply (Bales et al., 2006).

Snow albedo is a major control on snowmelt (Dozier et al., 1981) and is significantly modified by burned forests (Gleason et al., 2013; Gleason & Nolin, 2016). For fresh, clean snow, the albedo values in the visible wavelengths range from 0.9 to 0.95 since fresh, clean snow is a highly reflective surface characteristic (Warren, 1982). However, after a fire, burned trees and other vegetation shed black carbon (BC) and charred woody debris onto the snowpack decreasing the snow albedo (Gleason et al., 2013; Gleason & Nolin, 2016). At the same time, high severity wildfires also removed the forest canopy reducing the leaf area index (LAI), which increases light transmitted to the snowpack surface. As a result, the snowpack net shortwave radiation increases (Burles & Boon, 2011; Gleason et al., 2013; Pomeroy & Dion, 1996; Winkler, 2011).

The snowpack energy and mass balance are highly dependent on the shortwave albedo, especially in environments with high solar energy (Dozier et al., 1981, 2009; Skiles et al., 2012). Because snow is highly reflective in the visible wavelengths (400-700 nm), small changes in visible albedo due to light-absorbing particles (LAPs) will increase net shortwave radiation (Dozier et al., 2009; Gleason & Nolin, 2016; Painter et al., 2007; Warren & Wiscombe, 1980). As the snow albedo decreases, the snowpack absorbs more solar energy, which accelerates the rate of near-surface warming and melt. As a result of accelerating melt, the snow disappears 4-23 days earlier (Gleason et al., 2013; Molotch et al., 2005; Wiscombe & Warren, 1980). Black carbon (BC) and charred woody debris from burned trees are an order of magnitude more effective at absorbing solar energy in the visible spectrum compared to mineral dust (Gleason et al., 2019; Warren & Wiscombe, 1980). The impacts of deposited BC and LAPs are most significant during ablation and can decrease snow albedo by 40% (Gleason et al., 2013). Simultaneously, post-fire canopy removal increases incoming solar radiation by 60%, resulting in a nearly 200% increase in net shortwave radiation at the snowpack surface (Gleason et al. 2013). Maximum snow water storage in burned forests may be reduced by decreased snow albedo and increased insolation amplified by mid-winter melt events mimicking the process of “slower melt in a warmer world” (Musselman et al., 2018; Smoot & Gleason, 2021). Variability in snow albedo, and in turn the snowpack energy balance, especially during ablation periods, have important implications for the timing and quantity of spring and summer streamflow, especially as winter snowpacks continue to decline (Burles & Boon, 2011; Skiles et al., 2012; Thackeray et al., 2014; Warren, 1982).

While snow albedo is a major control during ablation, canopy structure impacts patterns of snow accumulation. A healthy forest canopy can intercept falling snow resulting in up to a 40% decrease in accumulation (Varhola et al., 2010). The forest canopy also emits longwave radiation and provides shading from incoming solar radiation which influences the timing of forest snowmelt (Lundquist et al., 2013; Roth & Nolin, 2017). However, previous work has shown that a loss of canopy from a wildfire can increase snow depth in burned areas during the accumulation compared to nearby control plots (Burles & Boon, 2011; Harpold et al., 2014). Simultaneously, increased total incoming energy to the snowpack from the loss of canopy cover, increases the snow sublimation (Faria et al., 2000; Harpold et al., 2014; Varhola et al., 2010). An increase in sublimation and decrease in longwave radiation can offset and partially balance the increase in net shortwave radiation (Burles & Boon 2011; Harpold et al 2014). An increase in radiative heating and solar radiation from canopy lost in combination with decreased albedo from LAPs have amplifying effects and feedback on post-fire snowpack water retention.

As a result of climate change in combination with a history of fire suppression, the total annual burned area is projected to increase, especially in California (Dennison et al., 2014; Marlon et al., 2012; Williams et al., 2022). In 2020 alone, nearly 6% of the forested area in California burned (Williams et al., 2022). This poses a challenge for snow-dominated watersheds in the Sierra Nevada mountains and California's water resources. It is clear that wildfires can increase snowpack accumulation while also accelerating snowmelt, altering the timing of runoff. These implications, especially in high burned severity areas, can last up to 10 years following a fire (Gleason et al., 2019; Uecker et al., 2020; Williams et al., 2022; Smoot and Gleason, 2021). When assessing the impacts of wildfire on snowpacks, previous studies have examined burned vs. unburned forests. These studies have shown that, in burned forests, snow disappearances earlier, and snowmelt rates increase as much as 57% during ablation (Burles & Boon, 2011; Gleason et al., 2013; Winkler, 2011). However, fires do not burn uniformly across the landscape because of topography, weather, and fuel loading.

To fully understand the impacts of wildfires on a watershed scale, it is important to understand how the variability in burn severity alters the snowpack characteristics and snowmelt rates. The objective of this paper is to demonstrate that not all burn severities have an equal impact on snowpack accumulation and ablation. Specifically, this study evaluates the relationship between burn severity and snow albedo in a snow-dominated watershed in the central-southern Sierra Nevada of California and quantifies the changes in snow depth and snow disappearance across a burn severity gradient during the period of snow ablation. The observed changes are critical to our understanding of wildfire impacts on snow retention and demonstrate that burn severity matters when assessing post-fire impacts on mountain hydrology.

3. Study Area

3.1 Creek Fire

In the fall of 2020, the Creek Fire burned over 1,500 km^2, nearly 45% of the Upper San Joaquin Watershed (USJW). The fifth-largest wildfire in California at the time, the Creek

Fire ignited on September 4, 2020, and reached containment on December 24, 2020, costing the state of California nearly $200 million and destroying 856 structures (CAL FIRE, Inciweb). The fire's burned area has an elevation range of 430 m to 2917 m (Figure 1a) and annual average precipitation of 760 mm of which about 60% falls as snow between October and April (Lynn et al., 2020). Approximately 56% of the Creek Fire burned in the seasonal snow zone defined by average snow-covered frequency of greater than 20% from 2000-2021 (Figure 1b). High winds, steep terrain, and varied vegetation produced a mosaic of burn severities with extreme fire behavior leading to high severity crown fires (Figure 1c). Parts of the watershed have previously burned as recently as 2018, however the largest fire in this watershed prior to the Creek Fire only burned 95 km^2 (Figure 1d). As the headwaters of the San Joaquin River, the USJW is an important watershed to understand post-fire impacts. The San Joaquin River contributes a large portion of the water supply for the Central Valley's agricultural economy, and it is an important source of hydropower.

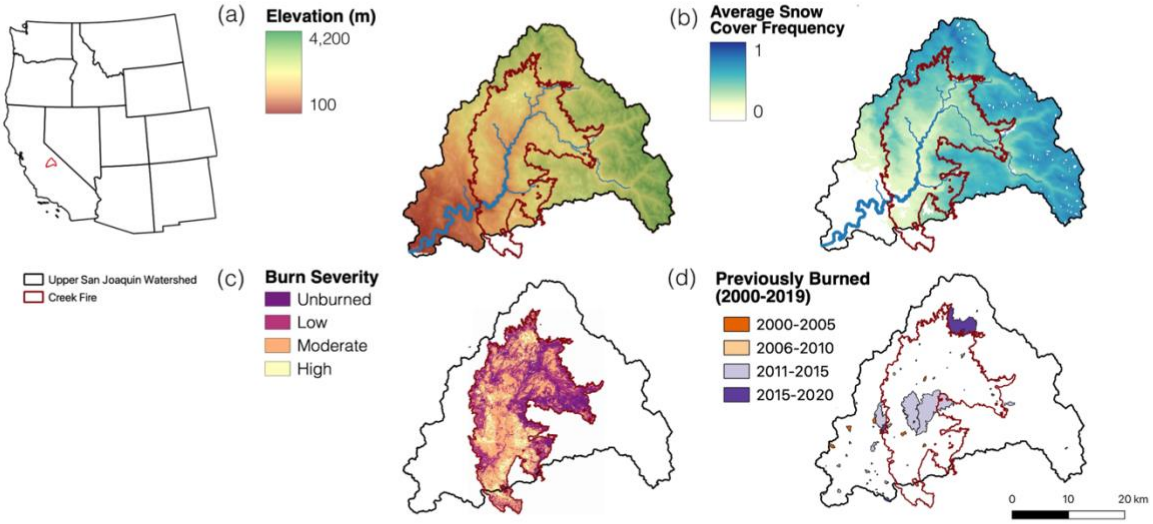

Figure 1. Maps of the Upper San Joaquin Watershed (USJW) located in the south-central Sierra Nevada, California. (a) Digital elevation and hydrography of the USJW (data

source: USGS); (b) average snow cover frequency derived from MODIS from 2000-2020; (c) burn severity map (data source: BAER, USDA Forest Service); (d) previously burned area from 2000-2019 in the USJW (data source: MTBS).

4. Methods

This study uses three measurement approaches that span a range of spatial scales: hyperspectral field spectrometry, airborne lidar, and satellite multispectral radiometry, to map and assess the impacts of burn severity on snow hydrology. The Creek Fire was used as a case study to understand the physical processes driving the differentiation in burn severities. These results are then scaled up to provide a first-order estimate of the effects across the Sierra Nevada and California to demonstrate the magnitude of wildfire impact on snow hydrology.

4.1 Remote Sensing

4.1.1 ASO Snow Depth and SWE

Spatially-explicit snow depth was mapped across the study area using airborne lidar from the Airborne Snow Observatories, Inc (ASO). ASO uses a lidar differencing approach by subtracting “snow-off” and subsequent “snow-on” co-located lidar data to calculate snow depth. Snow depth rasters for specific dates are produced at 3-m resolution by subtracting the snow-off bare digital elevation model from the snow-on data (Painter et al., 2016). ASO acquired snow-off data over the USJW in October 2016 and flew the fire scar again in December 2020. A small portion of the lower basin was reflown in 2019. Snow-on data for winter 2021 were collected on 27 February, 01 April, and 03 May. To produce a SWE raster, ASO multiplied the snow depth raster by a snow density raster. ASO uses the iSNOBAL model to estimate snowpack density over the study area (Marks et al., 1999). However, this model does not account for post-fire density changes due to altered snowpack energy balance (Micah Johnson, personal communications), therefore, we focused on snow depth measurements for this study. Outliers in the snow depth dataset were removed using 1.5 times the interquartile range (IQR).

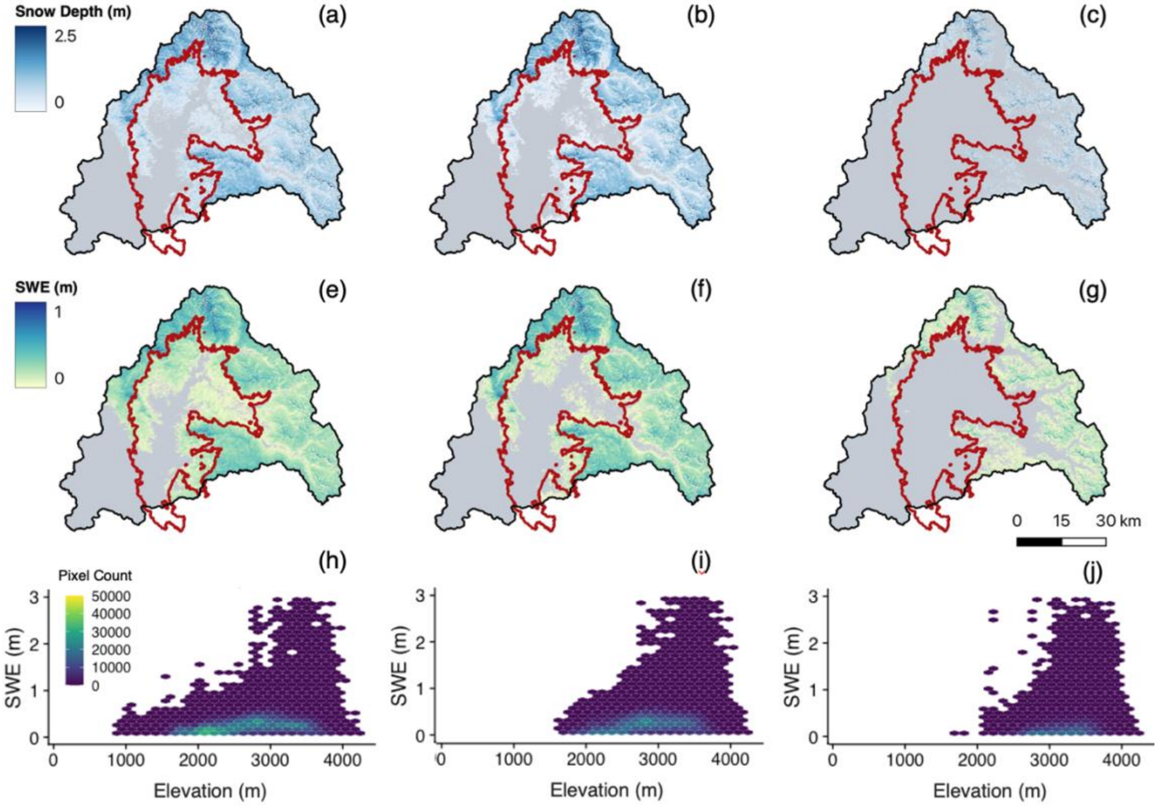

Figure 2. ASO lidar-derived snow depth at 3-meter resolution (a) 26 February 2021, (b) 1 April 2021, (c) on 3 May 2021. ASO modeled SWE at 50-meter resolution (e) 26 February 2021, (f) 1 April 2021, (g) 3 May 2021. Density plot comparing elevation and SWE on (h) 26 February 2021, (f) 1 April 2021, (g) 3 May 2021.

4.1.3 Burn Severity

For the Creek Fire, burn severity was derived from the USDA Forest Service (USFS) Burn Area Emergency Response classification (BAER) (Figure 1c). California statewide calculations of burn severity are a combination of the Monitoring Trends in Burn Severity (MTBS) dataset from 2000-2019 (Eidenshink et al., 2007) and BAER for 2020-2021. Both datasets calculate burn severity from the Difference Normalized Burned Ratio (dNBR) using Landsat satellite images at a 30-m resolution from pre-and post-fire dates (Cardil et al., 2019; Eidenshink et al., 2007; Key & Benson, 2006; Miller & Thode, 2007). To calculate the difference between burned and unburned vegetation, the dNBR normalizes the reflectance in the near-infrared (NIR) (0.85-0.88 µm) and shortwave-infrared (SWIR) (2.11-2.29 µm) wavelengths. Healthy vegetation is highly reflective in the NIR compared with SWIR, while bare earth and burned woody vegetation have high reflectance in the SWIR and lower reflectance in the NIR.

(1) $$\mathrm{NBR} = \frac{\mathrm{R_{NIR}} - \mathrm{R_{SWIR}}}{\mathrm{R_{NIR}} + \mathrm{R_{SWIR}}}$$

(2) $$\mathrm{dNBR} = \Delta\mathrm{NBR} = \mathrm{NBR_{pre-fire}} - \mathrm{NBR_{post-fire}}$$

where $\mathrm{R_{NIR}}$ is near-infrared reflectance, $\mathrm{R_{SWIR}}$ is shortwave-infrared reflectance and dNBR is the change in NBR from pre- to post-fire (Cardil et al., 2019; Eidenshink et al., 2007; Key & Benson, 2006; Miller & Thode, 2007).

4.1.3 Snow Disappearance Date

Snow Disappearance Date (SDD) for the water year 2021 in the USJW was computed using the daily, 500-m Moderate Resolution Imaging Spectroradiometer (MODIS) Snow Cover Binary (MOD10A1) product. MOD10A1 relies on the Normalized Difference Snow Index (NSDI) to discern between the presence and absence of snow. Using Google Earth Engine, SDD was calculated as described in Crumley et al. (2020), by locating and identifying the date at which each pixel switches from “snow” to “no snow”. A five-day time interval was used to ensure ephemeral late-season snow events were not captured while also not missing impactful late-season snow events. A cloud correction was also applied using the MOD32_L2 cloud mask, a built-in cloud mask in the MOD10A1 version 6 product. For more information on this algorithm please refer to Crumley et al. (2020) and SnowCloudMetrics.app.

4.1.4 Elevation

The Digital Elevation Model was downloaded from the USGS National Map dataset at a 1-m resolution produced by the 3D Elevation Program for consistency with previous research.

4.1.5 Snow-Water Equivalent (SWE)

Using the daily, 90-m SWE gridded reanalysis product for the Sierra Nevada from Margulis et al. (2016), the average volumetric maximum SWE was computed for each grid cell in the Sierra Nevada from 1985-2015. Volumetric SWE is computed as SWE depth (m) times grid cell area. Average volumetric SWE was computed using the annual maximum SWE value for each grid cell and then averaging those values over the period 1985-2015. To assess the mean volumetric SWE affected by each burn severity, these 90-m data were resampled to 30-m grid resolution and overlaid with the 30-m MTBS dataset.

Table 1. Relevant remote sensing products used in this study.

Measurement	**Data Source**	**Spatial Resolution (m)**	**Features**
Burned Area and Severity	USFS BAER for 2020-2021 and MTBS for 2000-2019	30	dNBR from pre-and post-fire changes using Landsat data
Snow Depth	Airborne Snow Observatory (ASO)	3	Three overflights using airborne lidar
Snow Disappearance Date (SDD)	Google Earth Engine- MOD10A1 calculated using methods of Crumeley et al., (2020)	500	MODIS/Terra Daily, gridded snow cover
Elevation	United States Geological Survey Digital Elevation Model (DEM)	1	Produced by the 3D Elevation Program (3DEP)
Snow Water Equivalent (SWE) for the entire Sierra Nevada	Margulis et al. (2016) SWE gridded reanalysis data product.	90	A Bayesian assimilated reanalysis of fractional snow cover from Landsat 5-8 from 1985-2015

4.2 Field Data

Ground-based data were collected at three adjacent sites at an elevation of approximately 2100 m. Each site represents a level of burn severity based on MTBS-derived categories: high burn severity, moderate burn severity, and unburned forest (Figure 3). At each site, snow measurements were collected along a 100-m transect. Measurements included spectral snow albedo, snow depth, snow density, snow water equivalent, and snow samples to bring back to the lab for analysis of black carbon and woody debris. In situ measurements of snow depth, snow density, and snow water equivalent (SWE) were used as point-based field validation for the ASO overflights. These field measurements were acquired on 26-27 February 2021 and 01 April 2021, within one day of the ASO overflights. Water year 2021 had lower than average snowfall and high than average temperatures, with long mid-winter dry periods. Therefore, the April ASO flight missed peak SWE in the USJW by 5 days and February measurements indicated that snow was actively melting.

Figure 3. Photos from three field sites in the Creek Fire near Huntington Lake, Calif. (a) High burn severity, (b) moderate burn severity, and (c) unburned on 27 February 2021. (d) Snow depth measurements in an unburned forest using a MagnaProbe and (e) Albedo measurements in a high burn severity forest using the Spectral Evolution RS-3500 Portable Spectroradiometer™). Photo credits: Anne Nolin (a-d), Ben Hatchett (e).

4.2.1 Spectral Snow Albedo

Snow albedo was measured every 10 m along a 100 m transect at all three sites. Albedo measurements were acquired using a Spectral Evolution RS-3500 Portable Spectroradiometer™ (RS-3500) fitted with a 180˚ field of view (FOV) diffuser. The spectrometer has a spectral range from 350-2500 nm, with a 1-nm spectral resolution. The diffuser was mounted to an extendable 1.2 m pole and had a bubble level attached to help keep the sensor level. Each measurement was acquired at a height of approximately 60 cm above the snow surface.

In addition to the effects of snow grain size and light-absorbing particulates, snow albedo varies depending on solar zenith angle and atmospheric conditions. To control for these variations, each measurement was taken within one hour of solar noon on clear days following the methods described in Gleason et al. (2013). Measurements that may have been affected by clouds, vegetation, and sun-dappling due to canopy shading were discarded from the dataset. The spectral albedo data require post-processing to remove sensor noise effects in the SWIR region at wavelengths longer than 1500 nm. The spectral albedo comparisons and spectrally-integrated broadband albedo values span the range of 400-1500 nm.

4.3 Laboratory Analysis

Snow samples were collected to measure and characterize impurities in the snowpack that contribute to changes in snow albedo. At each albedo measurement location, surface (1 m^2 x 0.5 m^2 area) snow samples were collected for lab analysis. Snow samples collected in the field were kept frozen and transported to the Ice Core Laboratory at the Desert Research Institute (DRI). Snow samples were melted and then sonicated with an ultrasonic bath to suspend the particles within the liquid samples in a homogenous mixture. Each melted and sonicated sample had 50 ml of liquid removed and placed in a plastic vial which was pre-rinsed with ultrapure deionized water.

4.3.1 Black Carbon

To measure black carbon concentrations from field-collected snow samples, the 50 ml liquid samples were processed with a Droplet Measurement Technologies Single Particle Soot Photometer™ (SP2). The SP2 uses laser-induced particle incandescent (LII) to measure individual aerosol particles for mass and was designed specifically for refractory black carbon (soot) (Stephens et al., 2003). By combining the theories of light scattering, absorption, and emission; the diameter, mass, and incandescence temperature of individual aerosol particles in the diameter range of 0.15-1 μm can be measured (Baumgardner et al., 2004; Stephens et al., 2003). The SP2 instrument was calibrated before use with controls of carbon particles with a known density and specific sizes. Liquid samples were then loaded on an autosampler and a line is inserted per sample which pumps the liquid through a 20 μm stainless steel filter that removes oversized particles. Next, the sample liquids were split for black carbon measurements in the size range of 0.09-0.6 μm while insoluble particles with particle sizes between 0.8-10 μm were run through an Abakus® laser-based particle counter. The Abakus® measures dust particle concentration based on particle sizes (Gleason et al., 2019).

4.4 Net Shortwave Calculation

To better understand the potential impacts of the combined effects of canopy removal and decreased albedo as a function of burn severity, we performed a set of calculations of snowpack net shortwave radiation using point field measurements for albedo and estimated Leaf Area Index (LAI) for each burn severity. Net shortwave radiation (Q_{ns}) is computed as:

(3) $$Q_{ns} = \boldsymbol{\varepsilon}_s (1-\alpha)$$

where, Q_{ns} is measured in Wm^{-2}, $\boldsymbol{\varepsilon}_s$ is the incoming radiation at the snowpack surface, and α is the average broadband albedo calculated from the field spectrometer measurements at each burn severity for February and averaged from 400 nm -1500 nm.

$\boldsymbol{\varepsilon}_s$ is dependent on the solar irradiance at the top of the forest canopy and the canopy density as represented by LAI. Using the Beer-Lambert law (Monsi & Saeki, 1953), which assumes a random distribution of branches and leaves, $\boldsymbol{\varepsilon}_s$ is computed as:

(4) $$\boldsymbol{\varepsilon}_s = \boldsymbol{\varepsilon}_0 \exp(- a_v \, LAI)$$

where $\boldsymbol{\varepsilon}_0$ is the daily average solar irradiance derived from the Clouds and Earth Radiant System (CERES) satellite on the first of each month for January through April. LAI is estimated for each burn severity based on hemispherical photography from Gleason et al. (2013) for unburned and high burn severity. a_v is the solar radiation extinction coefficient evaluated based on the theoretical calculation provided by Norman and Campbell (1989) for a random canopy and is calculated as:

(5) $$a_v = \frac{1}{2 \cos Z}$$

where Z is the solar zenith angle for a flat surface at solar noon derived from National Oceanic and Atmospheric Association (NOAA) database (Hellström et al., 2000). Q_{ns} was calculated for high burn severity, moderate burn severity, and unburned conditions for four solar zenith angles from January to April (Figure 7).

Canopy density and black carbon shedding vary across a burnt landscape. To account for this variation, we varied albedo values and LAI to assess the sensitivity of these calculations. Albedo was varied by 5%, using increments of 0.1%. LAI values were varied by 50% using increments of 1%. As a result, a range of Q_{ns} values was calculated.

4.5 Random Forest Analysis

We performed a preliminary random forest analysis to determine the variables affecting snow depth in the study area. The random forest evaluated elevation, slope, aspect, forest cover and burn severity. Elevation was the largest driver of snow depth, so we divided the basin into elevation bands to isolate the effects of burn severity on snow depth.

5. Results

5.1 Snow Depth Changes with Burn Severity

Snow depth decreased in high and moderate burn severities across elevations and months. Our field campaigns did not capture the accumulation season and therefore February, April, and May data all mimic patterns of the ablation season. Because of the inconsistencies in the winter of 2020-2021, we do not observe the typical patterns of increased accumulation in burned areas compared to unburned areas.

In the mid-elevation (1500-2500 m), where the largest overlap between fire and snow occurs (Figure 4a), high burned areas decreased the most from February to April, with the largest discrepancy at 2000-2500 m in April (Figure 4b). Snow depths at each burn severity were significantly different from each other at 1500-2000 m and 2000-2500 for February and April with a significance threshold of $p < 0.05$. However, in May the only remaining significant differences in snow depth were between unburned and high burn severity. At higher elevations in April, snow depths were not found to be significantly different. By May, the remaining snow was located above 2500 m, outside the fire perimeter (Figure 2). From the random forest analysis, we found that burn severity and elevation were the primary controls on snow depth. Slope as a variable was significant, but only at elevations above 2500 m where there was little overlap between the burned area and the seasonal snow zone (see Figure A1, Appendix A). We note that the same factors that affect fire behavior (e.g., slope and aspect) may also affect snow depth. However, this study and its results highlight the specific relationship between snow depth and burn severity.

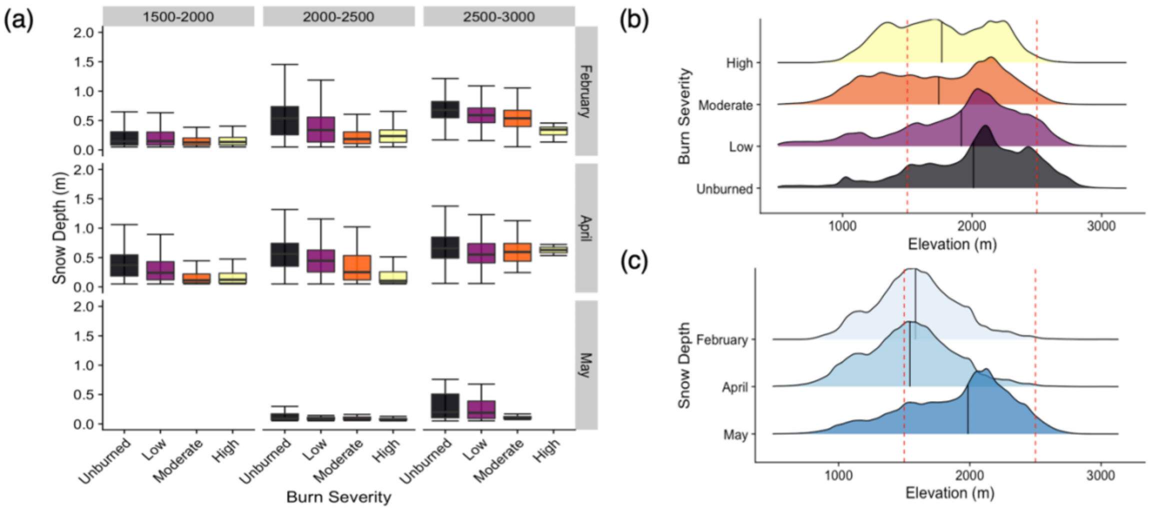

Figure 4. (a) Snow depths derived from three overflights, 26 February 2021, 01 April 2021, and 03 May 2021 categorized by burn severity and separated by elevation bands. (b) Density of burn severity pixels by elevation. (c) Density of snow depths for each overflight by elevation. Red dotted lines represent the largest overlap between burned pixels and snow depth at 1500-2500 m. Note: These measurements only capture the ablation period.

5.2 Black Carbon and Snow Albedo

Burned trees deposit black carbon (BC) and other light-absorbing particles (LAPs) onto the snow surface in the winter following the fire. BC concentrations increased by 81-88% from no burned to high burned in both accumulation and ablation seasons. From February to April, BC increased in concentration by 35-63% with the largest increase in the moderate burn. In February, concentrations increased by 47% between moderate and no burn while in April it increased by 70%. The high burned BC concentration in both February and April was an order of magnitude larger than the no burn. This change in BC is reflected in the snow albedo measurements as the percent change from moderate to high burn decreases in the visible wavelengths from 25% to 11% in February to April respectively. The opposite pattern was observed in the near-infrared wavelengths where moderate to high burn albedo decreased by 29% in February and 34% in April (Figure 5). Overall, during ablation, BC concentrations increased while average albedo values decreased showing the largest difference between high severity burn and unburned areas and the largest change from February to April in the moderate severity burn.

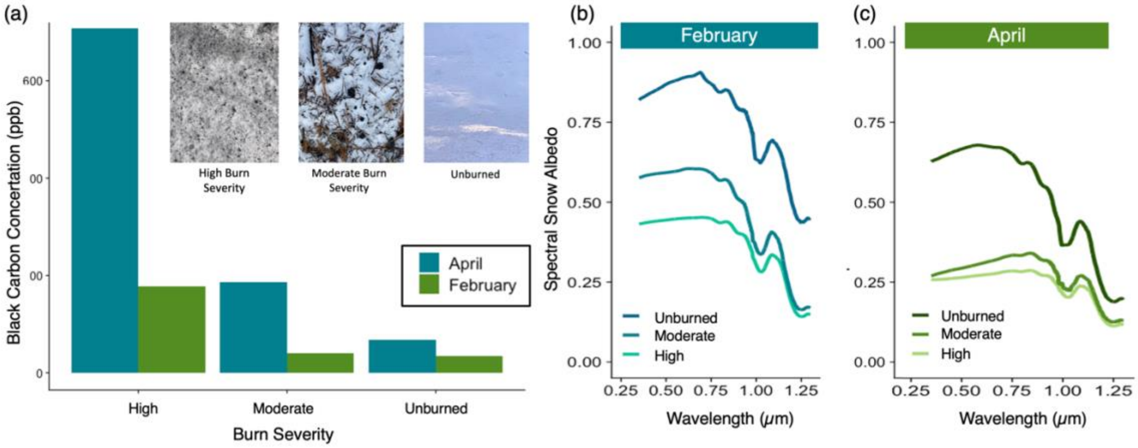

Figure 5. (a) Black carbon concentrations for high burn severity, moderate burn severity, and unburned snow samples collected on 27 February 2021 (green) and 1 April 2021 (blue) from the Creek Fire. Photos depict the snow surface for each burn severity taken on 27 February 2021. Mean spectral albedo measurements of high burn severity, moderate burn severity, and unburned areas were measured during spectrometer surveys on (b) 27 February 2021 and (c) 1 April 2021.

5.3 Snow Disappearance Date (SDD)

Snow disappeared earlier in the first spring following a wildfire in all burn severities compared to unburned areas. Across the watershed, SDD was the most impacted in high burn severity areas where the high burned pixels melted out, on average, 19 days earlier than the unburned pixels and 5 days earlier than the average for the entire watershed. Moderately burned pixels followed a similar trend, but held snow 3 days longer, only melting out 16 days earlier than unburned pixels and 2 days earlier than the average across the basin. Low burn severity pixels melted out 11 days earlier than unburned pixels but held snow 8 days longer than high burned pixels and 3 days longer than the basin-wide average. Unburned pixels had snow for 14 days longer than the basin average. High and moderate burns severities snow disappearance was statically significantly different (p<0.01) from all other burn severities while low burn severity was not statically different from unburned (Figure 6, Table 2).

Table 2. A table of average snow disappearance date (SDD) for the water year 2021 for each burn severity. Positive numbers indicate earlier melt while negative numbers indicate later snowmelt.

Burn Severity	Avg. SDD for WY 2021	SDD compared to unburned	SDD Compared to Avg. Watershed
High	186	19	5
Moderate	189	16	2
Low	194	11	-3
Unburned	205	0	-14

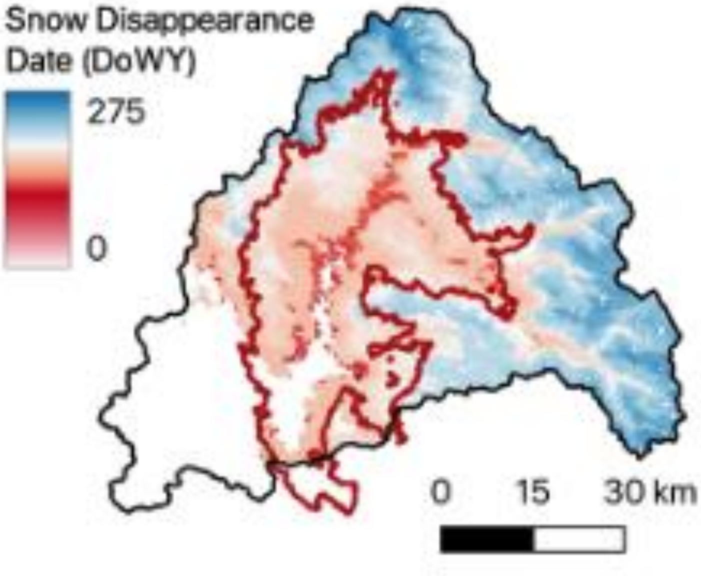

Figure 6. A map of snow disappearance date (SDD) for the USJW and Creek Fire derived from MODIS/MOD10A1.

5.4 Net shortwave radiation

The highest values of net shortwave radiation occurred in high burn severity pixels where it ranged from 47.6 Wm^{-2} in January to 128.0 Wm^{-2} in April. However, the largest percent increase from unburned to high burned occurred in January with a 2217% increase where unburned experienced 2.1 Wm^{-2} . Moderate burn severity pixels also experienced a large percentage increase in net shortwave radiation compared with unburned pixels with values ranging from 776% in January to 425% in April. The percent increase was lower when compared to high burn severity where it ranged from 164% in January to 97% in April. When assessing the sensitivity of these calculations, varied LAI and albedo indicate that the range of uncertainty of each calculation is independent of other burn severities (Figure 7).

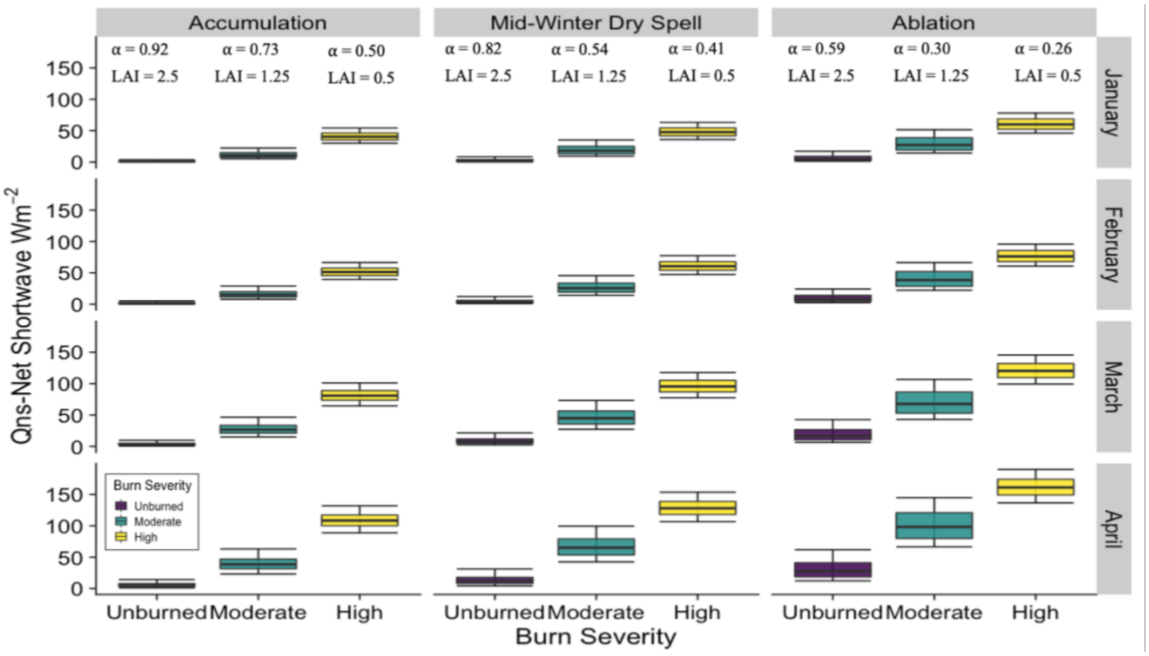

Figure 7. Range of net shortwave radiation (Q_{ns}) value displaying the sensitivity of the calculations for each burn severity from January to April under different snow conditions (accumulation, mid-winter dry spells, and ablation). Starting values for Leaf Area Index

(LAI), and albedo (α) are noted above. Calculations are based on empirical data from the field. Values are reported in Wm^{-2}.

5.5 Burn Severity across California

Wildfires that occurred from 2000-2019 in California had an average of 16% high burn severity, 37% moderate burn severity, 26% low burn severity, and 19% unburned areas. When only looking at fires in the snow zone, defined by 20% average snow cover per pixel, there was a statically significant difference ($p < 0.05$) from the total fires across California. For fires in the snow zone, there was 18% high severity burn, 37% moderate severity burn, 27% low severity burn, and 18% no burn (Figure 7). The Creek Fire had 11% high burn severity, 45% moderate burn severity, and 43% low burn severity (Table 1). However, in 2020-2021, of the fires assessed by the USFS in California, 7% of the area was classified as high burn severity, 38% were moderate burn severity, 35% were low burn severity and 21% were unburned.

The Sierra Nevada, on average, produces approximately 19.75 km^3 (16 MAF) of water annually from snowmelt based on the SWE reanalysis dataset from Margulis et al. (2016). By comparison, this is enough water to fill the Hetch Hetchy reservoir over 44 times. This volume can range from 2 km^3 (1.6 MAF) in WY 2015 to 30 km^3 (24 MAF) in WY 1993. When assessing all the fires that burned from 2000 to 2019 across the Sierra Nevada, high burn severity affects nearly 1.1% of the water produced from the snowpack or 0.21 km^3 (0.17 MAF). This is enough water to fill nearly half of the Hetch Hetchy reservoir. Moderate burn severity affects a similar proportion of 1.23% of total water produced from snow in the Sierra Nevada equating to 0.24 km^3 (0.19 MAF) filling over half of the Hetch Hetchy reservoir. Low burn severity accounted for a larger percentage of nearly 1.9% of all water produced from snow in the Sierra Nevada or 0.37 km^3 (0.3 MAF) which is enough to fill over two-thirds of the Hetch Hetchy reservoir. More than 4% of all water from the Sierra Nevada produced from 2000-2019 or two and a quarter of Hetch Hetchy reservoirs has been directly affected by wildfires.

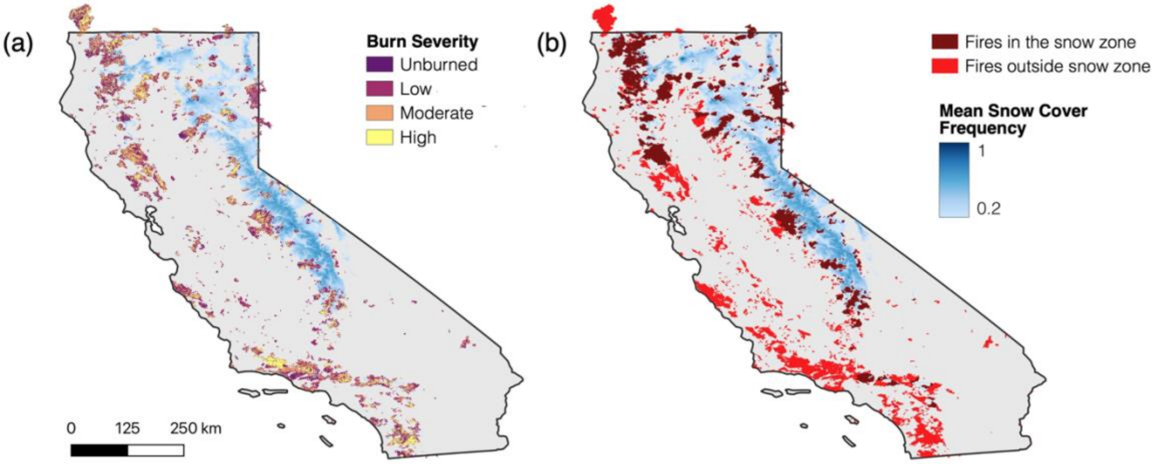

Figure 8. Fires across California for MTBS dataset for 2000-2019. (a) Burn severity for all fires from 2000-2019. (b) Fire perimeters delineated by snow zone. The snow zone is defined as the average snow cover frequency from 2000-2021 derived from MODIS/MOD10A1 with greater than 20% snow cover (Crumley et al. 2020).

6. Discussion

In the Sierra Nevada, snowmelt drives spring runoff and controls the volume and timing of downstream water resources (Li et al. 2017). Climate warming is driving earlier snowmelt and snow disappearance and reducing the volume of water stored in the snowpack (Mote et al. 2018). In this research, we found significant differences in snowmelt patterns across different burn severity. Burned forests melted out 11-19 days earlier than unburned forests with the largest impacts in high severity burned areas. Using a combination of ground-based, airborne, and satellite-based observations, we showed that in high severity burned areas, BC concentration increased by an order of magnitude, net shortwave radiation increased 24 times, while snow albedo and snow depth decreased, resulting in SDD being nearly three weeks earlier in high burn severity areas compared with unburned areas. Moderate burn severity areas followed similar patterns but impacts were lower. Low burn severity areas also showed earlier SDD but the magnitude of change compared to the entire watershed was not statically significant from unburned areas. Changes in the timing of the snow disappearance date can alter the patterns of runoff and water storage heavily impacting water availability for downstream users (Lundquist et al. 2013; Mote et al. 2018; Winkler et al. 2014).

The physical process behind these observations can be explained by the relationship between increased BC concentrations, decreased snow albedo, and the combined effect of increased net shortwave radiation as burn severity increases, especially during ablation. With increased BC on the snow’s surface, the reflectivity of the snow is altered, decreasing the albedo, and increasing the energy absorbed by the snowpack (Gleason et al. 2013). The increase in energy, in combination with the lack of canopy shading from the burned forest, increases the net shortwave radiation (Gleason et al. 2013). High burn severity forests experience the largest decrease in canopy density, and as a result, the greatest increase in solar energy that reaches the snowpack. We showed that net shortwave radiation increases over 2200% from unburned to high burn severity in January when snow cover reaches its greatest extent. In April, the net shortwave radiation still increases by nearly 1000% in the high burn severity compared to unburned. This may explain why snow is disappearing earlier in high burn severity areas compared to other burn severities. The relationship between burn severity and SDD is congruent with findings from Smoot and Gleason et al. (2021) who also demonstrated that high burn severity areas had a large decrease in SDD compared with unburned forest areas. As with Gleason et al. (2013), our data show that BC and LAPs decrease the snow albedo. Our results extend that work by showing that this effect is apparent in both moderate and high burned severity areas, although at different magnitudes. We also demonstrate the combined impacts of canopy removal in burned forests and decreased snow albedo drive an increase in net shortwave radiation in moderate and high burn severities.

Our results suggest that snow ablation in high burn severity areas, especially in mid-elevations where there is the largest overlap between fire and snow, is likely due to the decrease in snow albedo. During the snow accumulation period, a lack of canopy cover can increase snow depth (Harpold et al., 2014; Lundquist et al., 2013; Varhola et al., 2010). However, during ablation, the combined effect of increased solar radiation, and reduced snow albedo, decrease snow depth in high burn and moderate severity forests. Our study occurred during a warm winter where even in February, snow was already melting and exposing bare ground. This could explain why we see a decrease in snow depth in both moderate and high burn severities in February and April. The decrease in snow depth in high burned severity areas in April is consistent with the findings of Maxwell et al. (2019) who showed, that during ablation, snow depth decreased by 17% for every 20% decrease in burn severity defined by overstory tree mortality. Regardless of snow depth variability, these changes remained consistent between winters (Maxwell et al., 2019). The post-fire impacts of increased radiative forcing, including decreased snow albedo, canopy removal, and increased net shortwave result in a shift in the net snowpack energy balance. This could push mid-winter melt events earlier in the season and diminish maximum snow depth in burned forests (Musselman et al., 2018). The impacts of these large wildfires can last up to 10 years, with the longest-lasting effects in high severity burned areas (Smoot & Gleason, 2021)

Although nearly all publications on snow-fire interactions focus on high burn severity, we note that high burn severity forests account for less than 20% of all burned areas in California for the period 2000-2019. Indeed, nearly 65% of all burned areas in California are classified as moderate and low burn severity. Moderate and low burn severities affect over 3% of the Sierra Nevada water that originates as snow. This estimate is likely low as it does not consider the increase in fire activity in 2020 and 2021 in California. Hatchett et al., (2022) found 9.8 times increase in fire activity in 2020 and 2021 compared to the years 2000-2019 in California. More research needs to focus on the low and moderate burn severity impacts on snow, especially as forest managers look to increase low burn severity prescribed fires to limit future high severity wildfires.

7. Conclusions

Across the western U.S., wildfires have persistent and widespread effects on snow hydrology. Wildfires in the Sierra Nevada contribute to earlier snow disappearance and decreased snow depth. Through the post-fire deposition of BC, the snow albedo decreases, and in turn, the snowpack absorbs more incoming energy. Meanwhile, in high burn severity forests, the canopy is removed allowing more solar radiation to reach the snow surface. This study shows that the concentration of BC is an order of magnitude higher in high burn severity forests and the net shortwave radiation increases by 951% to 2217% from high burn severity to unburned areas, greatly reducing snowpack retention. With decreased snow depth and earlier snow disappearance date in high burn severity forests, these areas will have a larger impact on snow hydrology compared with moderate- and low burn severity areas. Still, moderately burned forests had an earlier snow disappearance date and decreased snow depth compared to low severity and unburned forests. Corroborated by previous work, our empirically derived results extend the conclusions of burned forests' impacts on snow to incorporate the nuance of different burn severities across a burned landscape.

Understanding the connection between declining snowpacks and wildfires has implications for water resource management and snowpack modeling. There has been observed warming of temperatures and decline of snowpacks both in extent and duration (Mote et al. 2018). Simultaneously, there is an increase in the frequency, severity, and size of wildfires across California and the western United States since the 1980s (Westerling, 2016). Current climate models continue to predict snowpack will decline (Elsner et al 2010) and annual burned area to increase (Flannigan et al. 2013) making it more important than ever to understand the connection between wildfire and declining snowpacks. These impacts from wildfires on the snow surface may have lasting impacts on snow dynamics and runoff patterns in burned snow-dominated watersheds. The snow disappearance date occurred 19 days earlier in high burn severity areas, compared with unburned forests, and is consistent with the results of Gleason et al. (2013) and Uecker et al. (2020). Earlier snow disappearance, particularly in high and moderate burn severity wildfires, can lead to a decrease in late spring snowmelt contribution, and place more strain on water availability during the drier summer months. Since snowmelt timing and volume are considerable controls of mountain headwaters, these observed changes may also affect streamflow and stream temperatures during the summer months (Macdonald et al. 2003)

The implications of this study support the notion that understanding the variable impacts of burn severities matters for snow hydrology. It is imperative that we understand the impacts of wildfires on snowpack retention and the implications for water resources management. These results demonstrate the need to quantify the spatio-temporal variability of wildfire's effects on snow hydrology and incorporate them into flood forecasting and runoff modeling. Understanding the nuance in burn severity can help inform runoff and forecast models after a severe wildfire in hopes of producing more accurate forecasts and improving water management strategies following disturbance. Since moderate and low burn severities are a large percentage of total acres burned and impact a larger percentage of total SWE across the Sierra Nevada than high burn severity, it is critical that more research and observations are conducted to better understand these impacts. This research may also help improve our understanding of snow ablation processes. Energy balance components contain large uncertainties and often do not account for black carbon or other light-absorbing particles (Skiles et al. 2018). Scaling this study up to multiple regions across a range of vegetation structure types and climatological characteristics to include the broad-scale and regional variability in wildfires effects on snow retention is essential to inform future water management policies in hopes of mitigating high severity fires impacts on snow retention on a watershed scale.

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CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Across the western U.S., wildfires have persistent and widespread effects on snow hydrology. Wildfires are increasing black carbon deposition leading to decreased snow albedo, decreasing snow depths, and as a result, snow is disappearing earlier. Earlier snow disappearance leads to earlier runoff and less water to sustain streamflow throughout the drier summer months. These impacts make forecasting runoff hard and planning for water storage and retention even more difficult. It is imperative that we can incorporate these large-scale landscape disturbances into models to understand snowpack changes in a warming world.

We found that high burn severity has an order of magnitude more black carbon than unburned areas. As a result, snow albedo decreases in high burned areas, especially during ablation. These combined effects, along with increased net shortwave radiation from lack of canopy cover after a fire, lead to snow depth decreasing and snow disappearing nearly three weeks earlier in high burned areas. These impacts were also observed in moderate severity burned areas with decreased snow albedo, snow depth, and snow disappearing over two weeks earlier, while low severity burned areas melted out 11 days earlier. Together, these impacts affect over 4% of all water originating in the Sierra Nevada with low burn severity having the largest spatial impact.

This study emphasizes the importance of burn severity demonstrating that all burned landscapes do not have equal impacts on snowpack processes (Figure 1). The majority of the current literature focuses on either unburned vs. burned or specifically the impacts of high burn severity fire on snowpack retention. The work in this thesis pushes the conversation forward to consider the nuance of burn severity and shows that high severity fires do have a more dramatic effect on snow, but only account for less than 20% of all acres burned and affect only 1% of SWE across the Sierra Nevada. Moderate and Low burn account for nearly 65% of acres burned and impact nearly 3% of SWE across the Sierra Nevada. This study begins to unpack the impacts of moderate and low burn severity and argues for more research to be conducted on these severities.

This study uses the Creek Fire and Upper San Joaquin Watershed as a case study of a large fire that burned over 44% of an important watershed, much of which is in the seasonal snow zone. Part of the analysis also points to the larger impacts across the Sierra Nevada and California. This study contributes to the conversation about the growing impact of wildfires on declining snowpacks, emphasizing the importance of burn severity, but is limited to one watershed. It demonstrates the need for landscape changes from wildfire to be incorporated into operational and research-based models, and SWE reanalysis to fully understand the changes in snowpack and water resource availability. The overlap between wildfire and snow is only going to increase in a warming climate. Therefore, there is an impending need for more research and observations to influence and adjust models to increase accuracy for runoff forecasting.

It is imperative that we understand the regional and broad-scale variability in the impacts of fire on snow. Future studies should focus on other snow climates including the Cascades and the Rocky Mountains to understand the variability across different snowpacks. In addition, conducting a long-term study to assess the impact of different burn severities 5 to 10 years after a fire would help understand how long these different effects last. Expanding this framework to other impacted watersheds such as the Cosumnes River Watershed (North Fork of the American River) that was burned by the Caldor Fire or the Feather River Watershed burned by the Dixie Fire, both in 2021, will provide a better understanding of the physical processes and consistency in the research.

As we continue to assess the damage to water resources caused by wildfires, we must continue to research the impacts of albedo changes on snowpacks. Albedo is a key driver of snowpack energy and control of snow ablation timing and intensity. A good next step to assess these changes would be to implement the different albedo values measured in the field for each burn severity into snowmelt runoff models (e.g., iSNOBAL and SnowModel) and assess melt rates and snow disappearance from a modeling perspective. This would demonstrate the direct impacts albedo changes have on melt rates and perhaps help link these processes to streamflow. Another way to assess impacts on streamflow could be to compare snow-dominated unburned and burned sub-basins that have reliable USGS gauge data. Comparing stream gage data can help understand the immediate impacts of fire on the volume and timing of streamflow in mountain watersheds. Overall, researchers need to continue to understand the sensitivity of watersheds across the western US to fire and the lasting impacts on declining snowpacks.

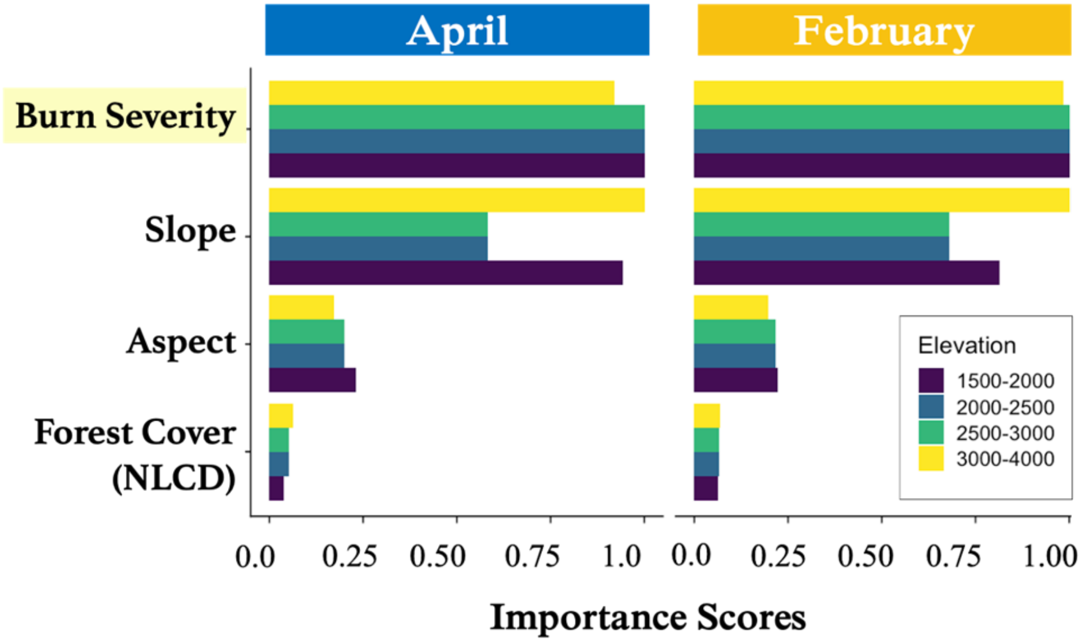
APPENDIX A

SUPPLEMENTAL FIGURES

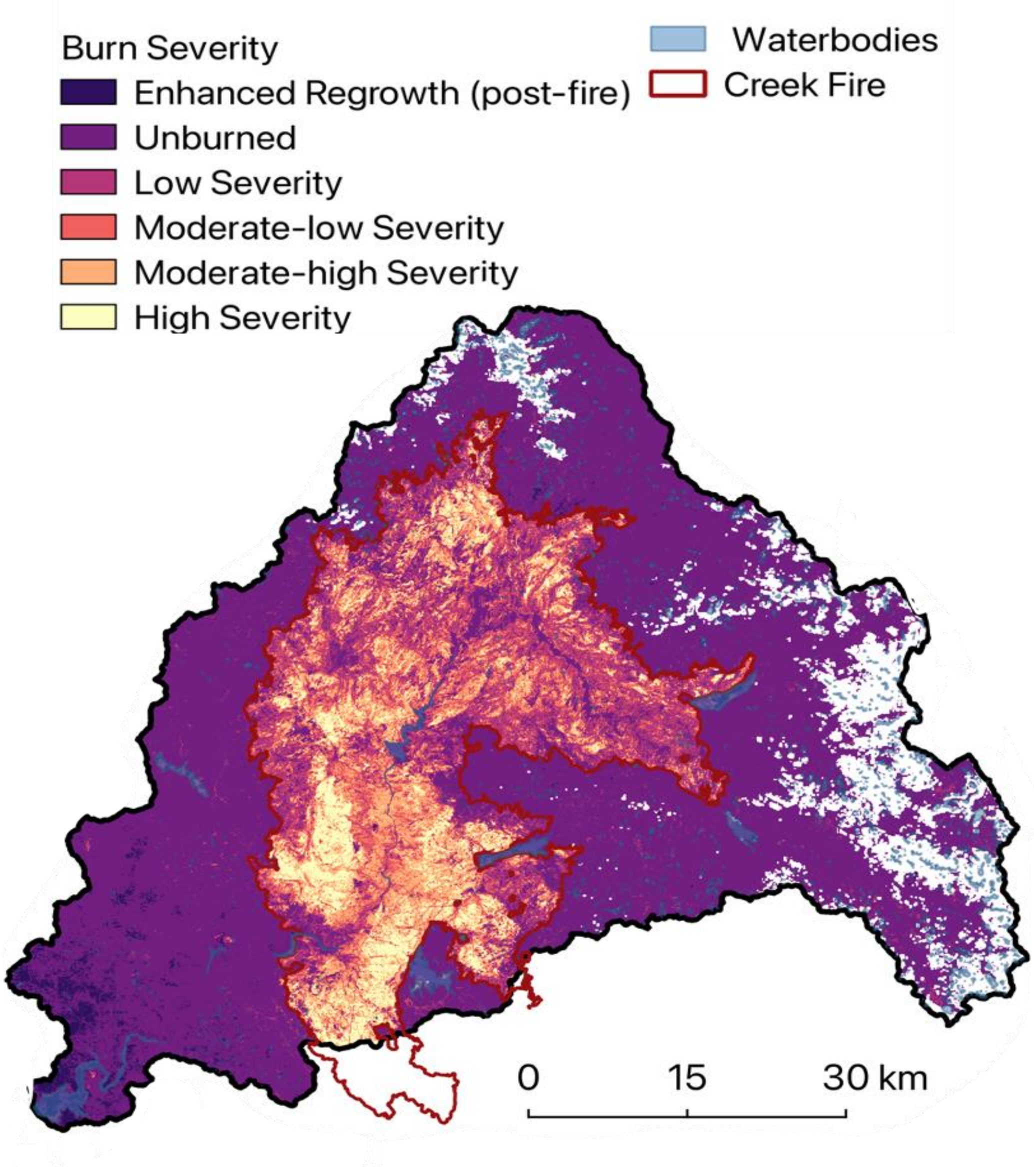
Contents of this file: Figures A.1-A.4

Introduction:

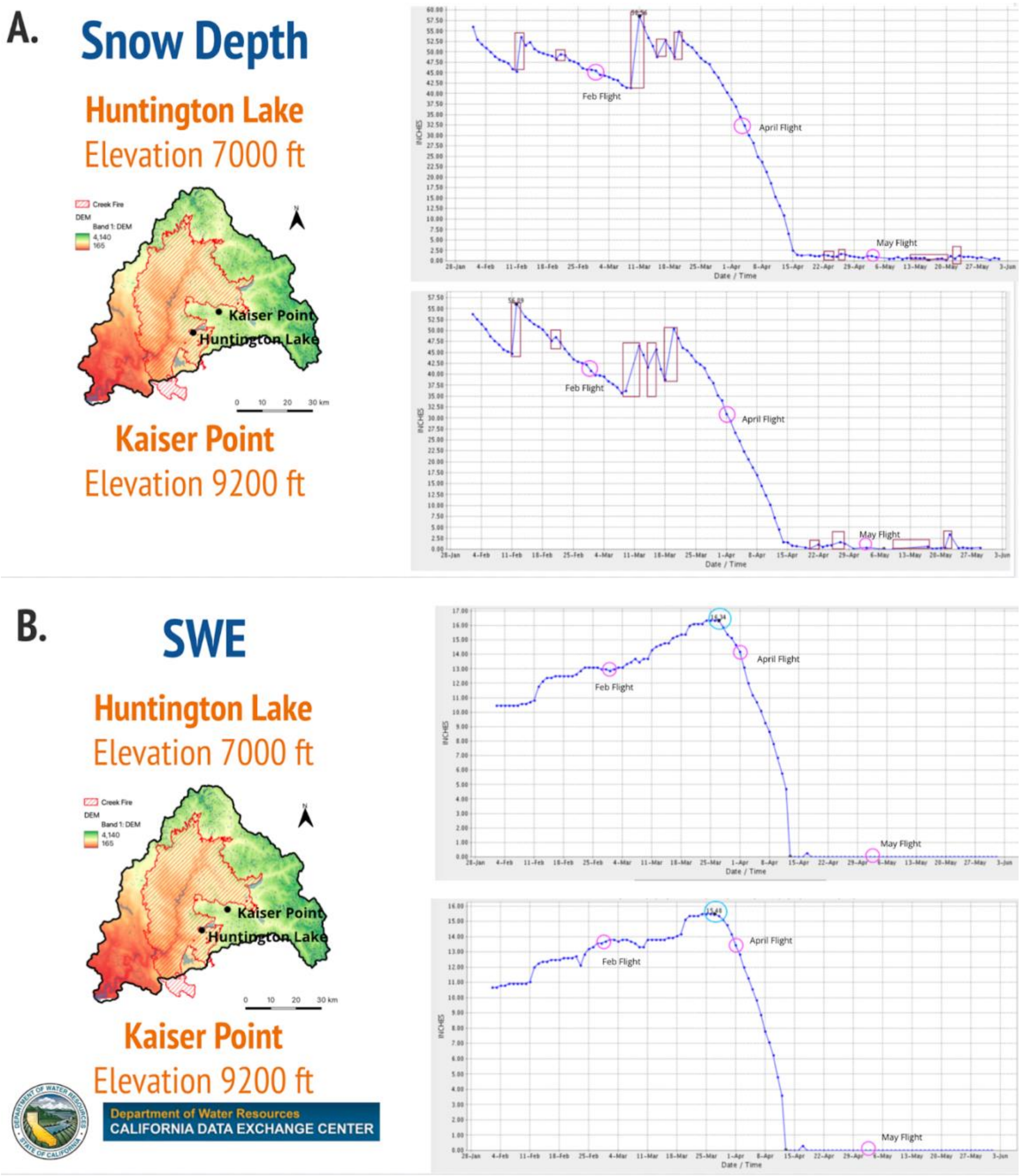
The following figures provide additional information about the research project. Figure A.1 shows the outcomes of a random forest model for predictive snow depth. Figure A.2 shows the pixel distribution overlap for snow and burned pixels. Figure A.3 is a burn severity map generated using dNBR for pre-and post-fire in Google Earth Engine. Figure A.4 provides station data context for the snow depth and SWE for winter 2021 highlighting when ASO flew and peak SWE.



A.1: Random Forest classification algorithm assessing importance scores for four variables to predict snow depth broken down by elevation for both February and April.



A.3: Burn severity map generated using dNBR for July 2019 to July 2020 in Google Earth Engine. This map did not match the forest service map, so the study was performed using the published dataset.



A.3 (A) Snow depth station and (B) SWE data obtain from the California Department of Water Resources for two elevations (Kaiser Point at 9200 ft and Huntington Lake at 7000 ft) in the USJW.

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