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Wildfire Impacts on Snowpack Phenology in a Changing Climate Within the Western U.S.

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Key Points:

- Most Snow Telemetry sites recorded reduced maximum snow water equivalent (SWE) and earlier maximum SWE dates, while nearly all sites had earlier melt-out dates post fire
- The wildfire signal for nearly all ecoregions results in earlier timing and reduced SWE
- Accounting for both climate change and inter-annual precipitation is important when assessing wildfire impacts on snowpack

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Snowpack in the western U.S. is critical for water supply and is threatened by wildfires, which are becoming larger and more common. Numerous studies have examined impacts of wildfire on snow water equivalent (SWE), but many of these studies are limited in the number of observation locations, and they have sometimes produced conflicting results. The objective of this study is to distinguish the net effects of wildfires on snowpack from those of climate. We consider 45 burned sites from the Snow Telemetry network. For each burned site, unburned control sites are identified from the same level III ecoregion. Impacts of climate changes on snowpack are analyzed by comparing pre-fire and post-fire snow water equivalent at the unburned sites. Combined climate and wildfire effects are considered by comparing pre-fire and post-fire SWE at the burned sites. Wildfire impacts are then isolated by taking the difference between the burned and unburned sites. The wildfire-induced changes in SWE are also compared to several possible controlling variables including burn severity, leaf-area index change, dominant pre-fire tree genus, years since the fire, and site elevation. On average, wildfires have advanced melt-out dates 9 days and maximum SWE dates 6 days and reduced annual maximum SWE by 10% across the sites considered. On average, the combined effects of climate and wildfire have advanced melt-out and maximum SWE dates approximately 14 and 10 days, respectively, while decreasing annual maximum SWE by approximately 10%.

Plain Language Summary

Snowpack accumulation and melt are critical for water supply in the western United States. As the number and size of wildfires have increased, it is important to understand how these events impact the seasonal snowpack. Using data from the Snow Telemetery monitoring network, we quantify the impacts of wildfires on snowpack for various regions across the western U.S. and Alaska. The results indicate that decreases in snowpack tend to occur following fires. Also, the snowmelt period usually begins and finishes earlier in the spring due to the conditions in the burned forests. In regions of the western U.S. that are already experiencing earlier snowmelt due to climate changes, wildfires are further shifting the melt earlier, which could have substantial consequences for water supply and flood risks.

1. Introduction

Snowpack is extremely important for agricultural production and domestic water supply in numerous regions of the world. In 2000, approximately one sixth of the world's population lived in snow-dominated, low-reservoir-storage regions (Barnett et al., 2005), and snowmelt contributes a large percentage of the total annual runoff in several major river systems (Barnett et al., 2005; Li et al., 2017; Mankin et al., 2015; Viviroli et al., 2007). The 11 western states within the contiguous U.S. include approximately one fourth of the country's population (U.S. Census Bureau, 2019) and greatly depend on snowmelt for their water supply. Snowmelt has been estimated to account for 75% of the total runoff in the western U.S. (Doesken & Judson, 1996) although estimates range from 53% (Li et al., 2017) to 80% (Stewart et al., 2004).

Changes in the magnitude and timing of snow accumulation and melt (i.e., snowpack phenology) could have trillions of dollars of economic impact in the western U.S. (Sturm et al., 2017). Impacts range from abbreviated winter sports seasons to changes in streamflow timing downstream. The timing and magnitude of peak snow water equivalent (SWE) are key variables in predicting peak streamflow (Clow, 2010; Curry & Zwiers, 2018). The melt rate of the snowpack is a key driver of the summer baseflow conditions (Barnhart et al., 2016) as well as streamflow temperatures (Du et al., 2020), which are important for aquatic ecology.

The snowpack phenology depends on the energy balance of the snowpack, and the snowpack energy balance is highly influenced by the forest canopy (Marks & Winstral, 2001; Musselman et al., 2012; Revuelto et al., 2015;

Varhola et al., 2010). Several studies have considered the net relationship between the canopy and snowpack, but the conclusions about this relationship vary substantially with location. For example, Veatch et al. (2009) found that forest edges strongly influence patterns of snow depth in New Mexico and have greater snow depths than either open or densely forested areas. In contrast, Hubbart et al. (2015) found greater accumulation and later melt-out dates for clear cut areas than forested areas in northern Idaho.

Changes in the canopy can occur for several reasons including tree mortality, drought, and land surface disturbance. The most abrupt of these causes is land surface disturbance, which can include blowdown events, avalanches, and wildfires. A recent review by Goeking and Tarboton (2020) summarizes the impacts of land surface disturbances on several aspects of the water balance. Overall, 34 of 42 studies they summarize found increases in annual maximum SWE following forest disturbances while 10 studies found decreases in annual maximum SWE (some studies reported both increases and decreases). Furthermore, 9 of 13 studies in Canada and the northern U.S. reported consistent increases in annual maximum SWE in response to disturbances. In contrast, only 5 of 13 studies conducted in lower latitudes of the U.S. reported consistent increases (Goeking & Tarboton, 2020).

Among the land surface disturbances, wildfire is of particular concern because it can impact large land areas and because the canopy changes can occur quickly. The occurrence and magnitude of wildfires are increasing in the western U.S. (Dennison et al., 2014; Littell et al., 2009; Westerling et al., 2006). Warmer and drier conditions in the western U.S. in part due to climate change have been found to be an important factor in the increased fire activity (Dennison et al., 2014; Yang et al., 2015). Nearly all studies of wildfire impacts on snowpack have focused on specific regions, and their results vary. Gleason et al. (2018) reported four-fold increase in solar energy absorbed by the snowpack after wildfires, which caused earlier melt-out dates at locations in Colorado, Utah, and Wyoming. Maxwell and St. Clair (2019) investigated whether peak snowpack varies with burn severity or percent overstory tree mortality in a mid-latitude, subalpine forest. They found that peak SWE increased 15% and peak depth 17% for every 20% increase in overstory tree mortality. They also found that slope, basal area, and canopy height did not have a significant influence on the SWE increase. During a 2-year study of the Twitchell Canyon fire in south-central Utah, Maxwell et al. (2018) found that snowpack disappeared earlier in burned areas compared to unburned areas, especially on south-facing slopes. However, peak SWE did not vary between burned and unburned areas. Stevens (2017) examined wildfire impacts on snow accumulation at the stand and tree scales in the Sierra Nevada mountains of California. The unburned forest had the highest overall snowpack depth, and snowpack depth decreased 78% for high severity burn areas. However, within the unburned areas, the depths were greatest in canopy openings. Stevens (2017) also found that open areas had greater average snow depth at the tree scale while unburned areas had a greater average depth at the stand scale. Harpold et al. (2014) evaluated snowpack changes in New Mexico following the Las Conchas Fire. Based on several hundred measurements of snowpack, the burned area had approximately 10% less average SWE than unburned areas. They concluded that a lack of strong vegetation controls in burned areas led to topographically controlled variability at peak snowpack. Overall, it is difficult to get a general picture of wildfire impacts on snowpack because each study focused on different aspects of snowpack, had different quantities and qualities of available data, and performed the comparisons in different ways. Specifically, studies that report pre- versus post-fire comparisons for the same location avoid the confounding effects of spatial heterogeneity of snowpack (Broxton et al., 2016; Sexstone & Fassnacht, 2014). However, that approach combines the effects of wildfire occurrence with any climate changes (i.e., interannual precipitation or temperature changes) during the study period. Anthropogenic climate change is impacting all regions within the western U.S. including observed increases in average annual temperatures (Vose et al., 2017) and decreasing trends in snowpack (Mote et al., 2018; Zeng et al., 2018).

The objective of this study is to distinguish the net effects of wildfires on snowpack from those of climate changes using a consistent methodology for different ecoregions in the western U.S. The study uses Snow Telemetry (SNOTEL) data, which is consistently collected and reported for numerous sites across the western U.S. and Alaska. We identified burned SNOTEL sites along with comparable unburned sites within the same level 3 ecoregions. The SWE records for the burned and unburned sites are divided into pre- and post-fire periods based on the date of the wildfire at the burned site. The difference between the post-fire and pre-fire SWE at the unburned sites is used to analyze the impacts of climate changes (climate signal). The difference between the post-fire and pre-fire snowpack at the burned sites is used to determine the combined impacts of climate changes and wildfires (combined signal). Finally, the difference between the combined and climate signals is used to isolate the effects

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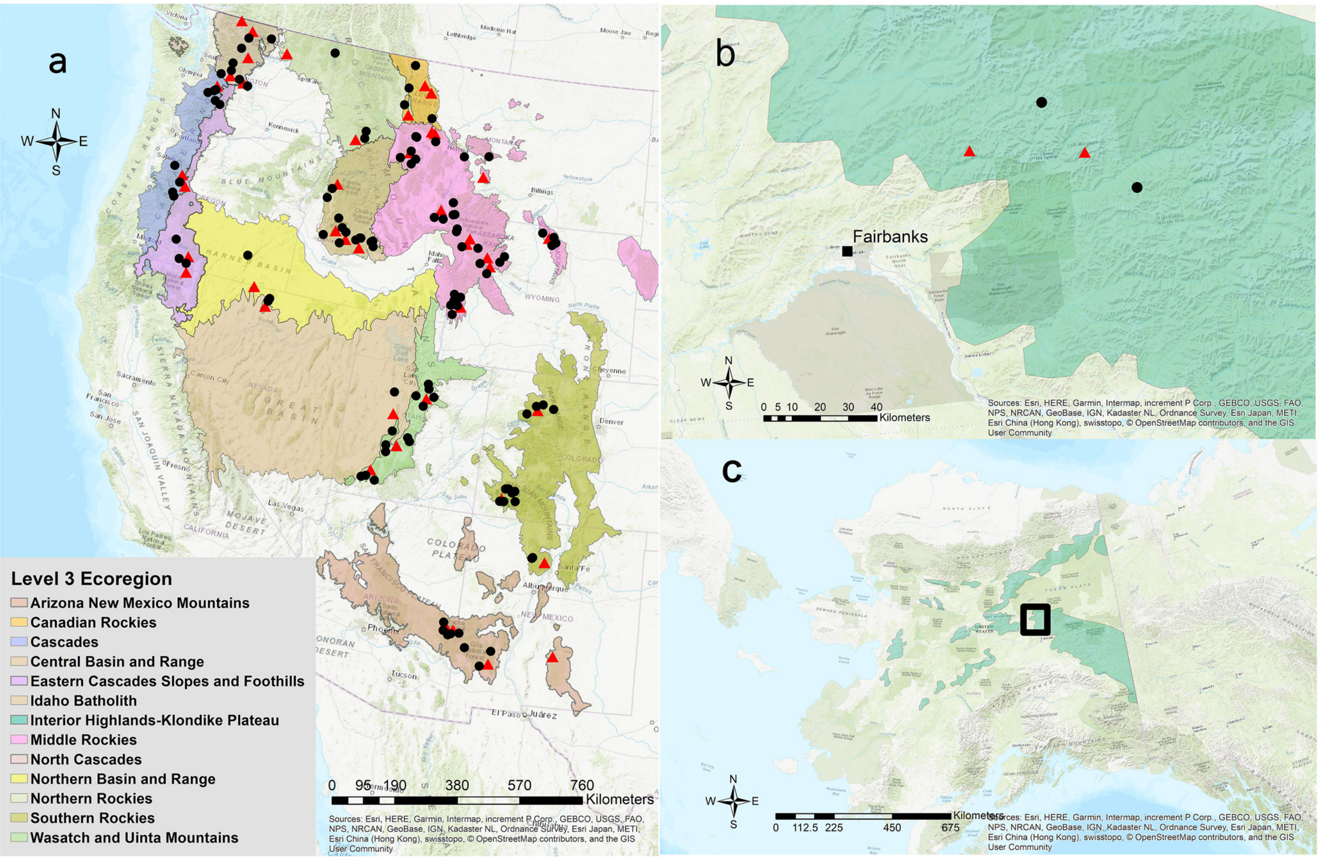

Figure 1. Map of burned (red triangles) and unburned (black circles) SNOTEL sites in (a) western coterminous United States and (b) Alaska. The Alaska sites are located northeast of Fairbanks in the central part of the state (c).

of the wildfires. The results are analyzed first by ecoregion. Then, they are divided by burn severity and other site characteristics to identify potential controls on the impacts of wildfires.

2. Data and Methods

2.1. SNOTEL Data

SNOTEL sites are operated by the Natural Resources Conservation Service (NRCS, 2021) and range from southern New Mexico (latitude 33.4°N) to central Alaska (latitude 65.1°N) (Figure 1). From SNOTEL, we use the daily SWE and precipitation values along with the site elevations. Quality control was performed through visual inspection of the SWE and precipitation time series. Any apparent reporting errors were discussed with local NRCS Snow Survey offices and removed from the analysis if confirmed. Any years with more than 10% of daily precipitation or SWE values missing were removed from the data set. Of the 1576 station-years available for the burned sites, 24 were removed.

Burned locations and dates were determined based on information provided by each NRCS Snow Survey Data Collection Office. Through 2019, 45 sites were identified as being directly impacted by wildfires across the entire network. Figure 2 shows the periods when both SWE and precipitation data are available for each burned site. The date each site burned is also shown on the timeline. The average pre-fire period is approximately 23 years with over 87% of the burned sites having at least 10 years. The average post-fire period is approximately 12 years with 44% of the sites having at least 10 years. Additional information about each burned site is provided in Table S1 in Supporting Information S1 (Giovando, 2022a).

For each burned site, at least two similar SNOTEL sites were identified that were not burned. The unburned sites were selected to be in the same level 3 ecoregion. A level 3 ecoregion represents a region that is similar in

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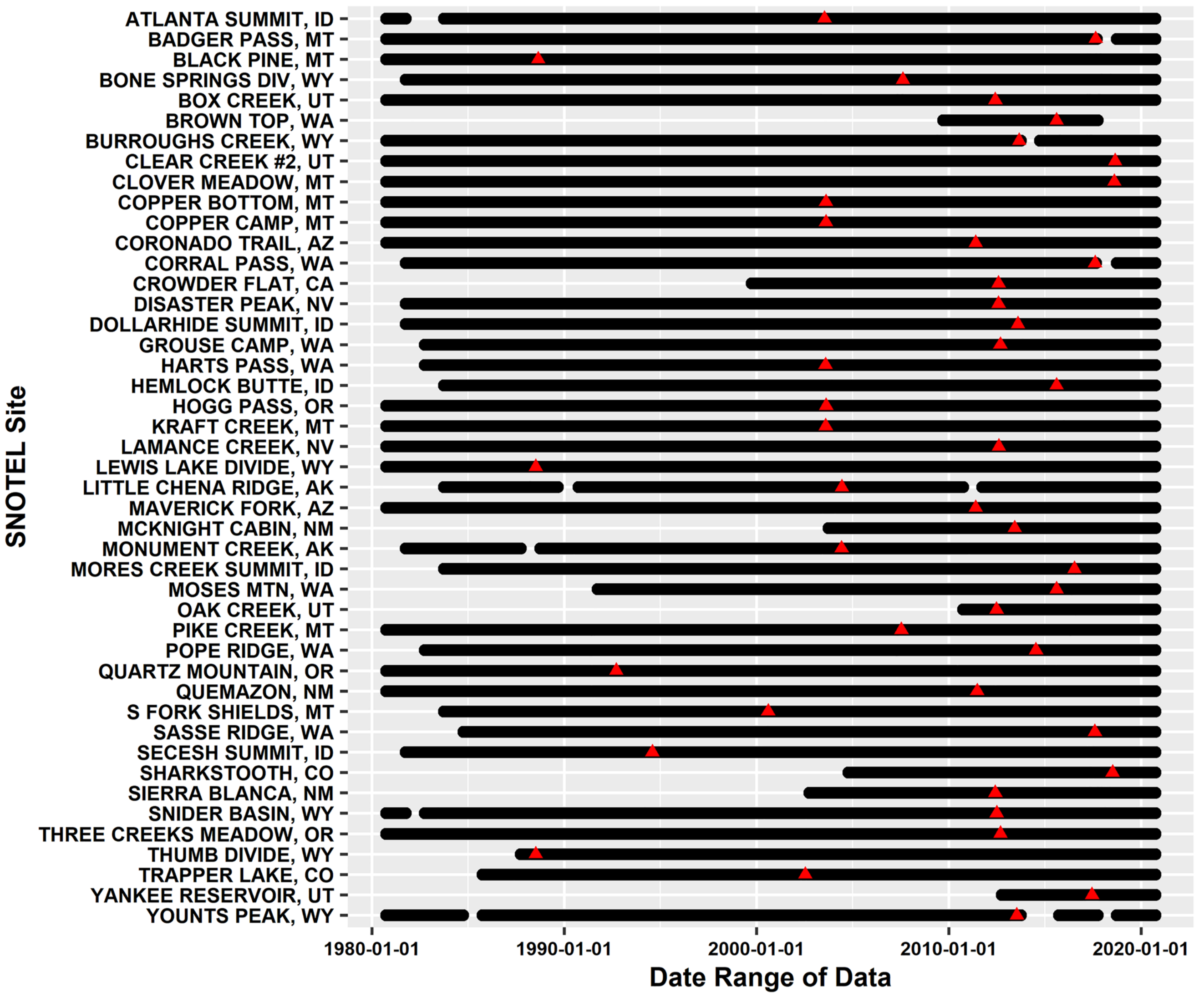

Figure 2. Period of record used for each burned SNOTEL site. The red triangles identify the wildfire dates.

geology, physiography, vegetation, climate, and soils (Omernik & Griffith, 2014). For approximately 80% of the burned locations, we identified at least two unburned sites within a distance of 50 km and an elevation difference of ±300 m. The remaining unburned sites required expansion of the search radius or elevation range. The sites that did not meet the initial search criteria are noted in Table S2 in Supporting Information S1.

In this study, the use of nearby unburned sites is interpreted as being representative of the expected behavior of the nearby burned site had the fire not occurred. Because the SNOTEL network was developed without any intentional pairing of sites, nearby sites are not exact analogs to the burned sites. The similarity of the SWE at the nearby unburned sites to the SWE at the associated burned sites was investigated for the pre-fire periods using the Kling-Gupta efficiency (KGE) (Gupta et al., 2009). The average KGE of the selected unburned sites is 0.84, which suggests that they are usually reasonable estimates of the burned site behavior for the pre-fire period and thus reasonable comparison sites. The KGE values of the selected unburned sites are also generally higher than more distant sites that were not used (see Table S3 in Supporting Information S1 for complete KGE values).

The time series for each of the 110 unburned sites was divided based on the fire date of the associated burned site (Giovando, 2022b). For example, if a site has a period of record from 1985 to 2019 and was burned at the end of 2007, then the pre-fire period at this site would be 1985 through 2007 and the post-wildfire period would be 2008 through 2019. This same division would be used at all unburned locations associated with the burned site.

2.2. Site Characteristics

Pre-wildfire tree genus and canopy density were considered as potential mediators of wildfire's impact on SWE. U.S. Department of Agriculture Forest Service (USDA-FS) Forest Inventory and Analysis (FIA) data from 2017 were used to obtain the dominant tree genus for the area around each burned SNOTEL location (FIA data were not available for all pre-fire periods). The date of the data set may reduce the data's explanatory power if the dominant tree genus changed after the fire. However, the FIA data set provides consistent forest stand level information on the extent, distribution, and forest composition (Burrill et al., 2018). The dominant tree genus was determined as the most common genus in a 1 km^2 box centered on the burned SNOTEL site (Table S1). Frequently occurring genera were pine (*Pinus*), fir (includes both *Abies* and *Pseudotsuga*), and spruce (*Picea*). Only three sites were hemlock (*Tsuga*), and three sites were other genera. For analysis purposes, those six sites are grouped as "hemlock/other."

Canopy density was quantified using leaf-area index (LAI), which for coniferous canopies is defined as one-half the total needle surface area per unit ground area (Jonckheere et al., 2004). We used the MODIS 8-day 500 m (MCD15A2H) LAI product (Myneni et al., 2015), which has good agreement when compared with ground-based measurements of LAI (Jensen et al., 2011). The phenology of the canopy can cause LAI to vary seasonally. Because winter LAI is most relevant to snowpack (Xiao et al., 2019), LAI values from the beginning of October were used for all locations (LAI from summer dates were also used in the analysis and produced similar results). The October LAI represents the beginning of the snow accumulation season and the lowest LAI prior to snow cover (Yang et al., 2006). The average pre-fire and post-fire LAI values at the burned SNOTEL sites are 5.0 and 3.1, respectively. The change in LAI was calculated by subtracting the October LAI that immediately followed the fire from the October LAI that immediately preceded the fire. Due to the limited period of MODIS observations, LAI was not available for fires that occurred prior to 2003. Therefore only 37 of the 45 burned sites are used in analyses that consider LAI.

Burn severity was obtained from the Monitoring Trends in Burn Severity program (MTBS) (https://www.mtbs.gov/project-overview). This program is an inter-agency effort led by the USDA-FS and the U.S. Geological Survey with the goal of providing consistent categorized burn severity information for all fires since 1984 (Eidenshink et al., 2007). In the western U.S., the MTBS information is available through 2019 for fires greater than 1,000 acres. Burn severity from MTBS has been used in other studies that examined patterns and impacts of burn severity on the landscape (Arkle et al., 2012; Baker, 2015; Bradley et al., 2016). For our study, the categorical burn severity (i.e., low, moderate, and high) was used, which is based on threshold values of the differenced Normalized Burn Ratio (dNBR) (Eidenshink et al., 2007). Burn severity is defined as the loss of above ground organic matter and organic matter in the soil (Keeley, 2009). The near infrared and shortwave infrared wavelengths are used to quantify NBR, and the difference between pre-fire and post-fire values is the final dNBR estimate. The consistency of these categories between fires has been questioned (Kolden et al., 2015), but Meigs et al. (2011) showed that the MTBS burn severity categorization is related to tree mortality, so it can indicate the change in canopy condition during the snow season. Picotte et al. (2020) also noted that the MTBS program uses various measures to promote consistency between analysts. Due to the temporal and spatial extents of the SNOTEL data set and associated fires, the MTBS data burn severity categories provide the most consistent data available.

2.3. Summary Methods

Four measures are used to quantify the snow phenology: (a) annual maximum SWE, (b) annual maximum normalized SWE (nSWE), (c) date of annual maximum SWE, and (d) annual melt-out date. The annual maximum SWE was determined using a 01 October through 30 September water year. If the maximum value occurred over multiple dates, the first date was selected. nSWE normalizes the SWE to account for interannual variations in precipitation. The annual maximum nSWE was calculated as the maximum SWE divided by the total October through April precipitation. The melt-out date is identified as the first day when SWE equaled zero. For each measure of snow phenology, median values were calculated for the pre- and post-fire periods. Then, the difference between the post-fire and pre-fire medians was calculated. The difference was evaluated at each burned and unburned site. An average of individual unburned sites associated with the specific burned sites was used for comparison. At unburned sites, this change is expected to reflect changes in climate between the two periods. At burned sites, this change reflects the combined changes in climate and the effects of the wildfire. To isolate the effect of the fire, we calculated the fire signal as the difference between the change at the burned sites and the unburned sites. The

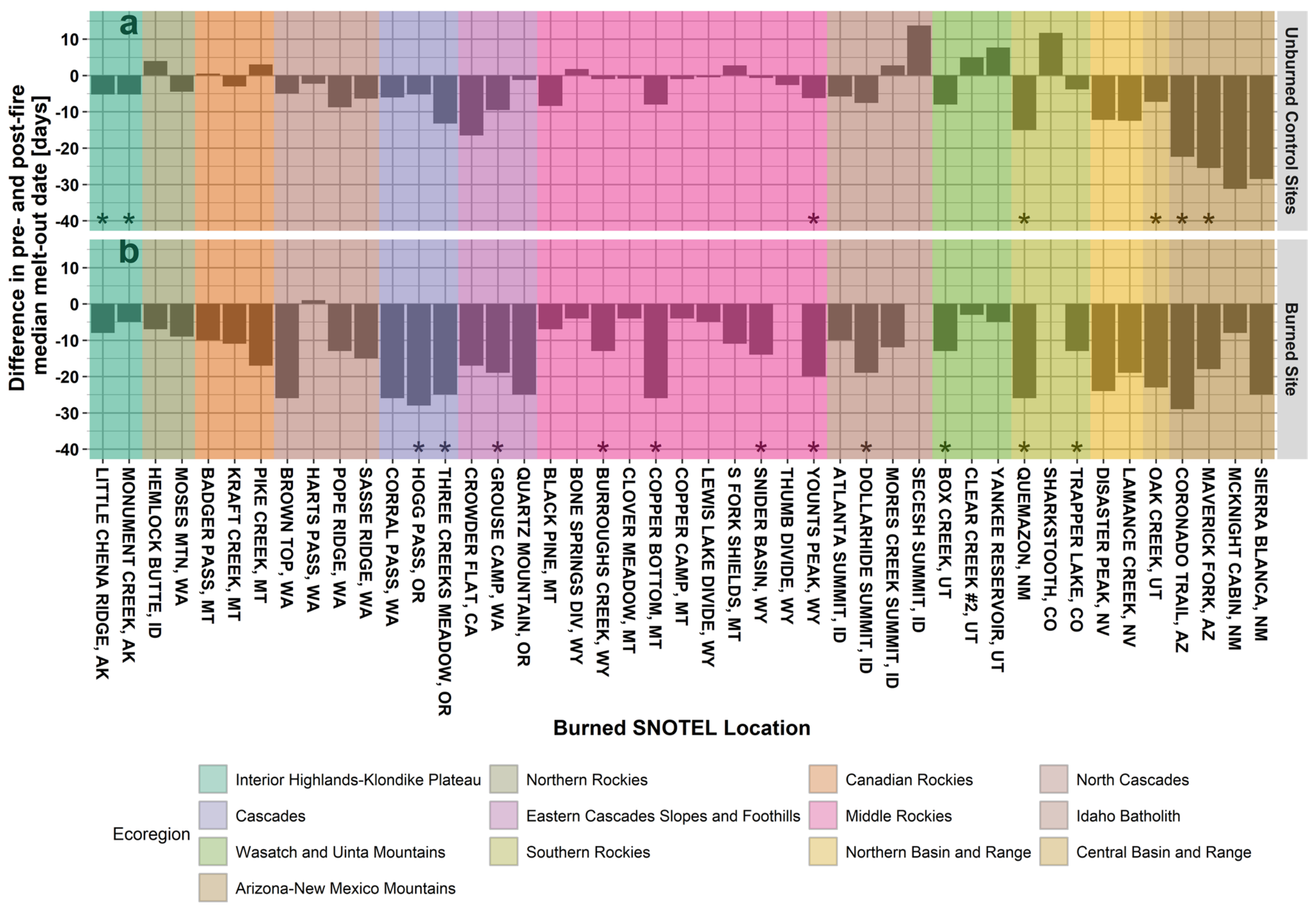

Figure 3. Difference in pre- and post-fire melt-out dates at (a) unburned control sites and (b) associated burned sites. For each unburned site, the difference is calculated using the similar pre- and post-fire periods for the associated burned SNOTEL site listed. A negative value indicates an earlier melt-out date post-fire than pre-fire. An asterisk indicates a statistically significant (p-value < 0.05) difference between the pre- and post-fire periods. Ecoregions are listed approximately from northwest to southeast (see Figure 1).

use of differences in these comparisons assumes that the impacts of climate changes and wildfires are additive. This assumption has also been made in other studies which analyze several years of post-wildfire data (Gleason et al., 2018; Hallema et al., 2018; Micheletty et al., 2014).

To assess the significance of the changes, the non-parametric Wilcoxon Rank Sum Test was applied to evaluate the hypothesis that the snow phenology measures from the pre- and post-fire periods are drawn from the same populations (Helsel et al., 2020). The test was applied both the burned and unburned sites and significance was determined using a p-value of 0.05.

3. Results

3.1. Changes in Snow Phenology Measures

The changes in median melt-out dates between the pre-fire and post-fire periods are shown in Figure 3. The sites are also grouped by level 3 ecoregions (Omernik & Griffith, 2014) to examine the behavior for regions that are similar in geology, physiography, vegetation, climate, and soil. Overall, 78% of the unburned locations had earlier melt-out dates for their post-fire periods than their pre-fire periods (Figure 3a). The sites in the Arizona-New Mexico Mountains ecoregion in particularly had much earlier melt-out dates for the post-fire periods. Some site-to-site variability is observed within ecoregions (e.g., 5 of the 12 ecoregions contain sites with later post-fire melt-out dates), but the changes tend to be similar within ecoregions. Overall, the results suggest that the climate during the post-fire periods was less favorable to late season snowpack than the pre-fire period for most ecoregions.

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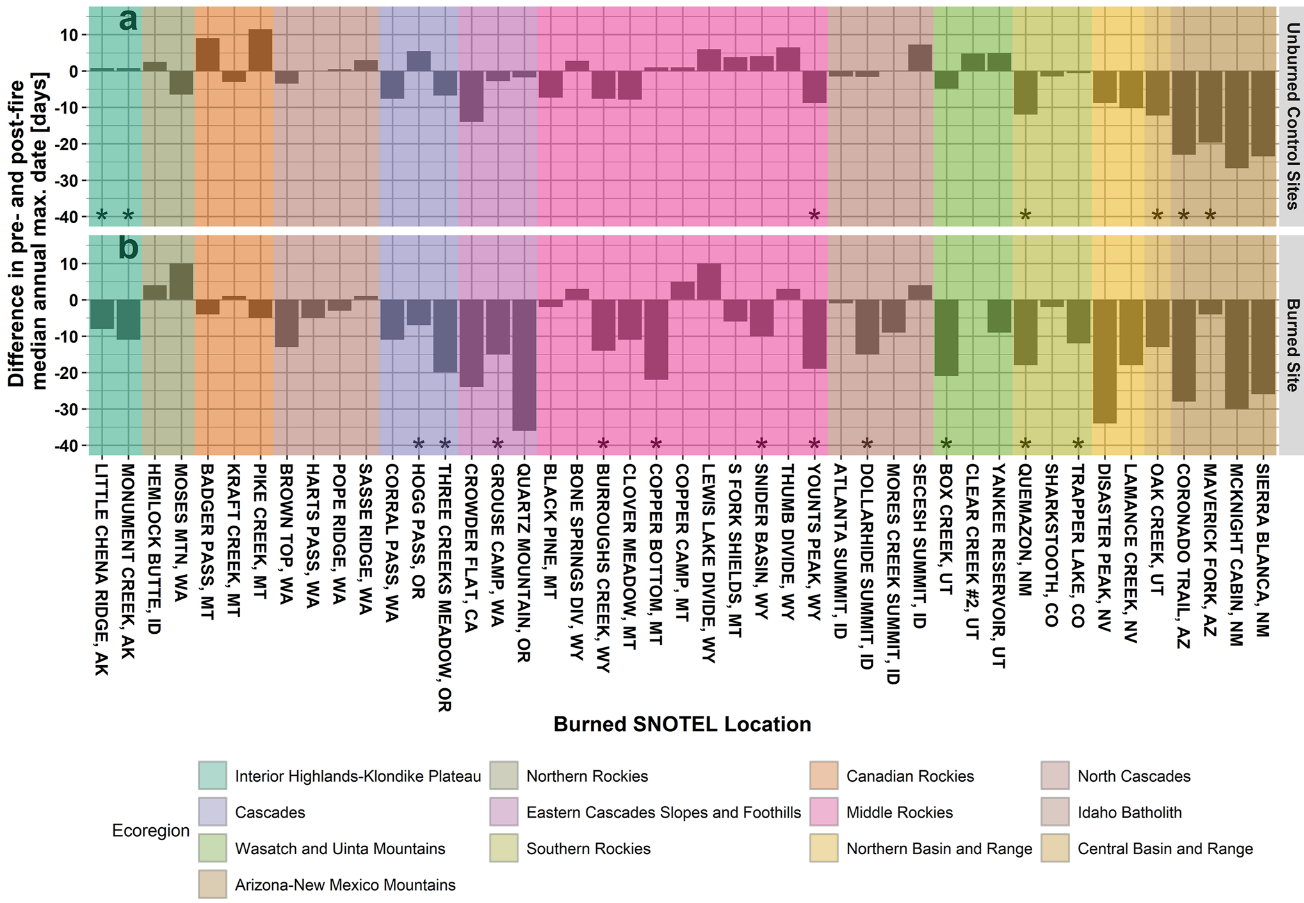

Figure 4. Difference in median dates of maximum snow water equivalent (SWE) for pre- and post-fire periods and (a) unburned control sites and (b) associated burned sites. For each unburned site, the difference is calculated using the similar pre- and post-fire periods for the associated burned SNOTEL site listed. A negative value indicates an earlier date of maximum SWE post-fire than pre-fire. An asterisk indicates a statistically significant (p-value < 0.05) difference between the pre- and post-fire periods. Ecoregions are listed from approximately from northwest to southeast.

In contrast, the burned SNOTEL sites almost uniformly (42 of 45 sites and all ecoregions) had earlier melt-out dates for their post-fire periods (Figure 3b). About half of the ecoregions contain one or more burned sites where the change in melt-out date is statistically significant according to the test described earlier. At the 11 statistically significant sites, the melt-out dates advanced on average 20 days. The change in the melt-out date is also more negative at the burned sites than the unburned sites. Overall, 84% (38 out of 45) burned sites had larger changes in melt-out date than the unburned comparison sites. The earlier melt-out dates likely occur in part because the wildfires reduce the canopy coverage and decrease the snowpack albedo (due to pyrogenic carbon particles and burned wood debris), both of which increase the available energy and promote snowmelt (Gleason et al., 2013).

The changes in the median date of maximum SWE between the post-fire and pre-fire periods are presented in Figure 4 for both the unburned and burned sites. A weak majority of unburned sites (56%) had earlier maximum SWE dates for the post-fire period than the pre-fire period (Figure 4a). Clear differences are observed in the behavior of different ecoregions. The northernmost ecoregions (left side of figure) typically had later maximum SWE dates for the post-fire period while the southern ecoregions (right side of figure) typically had earlier maximum SWE dates. Sites that had earlier post-fire melt-out dates (Figure 3a) also tended to have earlier maximum SWE dates (Figure 4a), and the average magnitude of change is often similar. This similarity suggests that the factors producing the changes at the unburned sites (likely precipitation and temperature changes) are similarly impacting both the accumulation and ablation periods for the snowpack.

Most burned sites (78% or 35 out of 45) had earlier maximum SWE dates post-fire than pre-fire (Figure 4b). About half the ecoregions contain one or more sites where the change in maximum SWE date is statistically

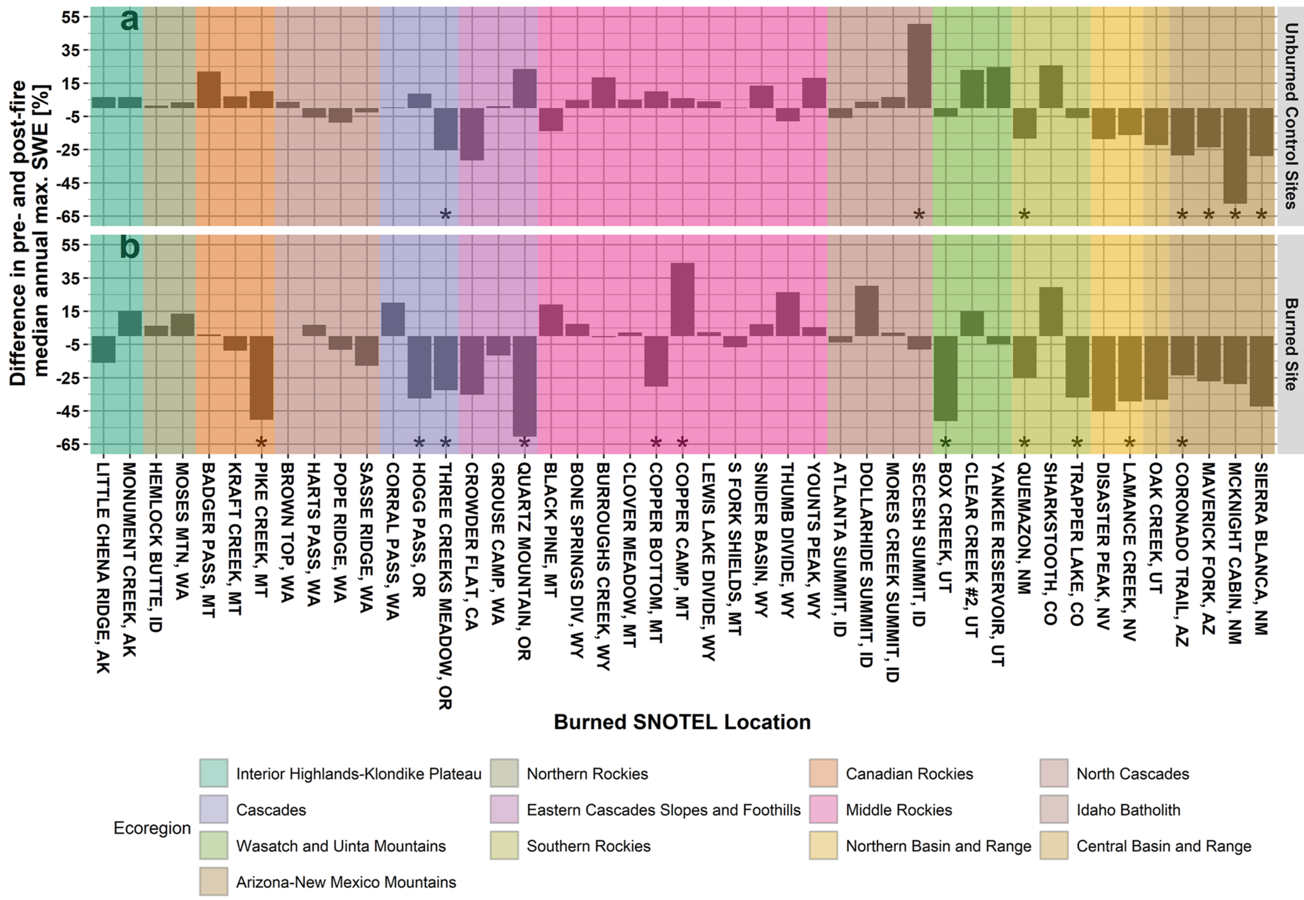

Figure 5. Percent difference in median annual maximum snow water equivalent (SWE) for pre- and post-fire periods for burned and unburned sites. The average percent difference for unburned sites is based on similar pre- and post-fire periods for the associated burned SNOTEL site listed. Negative value indicates lower SWE post-fire. An asterisk indicates a statistically significant (p-value < 0.05) difference between the pre- and post-fire periods.

significant. At the 11 statistically significant sites, the maximum SWE occurred on average 13 days earlier. Overall, the values are more negative for the burned sites than the unburned sites. The burned sites also exhibit more variability within ecoregions than the unburned sites. Within a given ecoregion, the unburned canopy may promote similarity between sites because the dominant vegetation type is one criterion for defining ecoregions.

The changes in the maximum depth of SWE between the pre-fire and post-fire periods are shown in Figure 5. Overall, 62% of unburned sites (28 out of 45) had an increase in maximum SWE for the post-fire period (Figure 5a). Thus, the earlier melt-out and maximum SWE dates are not necessarily associated with lower maximum SWE values. For the unburned sites, the direction and magnitude of change tends to be similar within a given ecoregion, but it varies notably between ecoregions. The largest changes are observed in the southern ecoregions (Northern Basin and Range, Southern Basin and Range, and Arizona-New Mexico Mountains). The large differences in these ecoregions suggests that precipitation and/or temperature differed substantially between the pre- and post-fire periods.

In contrast to the unburned sites, 60% of burned sites (27 out of 45) had reductions in maximum SWE in the post-fire periods (Figure 5b), and 8 of 13 ecoregions contain one or more sites where the change was statistically significant. At the 11 statistically significant sites, the maximum SWE decrease on average 26%. More site-to-site variability is observed within ecoregions for the burned sites than the unburned sites with some locations having very large changes in the maximum SWE. These results suggest that the change in maximum SWE from a single burned location may not be representative of other burned parts of an ecoregion.

The change in annual maximum nSWE between the post-fire and pre-fire periods is shown in Figure 6. Inter-annual precipitation variations are reduced when using nSWE in the analysis, so the remaining differences

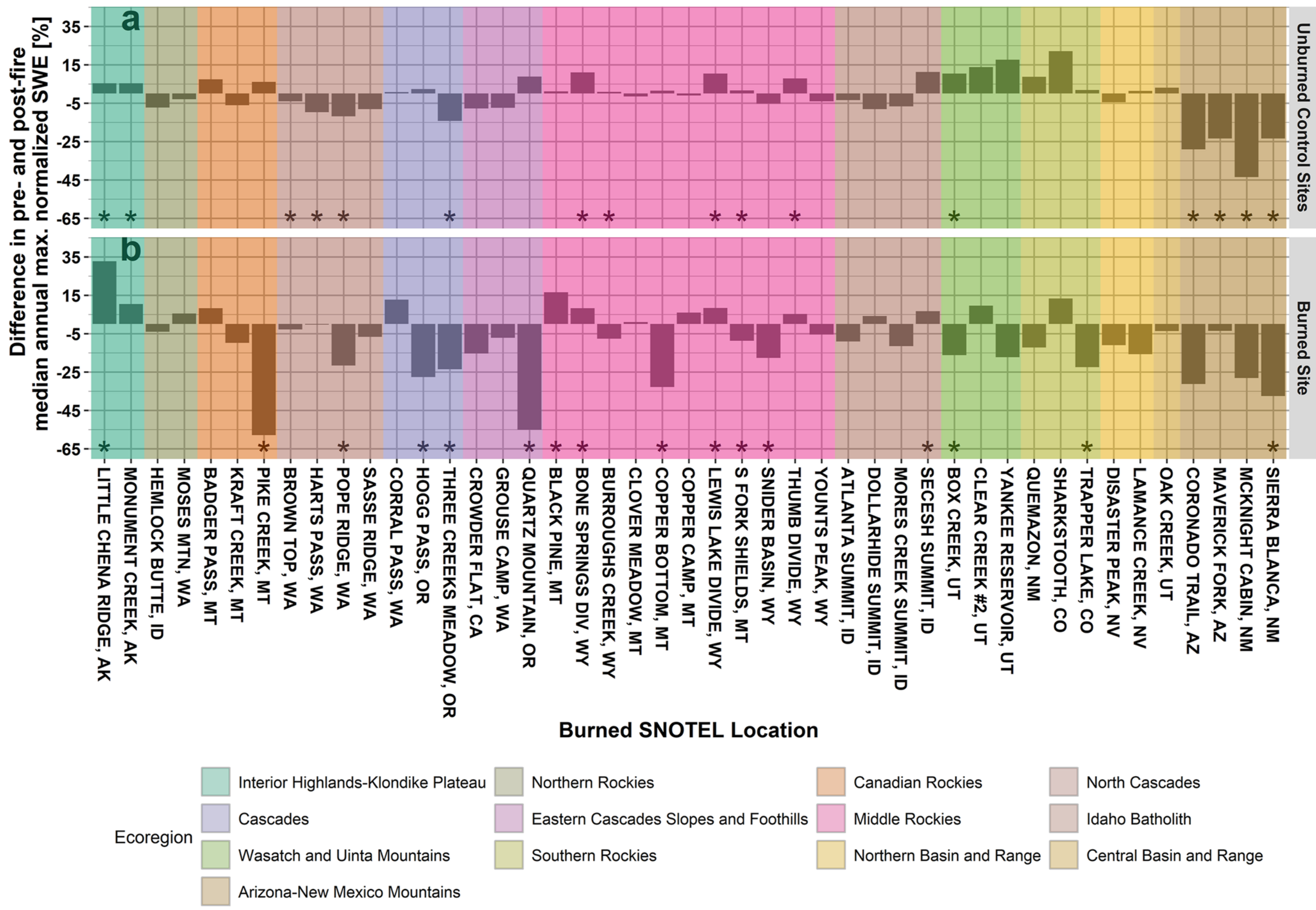

Figure 6. Percent difference in annual maximum nSWE between pre- and post-fire periods. The average percent difference for unburned sites is based on similar pre- and post-fire periods for the associated burned SNOTEL listed. Negative value indicates lower nSWE post-fire. An asterisk indicates a statistically significant (p-value < 0.05) difference between the pre- and post-fire periods.

at the unburned sites reflect changes in other climatic factors. Slightly less than half (49% or 22 out of 45) of the unburned sites had decreases in maximum nSWE between the pre- and post-fire periods, and in most ecoregions, the changes in nSWE are small. Thus, differences in precipitation between the two periods primarily caused changes in the maximum SWE at the unburned sites. However, for the Arizona-New Mexico Mountains, large changes are still observed in nSWE between the pre- and post-fire periods. This persistence suggests other climate factors (such as wintertime temperature) are the main sources of change in maximum SWE for this ecoregion.

Maximum nSWE decreased in the post-fire periods for approximately 67% (30 out of 45) of the burned sites, and 10 of 13 ecoregions contain at least one site where the difference is statistically significant. At the 16 statistically significant sites, the nSWE decreased on average 16%. While most burned sites had decreases in maximum nSWE, most ecoregions also include sites where the maximum nSWE increased. The exceptions are the most northern and southern ecoregions considered. The Interior Highlands-Klondike Plateau in Alaska had consistent increases in nSWE while the Arizona-New Mexico Mountains had consistent decreases in nSWE.

Table 1 summarizes the average change between the pre- and post-fire periods for the unburned and burned sites by ecoregion. The climate signal results consider the unburned sites. They show that the melt-out and maximum SWE dates advanced by averages of 6 and 4 days, respectively, for the post-fire period when all ecoregions are combined. The climate signal also reduced maximum SWE values for the post-fire period by an average of about 2%. For regions within the Cold Desert level 2 ecoregion (10.1), climate-related reductions in maximum SWE are largely explained by reductions in precipitation. This is apparent because the reductions in nSWE are much smaller than the reductions in SWE. The efficiency of snowpack production changed little between the two periods. In the Upper Gila Mountains level 2 ecoregion (13.1), the change in maximum SWE is mostly unrelated to

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Table 1
Average Changes in the Melt-Out Date, Date of Maximum Snow Water Equivalent (SWE), Maximum SWE, and Normalized Maximum SWE Within Ecoregions

Ecoregion		Climate signal					Combined signal					Wildfire signal				
		Post-fire minus pre-fire at unburned sites					Post-fire minus pre-fire at burned sites					Burned diff. Minus unburned diff.				
Number	Name	Melt-out date [days]	Max. SWE date [days]	Max. SWE [%]	Max. nSWE [%]	Number of unburned sites	Melt-out date [days]	Max. SWE date [days]	Max. SWE [%]	Max. nSWE [%]	Number of burned sites	Melt-out date [days]	Max. SWE date [days]	Max. SWE [%]	Max. nSWE [%]	Number of burned sites
6.1.1	Interior Highlands-Klondike Plateau	−5	1	7.3	6.0	2	−6	−9	−4.3	22.9	2	−1	−10	−11.5	16.9	2
6.2.3	Northern Rockies	0	−2	2.8	−4.7	2	−8	7	9.8	0.7	1	−8	9	7.0	5.4	1
6.2.4	Canadian Rockies	0	6	13.3	2.6	4	−13	−3	−19.4	−19.8	3	−13	−9	−32.7	−22.4	3
6.2.5	North Cascades	−6	0	−4.1	−8.5	7	−13	−5	−4.8	−7.8	5	−8	−5	−0.8	0.6	5
6.2.7	Cascades	−8	−3	−4.1	−2.7	8	−26*	−13*	−16.7*	−12.8*	3	−18	−9	−12.6	−10.1	3
6.2.8	Eastern Cascades Slopes and Foothills	−9	−6	−1.1	−0.9	4	−20	−25	−35.9	−25.9	3	−11	−19	−34.8	−24.9	3
6.2.10	Middle Rockies	−2	0	7.6	3.2	32	−10	−6	6.9	−2.4*	11	−8	−5	−0.7	−5.7	11
6.2.15	Idaho Batholith	1	1	13.6	−1.6	13	−10	−5	5.1	−2.4	4	−11	−6	−8.5	−0.8	4
6.2.13	Wasatch and Uinta Mountains	2	2	15.4	14.9	12	−7	−10	−13.7	−8.0	3	−9	−12	−29.1	−22.9	3
6.2.14	Southern Rockies	−2	−5	0.8	11.1	13	−13*	−11*	−10.9*	−7.1	3	−11	−6	−11.7	−18.2	3
10.1.3	Northern Basin and Range	−12	−10	−13.5	−1.2	3	−21	−26	−42.4	−13.4	2	−9	−16	−28.9	−12.2	2
10.1.5	Central Basin and Range	−7	−12	−25.0	3.3	2	−23	−13	−38.3	−3.7	1	−16	0	−13.4	−7.1	1
13.1.1	Arizona-New Mexico Mountains	−27	−23	−37.6	−30.2	8	−20	−22	−30.6	−25.1	4	7	1	7.0	5.1	4
	Average	−5.8	−4.0	−1.9	−0.7		−14.7	−10.8	−15.0	−8.1		−8.9	−6.7	−13.1	−7.4	
	Median	−5.0	−2.0	0.8	−0.9		−13.0	−10.0	−13.7	−7.8		−9.0	−6.0	−11.7	−7.1	

Note. The climate signal section calculates the changes using the unburned sites, and the combined signal section uses the burned sites. The wildfire signal section takes the difference of the combined and climate signals. An asterisk indicates more than half of the burned sites within the ecoregion had statistically significant changes (p-value < 0.05).

precipitation changes. In the Boreal Cordillera level 2 ecoregion (6.2), SWE changes are due to a combination of precipitation and other factors. The largest changes in SWE properties occurred in southern part of the Boreal Cordillera (6.2) ecoregion and the Cold Desert (10.1) and Upper Gila Mountain (13.1) ecoregions.

The combined signal results in Table 1 considers the burned sites. Overall, the largest changes in the snow phenology measures occurred in the Cascades, Eastern Cascades Slopes and Foothills, and Southern Rockies level 3 ecoregions. For the Cascades and Southern Rockies, a majority of sites exhibited statistically significant changes for the phenological measures.

The wildfire signal results are derived by taking the difference between the combined signal (burned sites) and climate signal (unburned sites). Overall, wildfires advanced melt-out and peak SWE dates in the ecoregions by averages of 9 and 7 days, respectively. In addition, wildfires reduced peak SWE values in the ecoregions by an average of about 13%. While these reductions varied by ecoregion, nearly all ecoregions experienced an average reduction. The changes in melt-out and maximum SWE dates are more consistent across ecoregions than the changes in maximum SWE. The maximum SWE changes ranged from −35% to 7% between the ecoregions. Overall, the wildfires had stronger impacts on SWE properties than climate changes during the period of study.

3.2. Potential Controls on SWE Changes

In this section, we examine whether the effects of wildfire on SWE phenology can be explained by information that is readily available after a wildfire. Similar to Table 1, the change in the snow phenology measures between the pre-fire and post-fire periods is calculated first. At the unburned sites, this difference is considered a climate signal, and at the burned sites, this difference is a combined wildfire and climate signal. The wildfire signal is then obtained by comparing the changes at the unburned and burned sites. The readily available information includes the burn severity, change in LAI, dominant pre-fire tree genus, time since the fire, and land surface elevation.

3.2.1. Burn Severity

Figure 7 compares the changes in the snow phenology measures at the unburned and burned sites when the sites are grouped according to the burn severity (at the burned site). In Figures 7a and 7b, the unburned sites typically exhibit negative values, which suggests that those sites typically had earlier melt-out and maximum SWE dates in the post-fire period (due to changes in the climate). However, the burned sites are typically more negative, which suggests that the wildfires typically advanced the dates further. The effect of the wildfire is seen for all three burn severity categories and does not appear to depend on the burn severity (i.e., the differences of the average values for the unburned and burned sites does not exhibit a clear trend with changing burn severity). Similarly, Figures 7c and 7d show that the wildfires typically reduced SWE and nSWE for all burn severity categories with no clear dependence on burn severity.

3.2.2. Leaf-Area Index

Figure 8 compares the changes in snow phenology measures at the unburned and burned sites when the sites are grouped by the change in burned site LAI. The difference between the unburned and burned sites suggests that wildfires typically promoted earlier melt-out and maximum SWE dates when LAI decreased (Figures 8a and 8b). However, the burned sites typically had earlier melt-out and peak SWE dates than the unburned sites even if LAI increased at the burned site. All three sites in this LAI category (Mores Creek Summit, Bone Springs Divide, and Brown Top) had below normal annual precipitation immediately preceding the fire and above normal annual precipitation immediately post-fire. Therefore, the apparent dependence on LAI for these sites is partially due to local precipitation variations. Figures 8c and 8d suggest that more substantial LAI decreases at the burned sites tended to produce more substantial reductions in maximum SWE and nSWE. In particular, when LAI decreased by more than 1.5, the average difference between the unburned and burned sites was 13% and 9% for maximum SWE and nSWE, respectively. Smaller reductions in LAI are associated with much smaller average differences between the unburned and burned sites (2%–4%).

3.2.3. Tree Genus

Figure 9 compares the change in the snow phenology measures for the unburned and burned sites when the sites are grouped by dominant pre-fire trees genus. For melt-out dates (Figure 9a), substantial differences in behavior

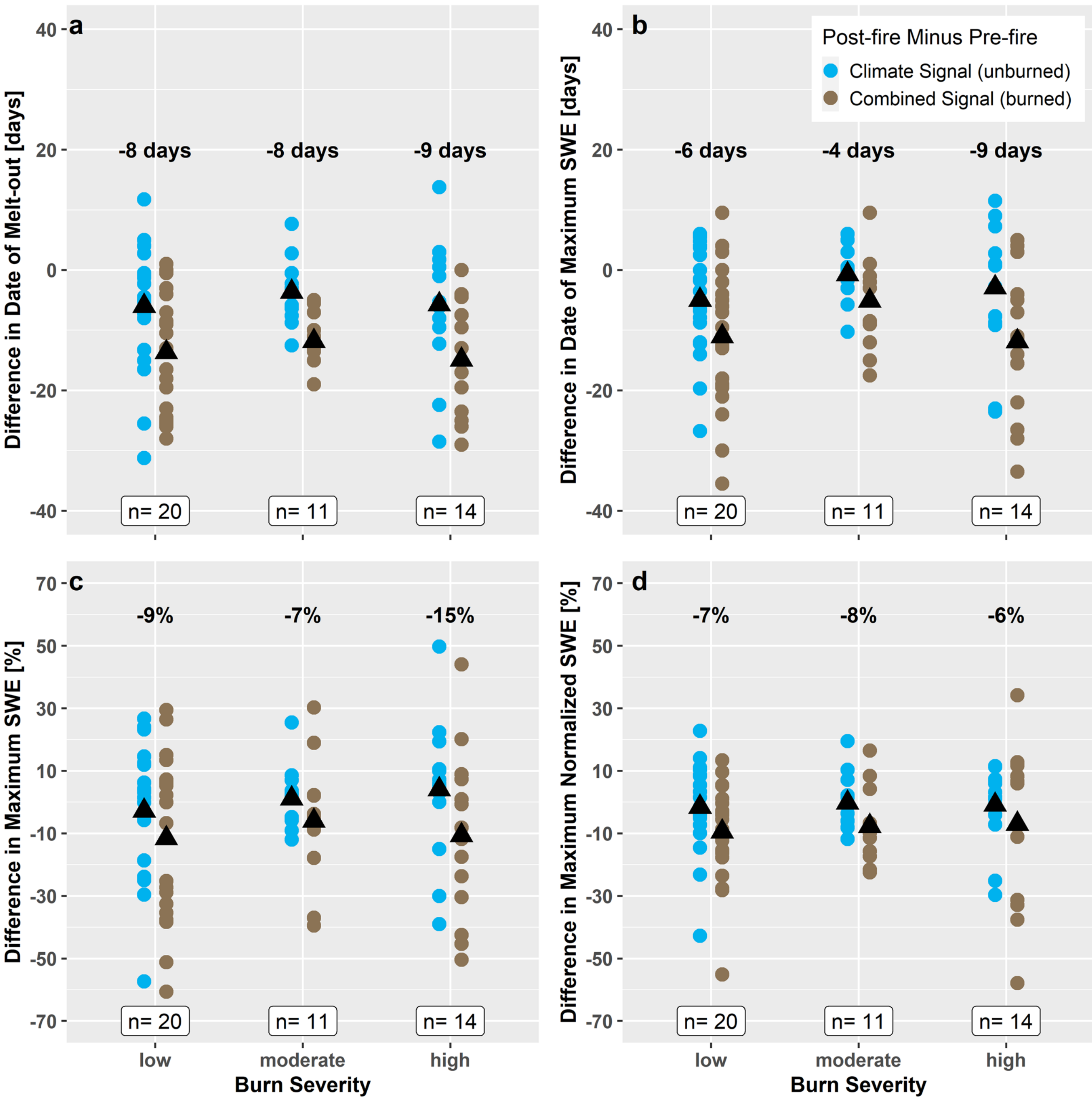

Figure 7. Differences in snow phenology measures between post-fire and pre-fire periods for the unburned sites (climate signal) and burned sites (combined signal) when the sites are grouped by burn severity (at the burned sites). The sample size *n* for each grouping is shown at the bottom of each panel. Black triangles show the average values. The differences in the average values (i.e., the fire signal) are shown at the top of each panel.

are observed between the different genera. The largest differences in melt-out dates between the unburned and burned sites occurred for the hemlock/other sites while the smallest differences occurred for the pine and spruce sites. The differences in the date of maximum SWE have less variability between the different vegetation types (Figure 9b). Wildfires typically advanced the dates of maximum SWE for all genus categories, but the largest average change occurred again for the hemlock/other category. In Figure 9c, the change in maximum SWE is typically more negative for the burned sites than the unburned sites for all genus categories. The largest difference between the unburned and burned sites (i.e., wildfire signal) occurs for the hemlock/other category (Figure 9c). However, the nSWE results (Figure 9d) show less variability in wildfire signal between the genus categories.

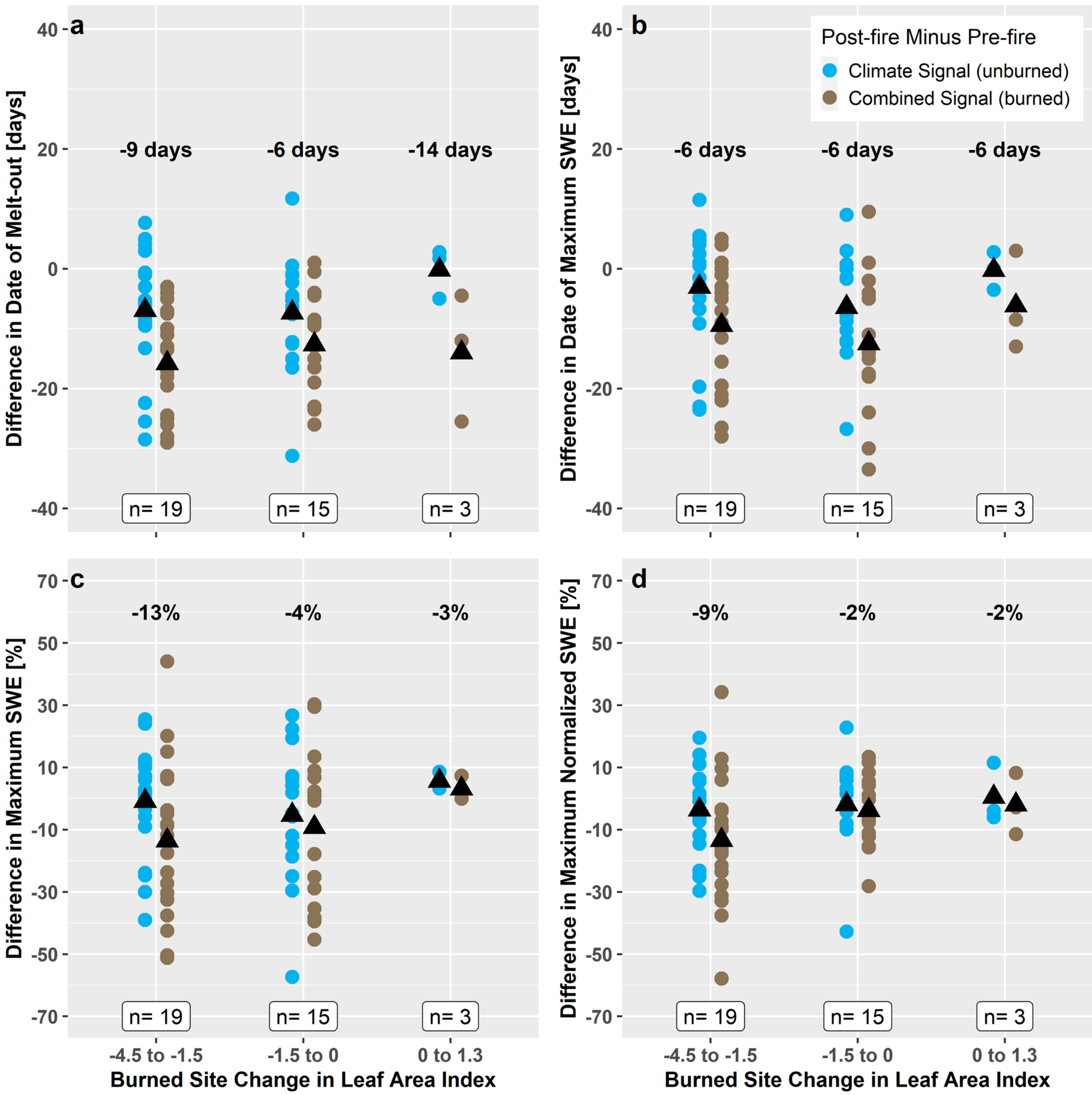

Figure 8. Differences in snow phenology measures between post-fire and pre-fire periods for the unburned sites (climate signal) and burned sites (combined signal) when the sites are grouped by change in leaf area index (LAI). A negative change indicates a post-fire reduction in LAI. The sample size *n* for each grouping is shown at the bottom of each panel. Black triangles show the average values. The differences in the average values (i.e., the fire signal) are shown at the top of each panel.

3.2.4. Time Since Fire

Figure 10 compares the changes in the snow phenology measures between the unburned and burned sites when the sites are grouped according to the time since fire occurrence. For both the unburned and burned sites, the changes in all four measures are typically most severe for the 5-to-10-year category while the 10-to-32-year category shows the greatest variability in the changes. Comparing the unburned and burned sites suggests that the effect of the wildfires on melt-out and maximum SWE dates typically persists beyond 10 years. For SWE and nSWE, the largest average impact of the wildfires occurs beyond 10 years. Overall, the results suggest that most sites have not recovered to pre-fire conditions within their available periods of record. Based on the studies summarized in Stevens-Rumann and Morgan (2019), it is not uncommon for little or no tree regeneration to occur

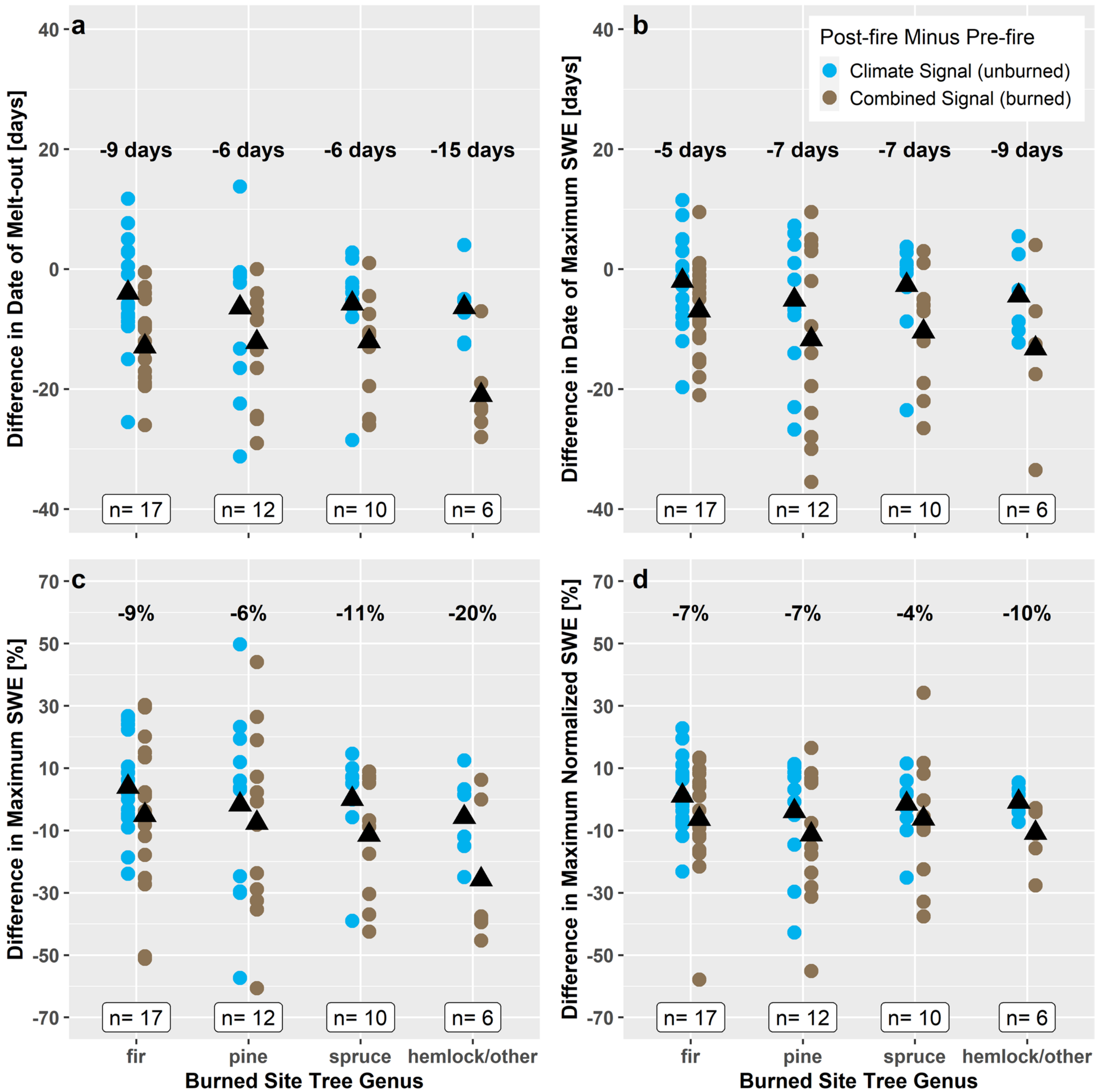

Figure 9. Differences in snow phenology measures between post-fire and pre-fire periods for the unburned sites (climate signal) and burned sites (combined signal) when the sites are grouped by tree genus. The sample size *n* for each grouping is shown at the bottom of each panel. Black triangles show the average values. The differences in the average values (i.e., the fire signal) are shown at the top of each panel.

after wildfires in parts of the western U.S. Several variables that can influence recovery include genus, distance to seed source, water stress, precipitation, elevation, slope, aspect, and plant competition.

3.2.5. Elevation

Figure 11 compares the change in the snow phenology measures for the burned and unburned sites when the sites are grouped by elevation. The changes in melt-out and peak SWE dates are typically more severe at burned sites than unburned sites irrespective of the elevation category, but the greatest advances in these dates typically occur at the lowest elevations (Figures 11a and 11b). Similarly, the burned sites usually exhibit greater reductions in SWE than the unburned sites (Figure 11c) for all elevation categories. Wildfires produced the greatest average

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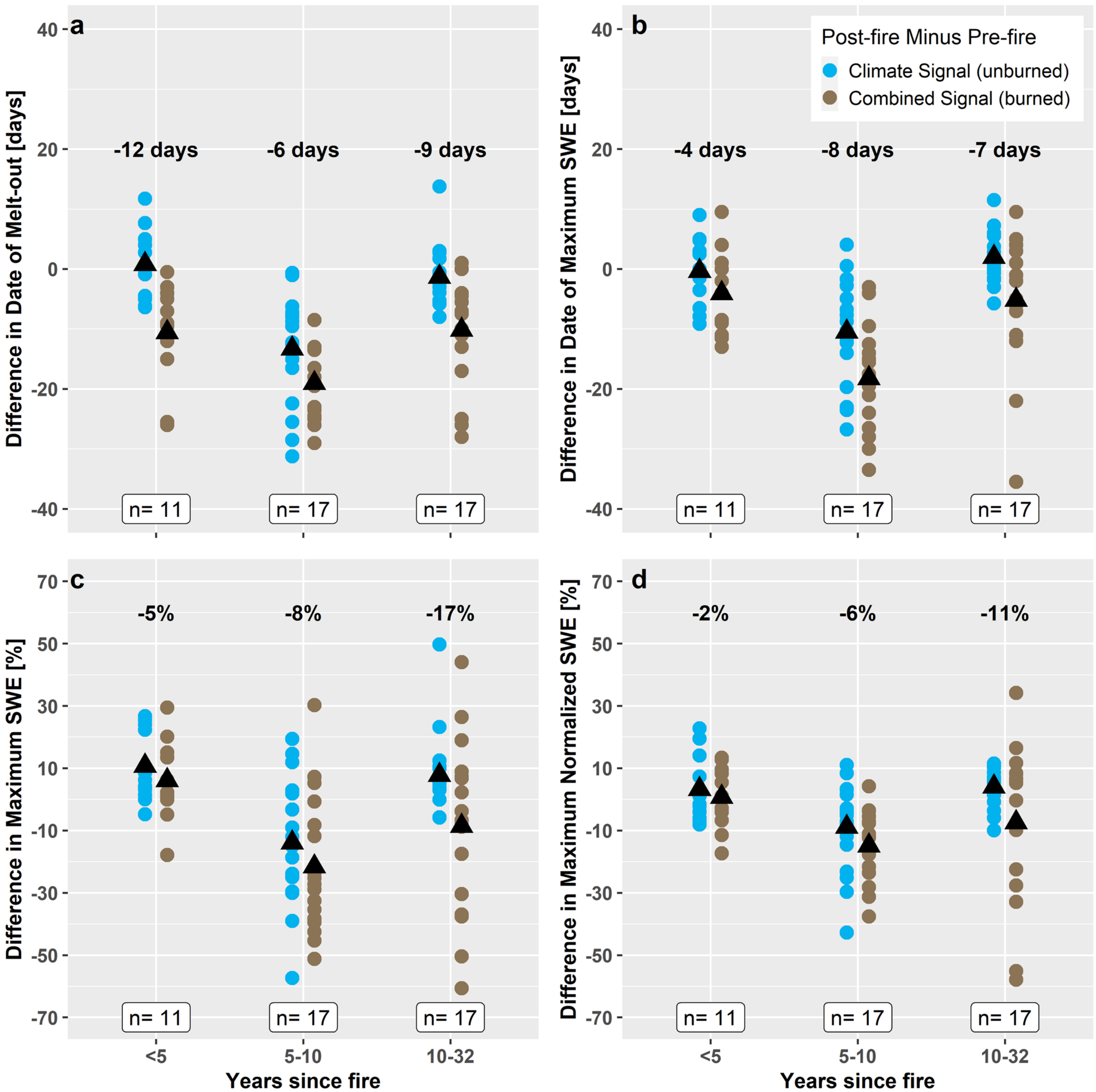

Figure 10. Differences in snow phenology measures between post-fire and pre-fire periods for the unburned sites (climate signal) and burned sites (combined signal) when the sites are grouped by years since the fire. The sample size *n* for each grouping is shown at the bottom of each panel. Black triangles show the average values. The differences in the average values (i.e., the fire signal) are shown at the top of each panel.

effect on SWE and nSWE for sites in the lowest elevation category (below 1960 m). Above 1960 m, the wildfire's impact on SWE and nSWE does not exhibit a consistent dependence on elevation. The lack of dependence of nSWE on elevation may occur due to varied geographic location, climate and vegetation for sites within each elevation category.

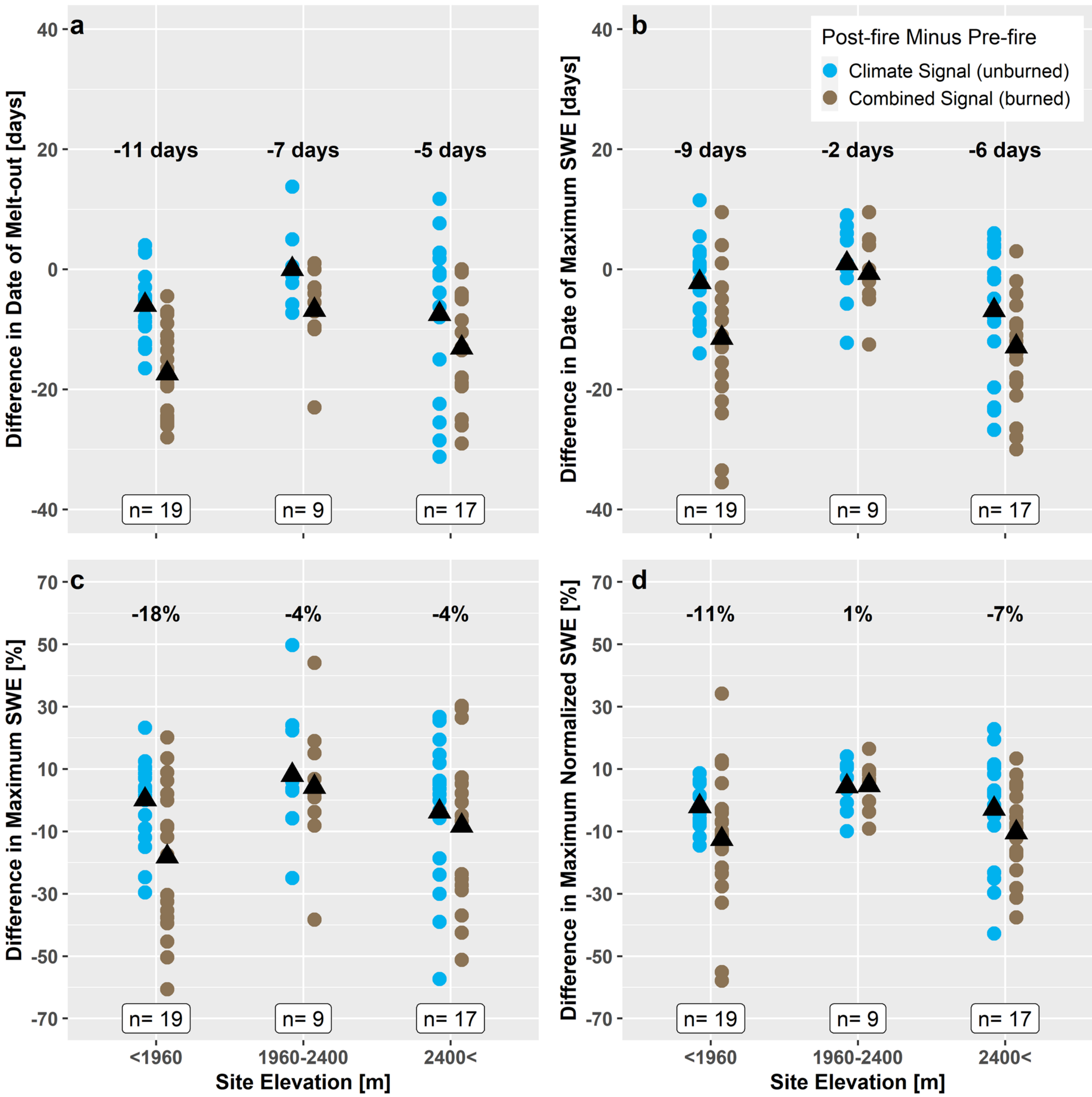

Figure 11. Differences in snow phenology measures between post-fire and pre-fire periods for the unburned sites (climate signal) and burned sites (combined signal) when the sites are grouped by burned site elevation. The sample size *n* for each grouping is shown at the bottom of each panel. Black triangles show the average values. The differences in the average values (i.e., the fire signal) are shown at the top of each panel.

4. Discussion

Overall, the results suggest that wildfires typically produce lower annual maximum SWE values compared to pre-fire or nearby unburned conditions. The reductions are likely related to increased shortwave radiation and albedo changes for the snow surface (Burles & Boon, 2011; Gleason et al., 2018; Gleason & Nolin, 2016). In addition to the increased shortwave radiation reaching the snow surface, increased wind and turbulent fluxes can also increase the total energy available for melt following a wildfire. Burles and Boon (2011) found both net shortwave radiation and sensible heat flux were important drivers of snowmelt in burned areas. In New Mexico, increased latent heat flux through sublimation was suggested as a cause for reduced SWE (Harpold et al., 2014).

The wildfire-induced changes to maximum SWE vary by ecoregion, and more northern ecoregions have some sites that show increases in maximum SWE due to wildfire (Figure 5). Our results generally support the summary by Goeking and Tarboton (2020), who found that studies in the higher latitude regions of the U.S. and southern Canada observed increases in SWE while studies in lower latitudes observed reductions in SWE due to wildfire. Our results for sites in Alaska indicate increases in nSWE even as the unburned sites in the region have minimal change in nSWE. Our results also agree with Hubbart et al. (2015), who observed increases in SWE in the Northern Rockies. However, our results differ somewhat in other northern ecoregions because the majority of burned sites still indicate decreases in annual maximum SWE or nSWE. Furthermore, our results support the findings from Stevens (2017), who found that SWE decreased substantially in burned areas of the Sierra Nevada Mountains.

The tendency of wildfires to produce earlier melt-out dates has also been documented in previous research (Gleason et al., 2018). The magnitude of change seen in our climate signal results is also similar to Harpold et al. (2012), who found changes from 2 to 5 days per decade for watersheds in the southwestern U.S. In addition, our results typically show earlier dates regardless of ecoregion, burn severity, change in LAI, tree genus, years since the fire occurred, and elevation. The earlier melt-out dates initially appear to conflict with Hubbart et al. (2015), who observed later melt-out dates in clear cut areas compared to undisturbed locations. However, the change in snow albedo due to pyrogenic carbon particles is significant in burn areas and can last for several years (Gleason et al., 2013, 2018; Gleason & Nolin, 2016). Furthermore, the snow surface energy balance after a fire can still include absorption of shortwave radiation and emission of longwave radiation by standing timber. Such absorption and emission do not occur if the canopy has been completely removed.

The relationship between post-fire changes in snow phenology measures and readily available fire, watershed or land surface variables is complex. None of the phenology measures were strongly controlled by a single explanatory variable, but certain measures indicated more substantial responses for certain variable classifications (e.g., larger reductions in LAI and sites with lower elevations). The complexities likely arise because reduced canopy density, and therefore interception, has been shown to generally increase snow accumulation (Varhola et al., 2010; Veatch et al., 2009). Yet the changes in snow albedo and energy fluxes in a burned landscape present unique conditions that may overwhelm any canopy interception changes. When the canopy is reduced and altered by a wildfire, site-specific factors such as slope and aspect may play larger relative roles as discussed by Harpold et al. (2014) and promote variability within ecoregions. Earlier dates are potentially a result of increased shortwave radiation on the snow surface during both the accumulation and ablation periods due to reduced canopy cover and increased snowpack albedo. The apparent insensitivity to burn severity could be due to errors in the categorization of burn severity. Shadows from snags and standing dead trees with remaining crown structure can influence the dNBR values and produce misclassifications (Fassnacht et al., 2021).

The use of the SNOTEL data set allows consideration of numerous climates and ecosystems, but it has important limitations. Small openings in the canopy are required to allow snowfall to accumulate on the snow pillows at the SNOTEL sites (https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/monitoringPrograms/automatedSnowMonitoring/). Thus, the sites are not directly influenced by snowfall interception and do not fully capture the changes in snowpack due to decreased canopy interception following a wildfire. However, these sites are expected to experience changes in windspeed and changes snow albedo associated with the fires.

In this study, the differences in the behavior of the burned and unburned sites are assumed to be caused by the wildfires. To partially evaluate this assumption, the cumulative SWE at the burned sites was plotted against the cumulative SWE at the associated unburned sites, and abrupt changes in the plots frequently occurred at the times of the fires. The abrupt changes eliminate many other possible causes for the observed differences. However, changes equipment or operation of the SNOTEL sites that were associated with the fires could also be a factor. Errors are also introduced by using unburned SNOTEL sites as analogs for behavior at the nearby burned sites if the wildfires had not occurred. Snowpack exhibits substantial spatial variability (Sexstone & Fassnacht, 2014) and local conditions significantly affect the energy fluxes and thus the SWE (Tennant et al., 2017). By using an average of nearby unburned sites, the effects of local differences are reduced. Also, the wildfire effect is determined by comparing the changes between the pre-fire and post-fire periods at the burned and unburned sites. If the burned and unburned sites have different average values over both periods, this difference is implicitly removed in the comparisons. Nonetheless, comparisons at individual sites are expected to include errors.

10.1029/2021WR031569

The results should also be interpreted in the context of other limitations. The sample size is not evenly distributed between ecoregions, so aggregated measures tend to emphasize ecoregions with more data. Similarly, the pre- and post-fire time periods are not the same across all sites, which emphasize individual years from sites with shorter records. When comparing to potential controlling variables, we also have assumed the burned SNOTEL sites provide reasonable representations of the snow accumulation and ablation processes for the area near the site. The spatial representativeness may be limited depending on the exact site location.

5. Conclusions

In this study, we used SWE data from 45 SNOTEL sites that have been impacted by wildfire and 110 comparison SNOTEL sites that have not been impacted by wildfire. The data set at the burned sites was divided into pre- and post-fire periods, and the data set at the comparison sites was divided using the same points in time. Several measures of snow phenology were derived from the SWE data at each site including annual melt-out date, date of maximum SWE, maximum SWE, and maximum normalized SWE (maximum SWE divided by October through April total precipitation). Data were grouped by ecoregion, burn severity, change in LAI, dominant pre-fire trees genus, years since fire, and elevation. The following conclusions can be drawn from the study:

- Overall, climate has a strong influence on SWE and should be considered when quantifying the wildfire signal. In most ecoregions, normalizing the peak SWE by the total winter precipitation reduced the changes in the snow phenology measures at the unburned sites between the pre- and post-fire periods to small values. Thus, much of the climate signal is due to variations in precipitation. However, for the southernmost ecoregion (Arizona-New Mexico Mountains), substantial differences persisted at the unburned sites even after this normalization. In that case, the difference between the pre- and post-fire periods was due to another factor, perhaps wintertime temperatures.
- Wildfires produced earlier melt-out dates for all ecoregions except the Arizona-New Mexico Mountains. On average, the wildfires advanced the melt-out date by 9 days for the ecoregions considered.
- Wildfires produced earlier peak SWE dates for all ecoregions except the Northern Rockies and the Arizona-New Mexico Mountains. On average, the wildfires advanced the peak SWE date by 7 days for the ecoregions considered.
- Wildfires produced lower maximum SWE values for most ecoregions. On average, wildfires reduced peak SWE by approximately 13% for the ecoregions considered. However, part of the reduction was likely due to localized precipitation occurring over some of the unburned sites. On average, wildfires reduced peak nSWE by 7% for the ecoregions considered. Nonetheless, increases in peak nSWE were observed for several of the northern ecoregions.
- When the climate and wildfire signals are combined, the largest changes in SWE timing and depth occurred in the Cascades, Eastern Cascades Slopes and Foothills, and Southern Rockies. For the Cascades and Southern Rockies, many of the changes were significant using a p-value of 0.05.
- The impact of wildfire on the snow phenology measures does not exhibit a clear dependence on burn severity but is more sensitive to the change in LAI. In particular, larger reductions in LAI typically produced larger changes in the peak SWE and nSWE values.
- The effect of the wildfire depends on the dominant pre-fire tree genus. The smallest changes in the snow phenology measures typically occurred for spruce and pine forests, while the largest changes usually occurred for the hemlock/other category.
- The effects of the wildfires on the snow phenology measures persist more than 10 years after the fires. The changes to the melt-out and peak SWE dates exhibit no clear dependence on the time since fire (for the periods of record available in this study), while changes to maximum SWE and nSWE were largest for times greater than 10 years.
- The effects of wildfires on the snow phenology measures are strongest at low elevations (below 1960 m). For higher elevations, the wildfire effects exhibit no clear dependence on elevation.

This study helps address some limitations of previous efforts while still prompting several opportunities for future research. Future efforts may include assembling additional pre- and post-fire snow measurements into a comprehensive data set that can be compared with the SNOTEL sites. Further research can also include an analysis of snowmelt rates in burned areas to understand potential hydrologic changes following wildfire. Finally, remote sensing products can be used along with ground-based measurements to quantify snowpack distribution changes between pre- and post-fire periods.

While this study presents results that are relevant to the scientific community, the results also have operational implications for water managers. Water managers should anticipate changes to snow accumulation and ablation following a wildfire. They can expect earlier initiation of snowmelt and a longer snow-free season, which may impact summer streamflow and water temperatures. In addition, an overall shift of the spring snowmelt hydrograph may occur in watersheds where large fires have occurred. The pre-fire flow regime is likely to take more than a decade to return to pre-fire conditions (if it does return to pre-fire conditions). Therefore, long-term adjustments to reservoir operating criteria or other management activities may be necessary to account for the changes caused by wildfire.

Data Availability Statement

The quality-controlled SNOTEL data used for quantifying differences between burned and unburned sites is available at Hydroshare via https://doi.org/10.4211/hs.689986daebb04348a754e9b9d94f4871. The processed pre- and post-fire snow measure data for each SNOTEL burned site is available at Hydroshare via https://doi.org/10.4211/hs.b9b7bc7aa70e464a8563d4e9880c1601.

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