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Snowpack decline kindles more severe fire in the western United States

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Abstract: *(300 words)*

Climate change is reducing winter snowpack and advancing spring snowmelt across the western United States (US), interacting with El Niño-Southern Oscillation (ENSO) teleconnections that drive spatially predictable interannual fluctuations that contribute to high- or low-snow winters. Early snowmelt extends the fire season, enhancing opportunities for ignition and increasing fuel dryness, both of which contribute to greater burned areas. However, relationships between snowpack on burn severity, a measure of forest loss and expected biogeochemical and hydrological impacts of fire, have not been examined. Here, using remotely sensed snow and fire data spanning 1985-2021, we examined how snowpack quantity and timing of spring snowmelt influence annual area burned and burn severity at the watershed scale. Early snowmelt was associated with earlier occurrences of fire ≥400 ha and greater annual area burned, whereas low snowpack water content was associated with more severe burn outcomes including greater mean composite burn index (CBI) and larger proportions of high severity fire (CBI ≥ 2.25). Thus, low-snow winters with early snowmelt may prime forested watersheds to dry, burn, and experience high severity fire. These outcomes are consistent with enhanced fuel dry-down: early snowmelt extends the dry-down window while low snowpack quantity portends greater fuel aridity during the dry period. Our findings also highlight how the ENSO interacts with directional warming: El Niño phases amplify trends of snowpack loss and increasing area burned severely in northwestern watersheds but dampen these trends in southwestern watersheds, while La Niña phases exert the opposite effect. Projected warming, potentially accompanied by greater ENSO variability and extremes, points toward a future of reduced snowpack, earlier snowmelt, and increased area burned at high severity in forests where snowpack historically buffered fire risk, with attendant losses in forest carbon storage and disrupted hydrological function of forested watersheds.

41 **Introduction:**

42 Climate change is promoting increasing fire activity in forests of the western United
43 States (US) through extended fire seasons and drier, more flammable fuels (Dennison et al. 2014,
44 Jolly et al. 2015, Jain et al. 2017, Abatzoglou et al. 2018b). One measure of increasing fire
45 activity is growth in annual area burned, which is closely linked to climate and fuel aridity
46 (Abatzoglou and Williams 2016, Higuera and Abatzoglou 2021). However, within any given
47 fire, the effects of fires on ecosystems – the *fire severity* – can range substantially (Whitman et
48 al. 2018), from low-severity fires that burn surface fuels with minimal impact on mature trees, to
49 high-severity fire that burns through forest canopies, causes high tree mortality, and may trigger
50 postfire flooding and debris flow events (Hudec and Peterson 2012, Coble et al. 2023, McGuire
51 et al. 2024). Despite rapid increases in area burned, many vegetation types are still experiencing
52 far less low-severity fire than is known to have occurred historically, due to a combination of
53 aggressive fire suppression, loss of Indigenous burning practices, and land-use changes (Parks et
54 al. 2025b). However, recent increases in high-severity fire appear to be historically anomalous in
55 a range of ecological settings (Higuera et al. 2021, McClure et al. 2024). Beyond immediate
56 impacts of high-severity fire to ecological processes such as carbon storage and hydrology,
57 severe fire may set the stage for long-term forest ecosystem conversion, particularly under a
58 warming and aridifying climate that diminishes forest recovery (Coop et al. 2020, Davis et al.
59 2023).

60 Winter snowpack is a particularly important seasonal hydrologic input to many western
61 US forests, with effects on wildfire activity. Snowpack quantity and melt timing influence soil
62 moisture throughout the spring and early summer (Maurer and Bowling 2014, Harpold et al.
63 2015). In turn, soil moisture predicts live fuel and vegetation moisture (Qi et al. 2012). Live fuel

moisture subsequently influences receptivity to ignition, area burned, and burn severity (Wotton et al. 2010, Parks et al. 2014, Flannigan et al. 2016). Consequently, declines in snowpack quantity and earlier melt are projected to increase the simulated frequency, extent, and severity of wildfires across the western US, as shown by Gergel et al. (2017). Compounded by shifts toward winter precipitation falling as rain (Littell et al. 2009), reduced snowpack preconditions landscapes for large fire years. Although it is well documented that increased annual area burned is associated with early snowmelt, warmer spring temperatures, and earlier fire seasons (Westerling et al. 2006, Kitzberger et al. 2017), the extent to which snowpack conditions are associated with observed burn severity outcomes remains unclear.

The US mountain west is broadly experiencing declines in snowpack amount and shifts toward earlier snowmelt (Stewart 2009, Clow 2010). However, climate teleconnections such as the El Niño-Southern Oscillation (ENSO) introduce systematic spatial and interannual variation in snowpack across the western US (Thakur et al. 2020). For example, during El Niño years, some regions may experience above-average snowfall while others experience below-average snowfall (Patten et al. 2003), creating spatially heterogeneous impacts on fuel moisture and fire season length. This ENSO-associated predictability matters for fire management because it provides a basis for seasonal forecasting and planning: regions with predicted low snowpack may require heightened preparedness or modified prescribed burning schedules, whereas regions with above-average snowpack may present safer windows for management interventions. A better understanding of how winter snowpack influences burn severity outcomes could improve our ability to adapt forest management to shifting hydrologic regimes across western landscapes, guiding proactive strategies ahead of dry seasons with elevated risk of stand-replacing fire, and

86 forecasting future changes as directional warming reduces snowpack (Siirila-Woodburn et al. 2021) and potentially produces greater extremes of ENSO variation (Cai et al. 2021).

88 Here, we examined the maximum annual snow water equivalent, the timing of peak snow storage and spring snowmelt, the length of the snow-free period between snowmelt and the next fall's accumulation, and spring temperature anomaly as predictors of fire season activity. Using remotely sensed and modeled SWE data spanning 1985-2021, we identified where and at what rate snowpack conditions are changing across Hydrologic Unit Code Level 2 (HUC2) watersheds of the western US (Fig. 1). We also assessed how ENSO teleconnections influenced snow conditions across the west. We then tested for associations with annual fire season activity at the HUC2 regional scale, including the first observation of fire, forested area burned, mean burn severity, and proportion of high severity fire.

Methods:

Study Area

Our analyses focused on forested regions in the contiguous western US that consistently accumulate a meaningful snowpack likely to influence wildfire activity, which we define here as peak annual snow water equivalent (SWE_{max}) ≥ 20 mm. To delimit these regions, we used the Western United States Snow Reanalysis dataset, a gridded dataset that reports daily SWE at a 500-m resolution (Fang et al. 2022). This modeled SWE product is generated by assimilating remotely sensed fractional snow-covered area (fSCA) data, an approach shown by Yang et al. (2023) to produce reliable snowpack estimates. To restrict our analyses to areas where snow conditions are ecologically and hydrologically relevant to wildfire activity, we included only pixels that maintained SWE_{max} ≥ 20 mm during the portion of the water year relevant to snowpack accrual and melt (October-June) in every year of the 1985-2021 study period. Pixels that did not meet this threshold in even a single year were excluded from subsequent analyses. Study area pixels were then aggregated by watershed using HUC2 regions from the Watershed Boundary Dataset (U.S. Geological Survey 2023; Fig. 1). To evaluate the sensitivity of our results to the 20 mm SWE_{max} threshold, we repeated all analyses using alternative thresholds of > 0 mm (inclusive of low-snow and rain-on-snow transition areas) and ≥ 50 mm (restricted to areas receiving more snow accumulation). Results from these sensitivity analyses are presented in Appendices S2 and S3, respectively. All geospatial operations and statistical analyses were conducted in R 4.4.3 using the "Terra" package (Hijmans et al. 2022, R Core Team 2022).

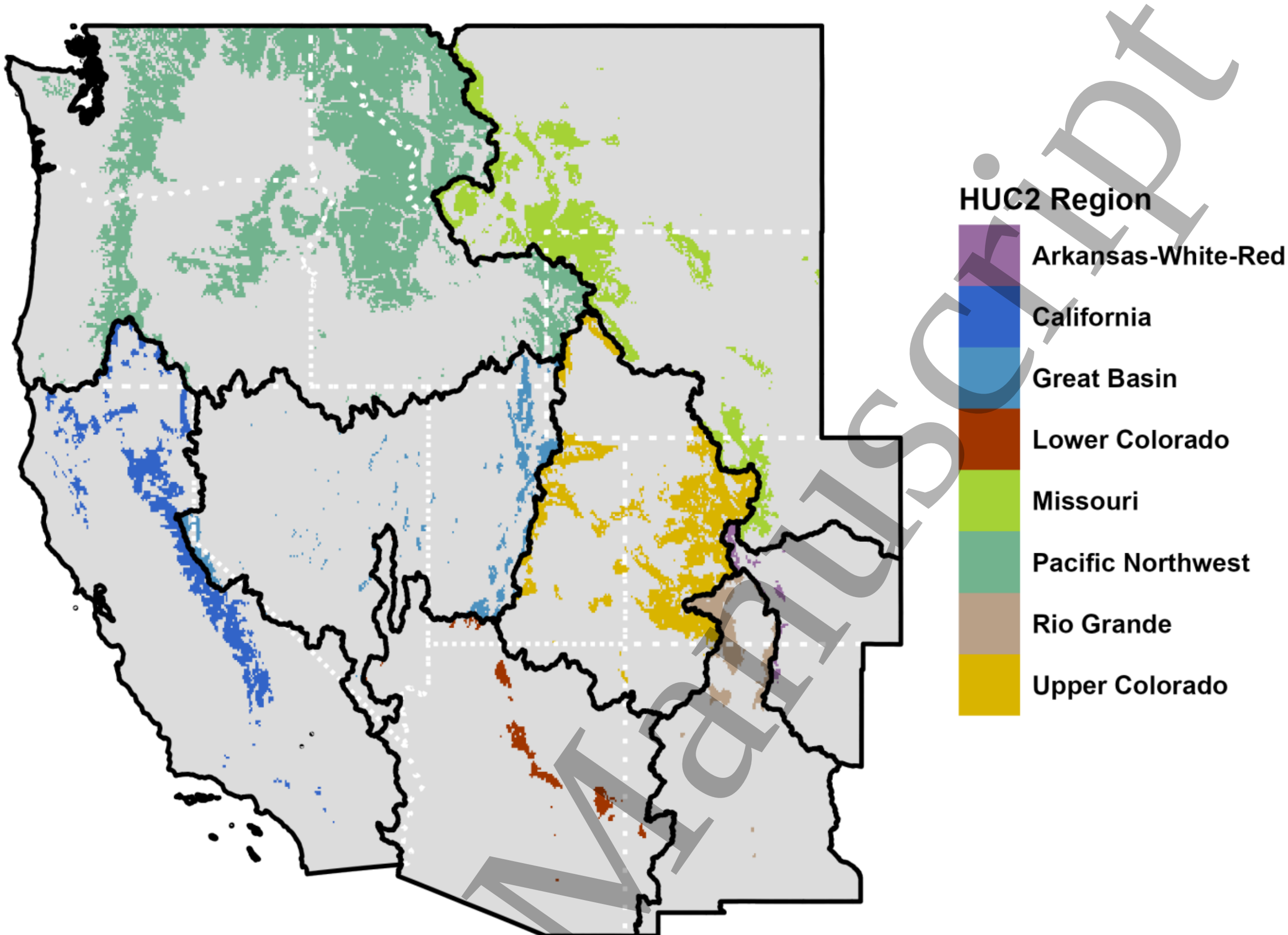

Figure 1. Forested regions across western contiguous US with ≥20 mm maximum snow water equivalent (SWE_{max}) over the 1985-2021 study period. Pixels are color-coded according to their respective Hydrologic Unit Code Level 2 (HUC2) regions. Solid black lines delineate extents of HUC2 regions, while dotted white lines denote state boundaries.

Region-specific Snowpack Quantity and Timing

We calculated four normalized snowpack metrics for each water year over 1985-2021 within HUC2 regions to capture snowpack quantity, timing, and persistence (Table 1). These metrics were chosen because they describe distinct aspects of seasonal snow dynamics that influence ecosystem water availability (Helms et al. 2008), which in turn may influence the fire season through fuel aridity. The first metric, %SWE_{max}, expresses annual SWE_{max} as percentages of the 37-year study period median SWE_{max} for each pixel, providing a measure of relative snowpack water quantity. The second metric, Peak.Date, is the z-score of each year's SWE_{max} date relative to the study period mean date and standard deviation for each pixel. Therefore, Peak.Date captures whether peak snow storage occurred earlier or later than typical. The third metric, Melt.Date, is the z-score of each year's snowmelt date, with snowmelt defined as the first day SWE dropped below 5% of annual SWE_{max}. This metric indicates whether snow disappeared earlier or later than average, thereby constraining the onset of the snow-free season. Fourth, the snow-free period (SFP) is the z-score of the interval between each year's Melt.Date and the subsequent fall snow-on date, defined as the first day SWE exceeded 5% of that year's SWE_{max}. SFP integrates both the start (melt) and end (first persistent snow) of the snow-free season and provides a direct measure of time available for fuel dry-down throughout spring and summer. Normalizing the four metrics relative to study-period conditions allows comparison of snowpack dynamics across years and regions while accounting for biogeographic variation in absolute snow quantity and timing. We summarized each metric by HUC2 region for each water year as regional medians of pixel-based values.

To explore where and how snowpack conditions are changing over time across the west, we developed per-pixel Sen's slopes of %SWEMax, Peak.Date, Melt.Date, and SFP over the

1985-2021 study period using the “trend” package (Pohlert 2023). Next, we sought to determine where and how the El Niño Southern Oscillation influences snowpack conditions. First, we obtained monthly Niño region 3.4 Sea Surface Temperature (SST) anomaly data (National Oceanic and Atmospheric Administration Climate Prediction Center 2024). Next, using monthly SST observations for October through March, we calculated average winter-spring SST anomaly for each water year. We then conducted per-pixel linear regressions of each snowpack metric against SST over the 1985-2021 study period. For both per-pixel Sen’s slope and linear regressions, significance was assessed at $p < 0.1$ after applying a multiple testing correction as implemented by the base R function ‘p.adjust’ using the method of Benjamini and Hochberg (1995).

Fire Season Outcomes

Monitoring Trends in Burn Severity (MTBS) fire perimeters from 1985-2021 (Eidenshink et al. 2007) were used to assign individual fires to the HUC2 region containing the majority of their area. Subsequent analysis included only those portions of fires that occurred within forested pixels that held ≥ 20 mm SWE_{max} throughout the study period. Forested pixels were identified using the LANDFIRE Biophysical Settings (BPS) Layer “GROUPVEG” categories of conifer, hardwood, and hardwood-conifer. Fires igniting between October 1st and January 1st were omitted to avoid confounding effects from the transition between water years, as these fires may be influenced by both the previous year’s conditions and the developing snowpack. On average, fires dropped due to this seasonal filter comprised 1.4% of the annual burned area.

We analyzed four metrics of annual fire season activity by HUC2 region. First, we identified day of year of the earliest fire observation. Second, we calculated annual proportions of forested area burned. Third, we quantified annual mean burn severity using satellite-derived bias-corrected composite burn index (CBI) rasters developed by Parks et al. (2019). These satellite-derived CBI rasters closely replicate field-based CBI assessments conducted one year after fire that consider cumulative aboveground effects of fire events on surface fuel consumption, vegetation mortality, scorched trees, and soil char on a scale from 0 (unburned) to 3 (highest degree of severity; Key and Benson 2006). Fourth, we calculated the annual proportion of high severity fire, defined as the area of burned pixels with CBI ≥ 2.25 divided by the total forest area burned (Miller and Thode 2007).

Analysis

We developed linear and generalized linear models to predict the four fire season outcomes described above using regionally-aggregated snowpack metrics. We initially sought to model each fire season outcome using all three snowpack metrics as predictors in a single model, but our initial data exploration revealed strong correlations between snowpack metrics ranging from $r = 0.43 - 0.82$ (Table S1.1). Given this collinearity, we used AIC to compare simpler models for each fire season outcome built using one snowpack metric at a time. To evaluate effects of warming independent of snowpack conditions, we also compared snowpack-based models to models using spring maximum temperature anomaly (Spring.Tmax). Spring.Tmax was derived from TerraClimate (Abatzoglou et al. 2018a) and calculated as the z-score of mean maximum temperature over a 3-month HUC-specific spring period, relative to the study-period mean and standard deviation. HUC-specific spring periods (Table S1.2) were defined based on

191 each HUC's interannual median snowmelt date, with the month of snowmelt included if
192 snowmelt occurred after the 15th.

193 Model comparison began with inclusion of interactions between each snowpack metric
194 (or Spring.Tmax) and region; nonsignificant interaction terms and intercepts were subsequently
195 removed (Tables S1.3-S1.6). Earliest fire observation and mean annual CBI were modeled using
196 linear models, while proportion of regional forest burned and proportion of high severity fire
197 were modeled using Beta regressions implemented in the "betareg" package (Zeileis et al. 2016).
198 Following model selection, we quantified residual variation in fire season activity attributable to
199 summer temperature anomaly (Summer.Tmax), thereby isolating the contribution of climate
200 warming after accounting for snowpack preconditioning. Summer.Tmax was calculated as the z-
201 score of mean maximum temperature over a 3-month HUC-specific summer period (Table S1.2),
202 with the snowmelt month included when median snowmelt occurred before the 15th.

Results

Snowpack water decline and earlier snowmelt

We found nonsignificant declines in snowpack water quantity (%SWE_{Max}) over 1985-2021 across the western US, with significant declines exclusively in the southwest (Figure 2A). The largest areas with significant declines in %SWE_{max} were observed in the Rio Grande (8.6%) and Arkansas-White-Red (1.8%). We found little evidence for changes in the timing of SWE_{max} (Peak.Date) across the west (Table 1; Figure S1.1A). In contrast, Melt.Date shows nonsignificant shifts toward later melt in parts of the Pacific Northwest and California, but earlier melt elsewhere. While no significant trends toward later Melt.Date were observed, significant earlier trends are concentrated in the southwest, ranging from 12% of the Arkansas-White-Red to 38.8% of the Rio Grande (Table 1; Figure 2B). The length of the SFP is similarly trending longer in these southwestern regions (Figure S1.1B; Table 1).

Significant SST effects on snow metrics are more apparent in all regions. As SST increases, %SWE_{Max} declines throughout the northwest (82.9% of Pacific Northwest, 49.6% of Missouri) but climbs in parts of the southwest (17.2% of Lower Colorado, 13.1% of Rio Grande; Figure 3A, Table 1). These geographic patterns of SST influence are consistent for the timing of Peak.Date, Melt.Date, and the SFP (Figure 3B, Figure S1.1, Table 1). Consequently, El Niño (positive SST phase) is associated with greater and later-melting snowpack in the northwest but reduced and earlier-melting snowpack in the southwest; La Niña (negative SST phase) is the opposite.

Table 1. Percent of pixels within each HUC2 watershed showing statistically significant ($P \leq 0.1$) trends over time (1985-2021) and El Niño–Southern Oscillation (ENSO) associated effects on snow metrics.

HUC2 Region	Area with ≥20 mm SWEmax (km^2)	% of pixels Trending ↓/↑ %SWEmax	% of pixels Trending Early/Late Peak.Date	% of pixels Trending Early/Late Melt.Date	% of pixels Trending Shorter/Longer Snow Free Period	% of pixels El Niño drives ↓/↑ %SWEmax	% of pixels El Niño drives Early/Late Peak.Date	% of pixels El Niño drives Early/Late Melt.Date	% of pixels El Niño drives Shorter/Longer Snow Free Period
Arkansas-White-Red	4,683	1.8/0	0/0	12.0/0	0/0.4	0/5.8	0/1.1	0/2.9	0/0
California	39,961	0.0/0	0/0	0/0	0/0	3.3/0	11.8/0.3	4.7/0	0/13.3
Great Basin	21,659	0/0	0/0	0/0	0/0.1	10.3/0	0.8/0.1	1.8/0.5	0/15.6
Lower Colorado	8,543	0.2/0	0/0	14.4/0	0/6.3	0/17.3	0/0.2	0/0.6	0.2/0
Missouri	68,328	0.0/0.0	0/0	0.1/0	0/0	49.6/1.9	10.6/0.1	38.7/0.2	0/54.1
Pacific Northwest	219,964	0.0/0	0/0	0/0	0/0	82.9/0	42.9/0	87.6/0	0/91.2
Rio Grande	15,292	8.6/0	0/0	38.8/0	0/19.4	0/13.1	0/0.8	0/6.0	2.2/1.6
Upper Colorado	64,220	0.1/0	0/0	0.2/0	0/1.7	5.5/0.7	0.2/0.7	0.2/0.8	0/0

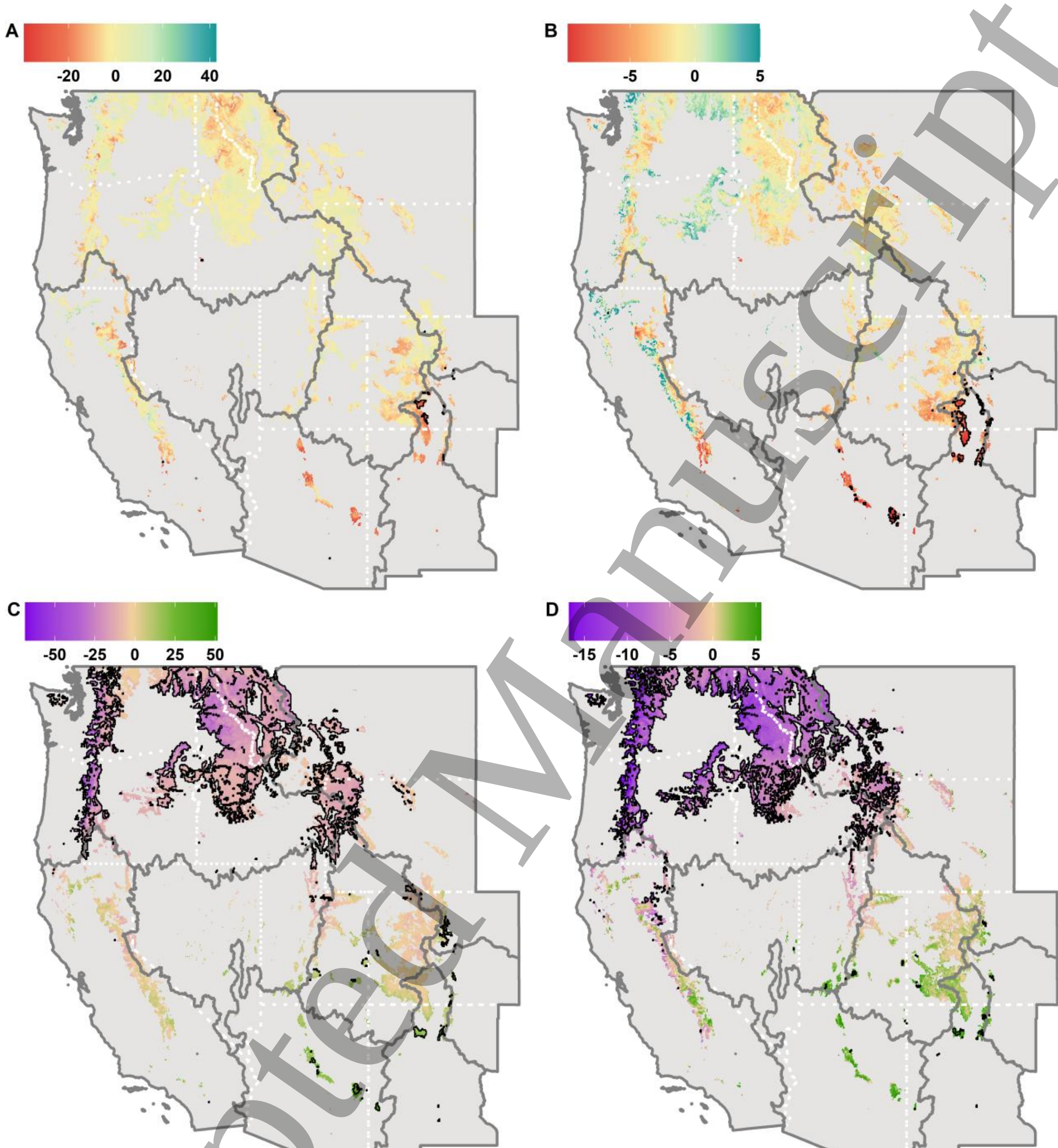

Figure 2. Per-pixel long term trends in snow conditions and effects of El Niño-Southern Oscillation (ENSO) Sea Surface Temperature (SST region 3.4) anomaly. In all panels, solid grey lines represent HUC2 region boundaries, and dotted white lines indicate state boundaries. **A:** Directional change in $\%SWE_{max}$ per decade (1985-2021), and **B:** Melt.Date per decade. **C:** ENSO influence on $\%SWE_{max}$ and **D:** Melt.Date, per degree SST anomaly. Regions of pixels with statistically significant Sen's or linear model slopes ($P \leq 0.1$, conditions 1985-2021) are outlined black. Positive SST anomaly indicates El Niño conditions, which strongly reduces snowpack and prompts early snowmelt throughout the PNW but increases snowpack and delays melt in portions of southwest. Effects of La Niña phases are the opposite.

Early snowmelt facilitates earlier fire seasons

Melt.Date yielded the AIC-best model of earliest fire ≥ 400 ha (Figure 3A; Table S1.3; earliest fire date ~ Melt.Date + HUC2; $P < 0.001$, Adj. $R^2 = 0.20$). Across all regions, early snowmelt was associated with early fire seasons. There was no evidence for region-specific slopes, but Lower Colorado had a significantly lower intercept, indicating earlier fire seasons across a range of melt timings ($P = 0.02$; Table S1.3).

Snowmelt timing is strongly related to area burned

Melt.Date also yielded the AIC-best model of proportion of forest burned (Figure 3B; Table S1.4; proportion forest burned ~ Melt.Date + HUC2; $P < 0.001$, Pseudo $R^2 = 0.3$). Across all regions, early snowmelt was associated with greater proportions of forest burned. There was no evidence for region-specific slopes, but Lower Colorado had a significantly greater intercept, indicating larger proportions burned across a range of melt timings ($P = 0.03$; Table S1.4).

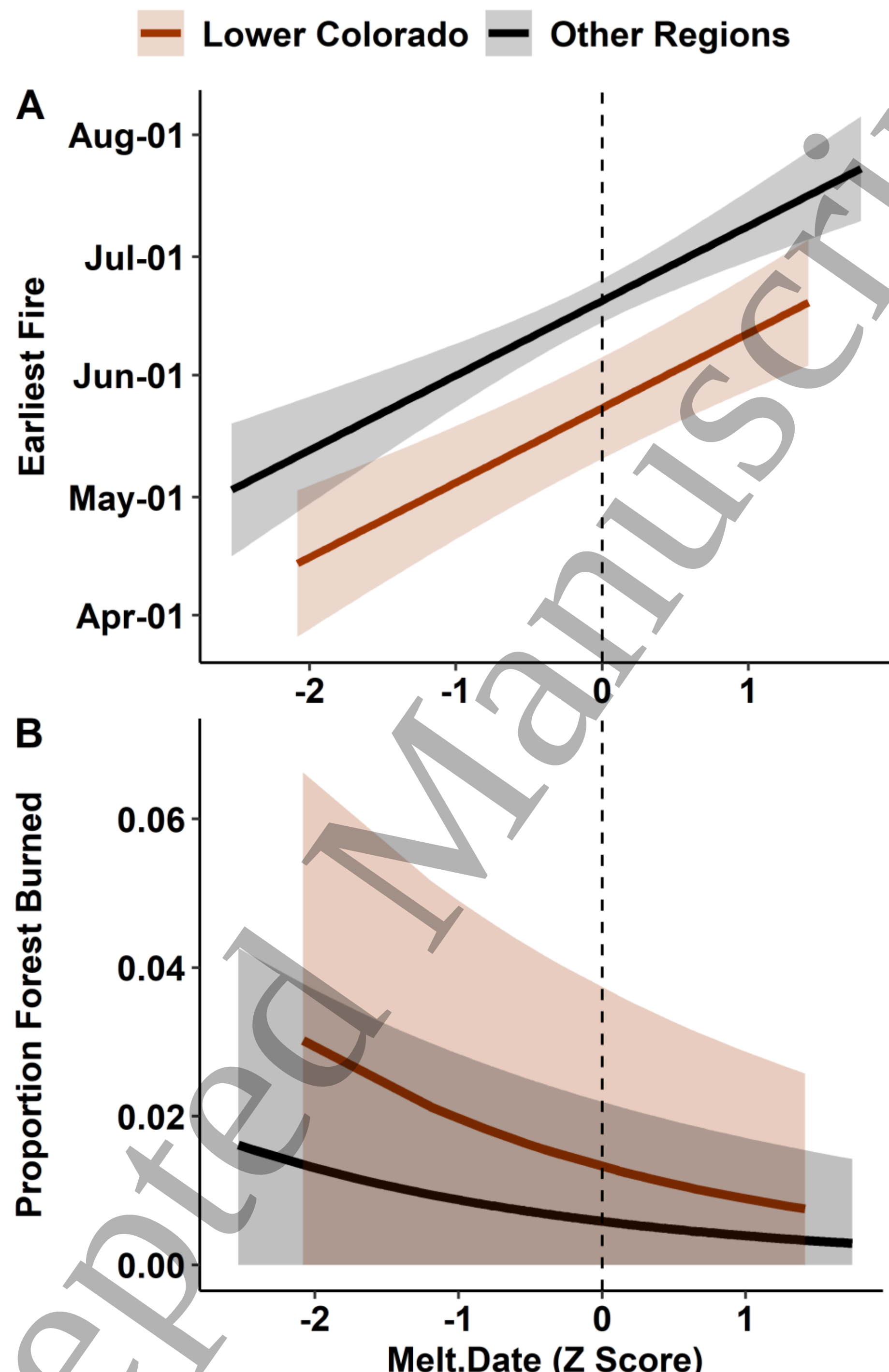

Figure 3. Relationships between snowmelt timing and fire season outcomes in forests. At the HUC2 Region scale, early Melt.Date (snowmelt timing) is associated with earlier ignitions of forest fires larger than 400ha (**A:** $P < 0.001$; Table S1.3) and greater proportions of forested areas burned annually (**B:** $P < 0.001$; Table S1.4). Summer.Tmax anomaly explains 2% of residual variation in earliest fire (Figure S1.2A) and 4% of residual variation in proportion of forested areas burned (Figure S1.2B).

257 ***Snowpack water quantity predicts burn severity***

258 $\%SWE_{max}$ yielded the AIC-best model of mean CBI (Figure 4A; Table S1.5; annual mean
259 CBI ~ $\%SWE_{max}$ + HUC2; $P < 0.001$, Adj $R^2 = 0.22$). Across all regions, low peak snow water
260 was associated with greater mean burn severity. Allowing region-specific slopes provided only
261 marginal improvement in model fit (Adj $R^2 = 0.23$; Table S1.5), but regional intercepts were
262 significant for Lower and Upper Colorado ($P < 0.001$ and $P = 0.06$, respectively; Table S1.5),
263 both indicating lower burn severities across a range of snowpack water contents.

264 The proportion of high severity fire was also best predicted by $\%SWE_{max}$ (Figure 4C;
265 Table S1.6; proportion of high severity fire ~ $\%SWE_{max}$ + HUC2; $P < 0.001$, Pseudo $R^2 = 0.29$).
266 Low snowpack water contents were associated with more high severity fire. There was weak
267 evidence for region-specific slopes which offered only marginal improvements in model fit
268 (Pseudo $R^2 = 0.3$; Table S1.6), and the interaction term was not statistically significant.
269 However, regional intercepts were significant for Lower Colorado ($P < 0.001$), indicating lower
270 severity fire across a range of snowpack conditions.

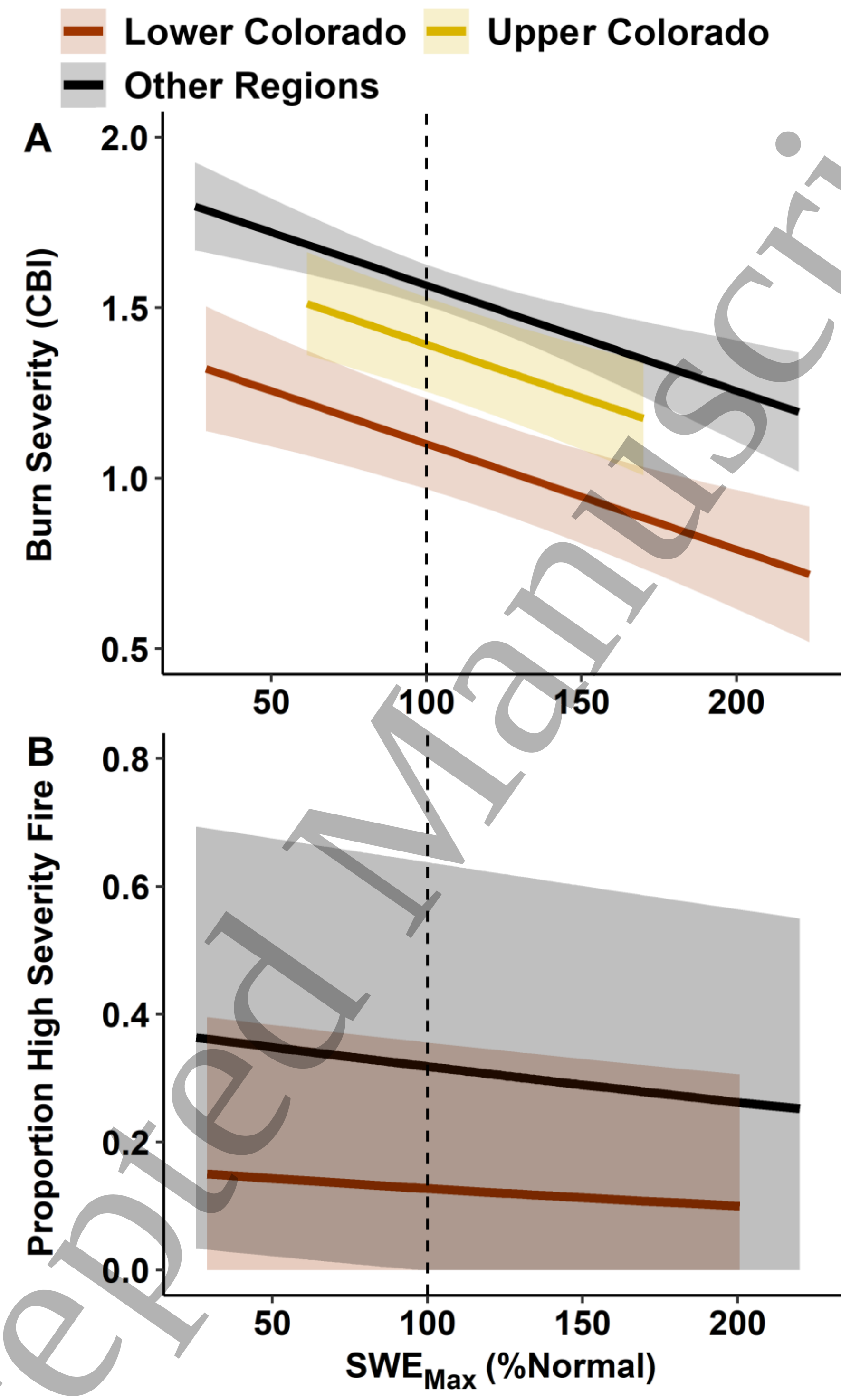

Figure 4. Relationships between Snow Water Equivalent and burn severity outcomes in forests. At the HUC2 Region scale, low %SWE$_{max}$ is associated with greater annual mean CBI (**A:** $P < 0.001$; Table S1.5) and greater proportions of high severity fire (**B:** $P < 0.001$, Table S1.6). Equivalent model using Z-scored SWE$_{max}$ included in appendix as Figure S1.3. Summer.Tmax anomaly explains 11% of residual variation in burn severity (Figure S1.2C) and 2% of residual variation in proportion of high severity fire (Figure S1.2D).

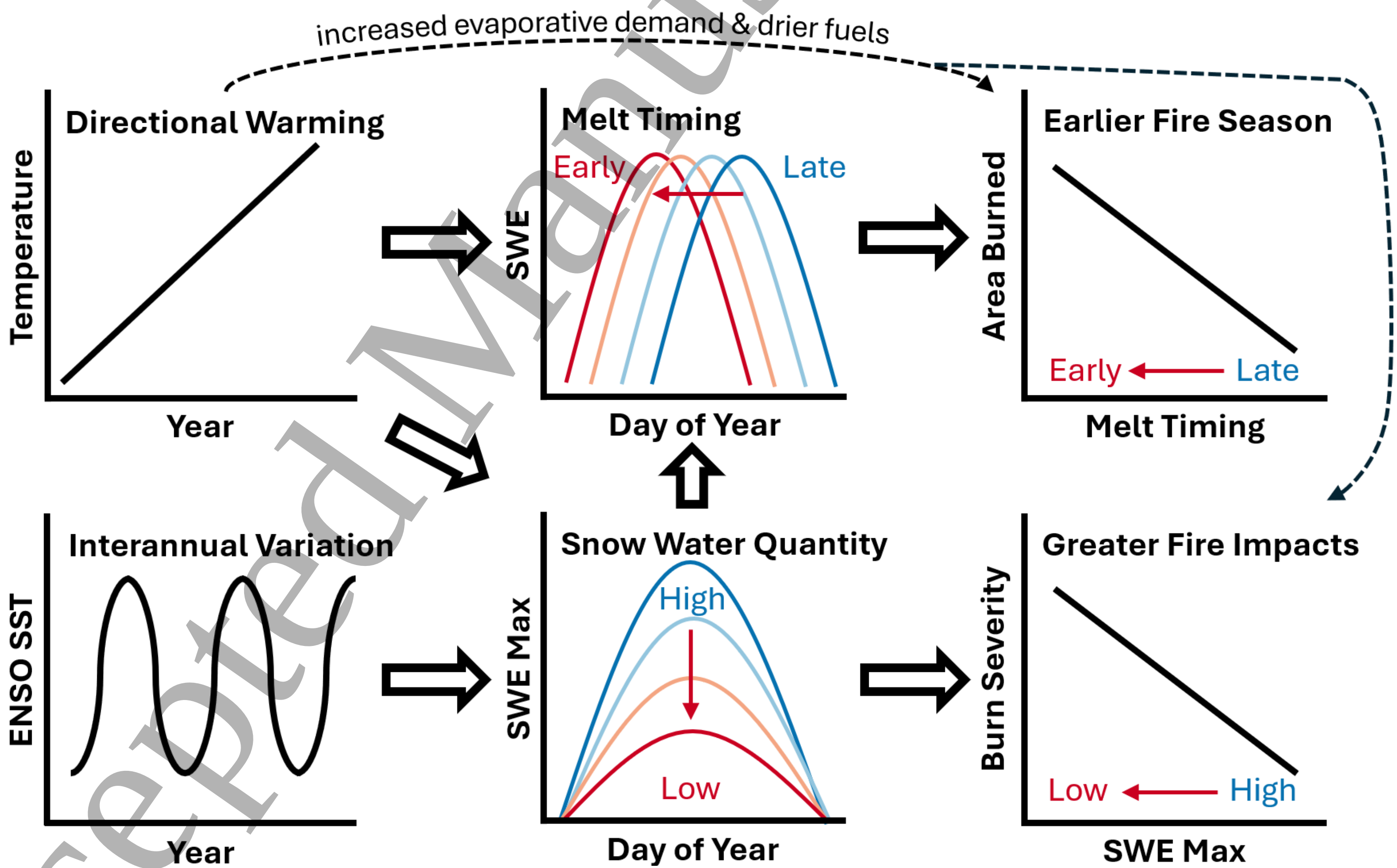

Figure 5. Climate warming, snowpack decline, and growing forest fire impacts to snow-dominated western US watersheds. Climate warming reduces snowpack and advances snowmelt timing, which is associated with longer fire seasons and greater area burned. Climate warming can also increase area burned and burn severity independent of effects on snowpack, through mechanisms not studied here, represented by dashed lines. Interannual variability in snowpack water quantity influences fire severity, with long-term decline and low SWE conditions associated with more severe burn outcomes that may promote increased tree mortality and altered watershed hydrologic function.

Discussion

Declining snowpack is linked with growing area burned and more severe fire

Changes in mountain snowpack associated with directional warming and climate teleconnections can alter fire season activity through two distinct but related influences: melt timing and total snow water. Over the 1985-2021 period, the timing of spring snowmelt consistently emerged as the strongest predictor of annual area burned across broad hydrogeographic regions, consistent with well-understood mechanisms. Early snowmelt provides more time for forests to dry with an earlier start to the fire season, thereby increasing opportunity for ignitions and fire progression, and increasing the total area burned during the fire season (Westerling et al. 2006). Novelly, however, we demonstrate here that years with low snow water storage are associated with more ***severe*** fire effects during the subsequent fire season. Low snow water quantity reduces soil moisture during the growing season (Maurer and Bowling 2014), which may have pronounced effects for deep-rooted woody species. Attendant reductions in live fuel moisture, particularly tree foliar moisture, would be expected to increase live fuel consumption, raise the probability of running crown fire, and increase tree mortality (Hood et al. 2018). Our findings contribute to a mechanistic understanding of broader climate-driven trends in which climate warming and intensifying aridity can amplify fire activity and exacerbate burn severity across the western US (Parks and Abatzoglou 2020).

While early snowmelt and/or low snow water storage set the stage for area burned and fire severity, their influences – and fire season outcomes – are also modulated by multiple climate factors, including precipitation, temperature, and the incidence of extreme fire weather events (Abatzoglou and Kolden 2013, Holden et al. 2018, Hart and Preston 2020, Potter and

McEvoy 2021). For example, early melt often coincides with warmer spring temperatures (Table S1.1; Stewart 2009, Clow 2010) that increase evapotranspiration and the drying of downed fuels. These temperature-driven reductions in fuel moisture (Flannigan et al. 2016) increase the likelihood of ignition and enhance fuel consumption, leading to higher burn severity (Sikkink and Keane 2012, Parks et al. 2018). Accordingly, Kitzberger et al. (2017) found that spring and winter temperatures exert stronger and more spatially consistent influences on area burned than snowmelt timing alone, highlighting temperature as a primary driver of both melt timing and fire activity across western North America. Although we found similar associations between spring temperature anomalies and subsequent fire season activity, here all four metrics of fire activity were more strongly associated with winter snowpack conditions. On average over the historical period, snowmelt is projected to occur 8.4 days earlier per degree of warming, with even larger shifts in California and the Lower Colorado HUCs (Figure S1.4). However, these estimates are a linear approximation over the historical record, and may not fully capture nonlinear responses under future warming scenarios (Gottlieb and Mankin 2025). Our findings reinforce that while early snowmelt may extend the seasonal window for fire, it is ultimately climate warming and increasing aridity—especially during the spring—that intensifies fire behavior and severity (Parks et al. 2025a). Subsequently, summer precipitation patterns, temperature, and the occurrence of extreme fire weather such as downslope wind events, also influence area burned and fire severity during the active fire season (Jolly et al. 2015, Abatzoglou et al. 2023). These summer conditions may contribute to or obscure the relationships with snowpack, with summer temperature anomalies accounting for a modest fraction of residual variation in the fire activity metrics studied here (Figure S1.2).

Annual area burned and burn severity are also linked through shared controls on flammability, fire growth rate, and fuel consumption across scales. Strong positive relationships exist between the extent of daily spread events, individual wildfires, annual area burned, and burn severity (Cansler and McKenzie 2014, McFarland et al. 2025). These relationships highlight the climate-mediated linkages between fire season duration and fuel moisture, as predicted here by early snowmelt and low snowpack. Low SWE_{max} is associated with early snow melt (Table S1.1; Elias et al. 2021, Musselman et al. 2017), which provisions a comparatively drier start to the fire season and may be an early signal of low-water conditions throughout the summer (Dierauer et al. 2018, Kinnard et al. 2022). Coupled with our finding that both burn severity outcomes were more strongly linked to SWE_{max} than to timing of peak accumulation or snowmelt, this suggests that while snowmelt timing governs amount of opportunity for dry-down and when fire activity begins, the compound effects of warming and reduced snow-derived moisture may precondition landscapes for more severe burn outcomes by reducing fuel moisture. Subsequent fire season climate and extreme weather conditions that promote fast-moving crown fires can then promote extreme spread events that are both disproportionately large and severe (McFarland et al. 2025).

Although melt timing and SWE_{max} appear to have direct and indirect influences on the fire season, the timing of peak accumulation and duration of the snow-free period were less explanatory snowpack metrics in our analyses. This may be because peak accumulation generally occurs midwinter well before the onset of the fire season, with melt timing simply more relevant for describing loss of snow cover and delivery of snow water to soils and vegetation. Similarly, SFP may be less explanatory because critical soil moisture and fuel conditions are set early in the fire season, making early-season snowpack quantity and melt timing more relevant than the total duration of snow-free conditions. Medler et al. (2002) similarly found no evidence linking maximum areal extent of winter snow cover to annual areas burned at the state level. This suggests that the critical mechanisms relevant to the fire season are not tied to the timing of peak snowpack, the maximum snow-covered area during winter, or the duration of snow-free conditions. Instead, snowpack persistence into the spring and the relative quantity of water delivered to the landscape are more consequential for shaping fire season dynamics. We note, however, that Melt.Date may appear most predictive not only because it is ecologically relevant, but also because the Western United States Snow Reanalysis dataset is most reliable for this metric, as the product is derived from observations of fractional snow-covered area that indicate snow disappearance (Fang et al. 2022), whereas peak SWE and its timing are modeled quantities subject to greater uncertainty.

Importantly, low SWE_{max} years that precondition drier fire seasons may result from altered snow accumulation processes, such as melt-freeze cycles or rain-on-snow events that are expected to become more frequent (Bouchard et al. 2024), rather than simply reduced winter precipitation. Even so, these dynamics still lead to reduced spring soil and fuel moisture, promoting fire spread (Holden et al. 2025), intensifying severity, and extending fire seasons. While our analyses isolate snowpack effects within historically snow-dominated pixels, this design necessarily excludes areas that may have already shifted away from reliable seasonal snow towards winter rain. Warming and increasing fire season fuel aridity have already increased fire activity in these transition zones (Alizadeh et al. 2021, Alizadeh et al. 2023), and further declines in upslope snowpack storage may further amplify these trends. Indeed, expanding our study area to include more of these transition zones (>0 mm SWE_{max} threshold; Appendix S2) indicates that SWE_{max} has the strongest association with all four fire activity metrics studied here, suggesting that the quantity of snowpack water delivered to the landscape plays a key role in preconditioning the fire season, even when lower elevation, low-snow areas are included. In contrast, restricting the study area to areas with historically greater snow accumulation (≥ 50 mm SWE_{max} threshold; Appendix S3) mirrors our primary findings (≥ 20 mm SWE_{max} threshold), with snowmelt timing portending fire season onset and area burned, and SWE_{max} influencing severity outcomes. Thus, our analysis of interannual snow-fire relationships exhibits consistent results across three study extents, complementing spatial analog approaches that relate climate gradients to snowpack (Luce et al. 2014).

Implications of directional change, ENSO, and long-term snowpack decline

Declines in SWE_{max} and earlier snowmelt over the 1985–2021 study period are most apparent in the southwestern US (in particular, the Rio Grande, Lower Colorado, and Arkansas-White-Red watersheds; Table 1, Fig. 2). Presently, forests in these watersheds appear most vulnerable to increases in area burned and more severe fire associated with snowpack decline. The fire season in the southwestern US typically occurs during spring months following snowmelt before the onset of the summer monsoon; thus, fire season outcomes may be more directly linked to snowpack here than in other regions, compounding biogeographic conditions that contribute to early fire seasons and greater areas burned (Crimmins et al. 2025). Following wildfire, forests in this region also appear most vulnerable to regeneration failure under a warmer and drier climate (Stevens-Rumann et al. 2018, Davis et al. 2023). In more northern regions with less widespread snowpack decline, areas with declining SWE_{max} and earlier snowmelt timing outpace those exhibiting increases or later melt. Despite this snowpack decline, northwestern US watersheds generally experience a later summer or fall fire season, and as such, fire season outcomes may be more strongly modulated by antecedent spring and summer conditions, and less strongly influenced by snowpack (Holden et al. 2018, Halofsky et al. 2020).

Our ability to detect long-term snowpack decline is limited by our relatively short timeseries, but ongoing climate warming coupled with shifts in precipitation regimes from snow to rain (Knowles et al. 2006, Musselman et al. 2021) suggest that areas currently exhibiting statistically nonsignificant snowpack decline may ultimately experience similar shifts (Mote et al. 2018). Our observational snowpack trends differ somewhat from projections in the intermountain West, which show smaller snowpack declines relative to maritime regions (Marshall et al. 2019, Siirila-Woodburn et al. 2021). These differences likely reflect the contrast between historical observations and modeled future scenarios, as well as local climate variability that can drive stronger declines in specific watersheds than suggested by regional-scale projections (Mote et al. 2018). Nevertheless, as the extent of snowpack decline expands, our findings suggest increasing area burned and more severe fire activity throughout western watersheds, with impacts to forest ecosystem functions.

Large-scale climate patterns such as ENSO introduce additional variability that can obscure or amplify long-term snowpack trends at regional scales. In turn, ENSO phases could extend or contract fire seasons and exacerbate or dampen severity differentially among regions. For example, we observed the largest areas with reduced $\%SWE_{max}$ and early melt during El Niño phases in northern regions where long-term trends were less prevalent, such as the Missouri and Pacific Northwest. Coupled with increases in fire season temperature and reductions in precipitation (Fasullo et al. 2018), our results highlight how El Niño conditions could produce longer and more severe fire seasons throughout the northwestern US. Meanwhile, El Niño phases bring wetter conditions with increased SWE_{max} and later snowmelt to the Lower Colorado and

Rio Grande regions in the south, potentially shortening fire seasons and reducing severity. In turn, La Niña phases would reverse these biogeographic patterns in snowpack conditions and their subsequent implications for the fire season.

Ongoing climate warming is projected to amplify ENSO variability, potentially increasing the frequency and magnitude of extreme events, although the extent and timing of such amplification remain uncertain (Cai et al. 2021, Maher et al. 2023, Stuecker et al. 2025, Swain et al. 2025). The implications of these changes for western North American temperature and precipitation patterns are highly uncertain. Because annual area burned tends to follow a heavy-tailed distribution (Strauss et al. 1989, Malamud et al. 2005), extreme ENSO years may disproportionately influence long-term fire activity through their effects on snowpack and seasonal climate. Thus, heightened fire activity following drier low snow years is unlikely to be offset by reductions after wetter high snow years. Accordingly, changing ENSO dynamics, extremes, and their influences on the fire season may further complicate regional snowpack trends and fire season predictability, highlighting the importance of incorporating evolving understanding of climate teleconnections into future assessments of fire risk and management strategies.

Adapting to snowpack decline

Here, we identify climatic mechanisms through which forests are burning at increasing extents and higher severities. Increasing area burned at high severity will increase the proportion of the landscape occupied by early-seral vegetation and immature trees (Parks and Abatzoglou 2020). Further, severe fire can promote conversion from forest to shrubland or grassland, particularly for tree species lacking adaptations to stand-replacing fire (e.g., resprouting or serotiny), and where postfire climate and disturbance regimes are increasingly divergent from the prefire conditions under which contemporary forests were established (Coop et al. 2020, Guiterman et al. 2022, Nemens et al. 2022). Postfire tree regeneration is strongly dependent on adequate moisture availability, which is also changing under the influence of directional warming and climate oscillations (Littlefield et al. 2020). Such changes have the potential to substantially alter biodiversity and habitat availability for dependent wildlife species (Jones et al. 2016, He et al. 2019), short-and long-term carbon dynamics (Hall et al. 2024), watershed hydrology and erosion (Ice et al. 2004). These potential effects of extended and more severe fire seasons underscore the need for adaptive strategies that enhance forest resilience and mitigate the risks of future fire seasons.

Forest management interventions such as thinning and prescribed fire may be essential to reducing the likelihood of severe fire under increasingly warm and dry conditions (Davis et al. 2024, Stephens et al. 2024). During years with poor snowpack conditions – particularly in southwestern regions experiencing pronounced long-term trends – forest thinning and surface fuel treatments may be especially valuable for reducing burn severity during extended future fire seasons. In contrast, years with high snowpack accrual and late melt could signal opportune conditions for prescribed fire and managed natural ignitions. Taking advantage of years with favorable snow conditions is crucial, as climate change is expected to reduce the number of days suitable for springtime prescribed burning by 25% (Swain et al. 2023). In the near term, these conditions may coincide with La Niña phases in the northwest, and conversely with El Niño phases in the southwest. Still, recent incidents of escaped managed fires such as the 2022 Calf Canyon/Hermits Peak fire in New Mexico emphasize that local fuel moisture conditions can override regional climate patterns. While broader drought conditions had improved before the

Las Dispensas prescribed fire that ultimately became the Hermits Peak fire, moisture levels in local fuels were lower than expected, highlighting the importance of thoroughly assessing site-specific conditions to mitigate escape risk (Mark et al. 2022).

Fire–snowpack feedbacks may further complicate future dynamics**.** While we focused on the influence of snowpack on regional fire seasons, fire activity may in turn alter snowpack dynamics. High-severity fire reduces forest cover and carbon storage while increasing snow exposure and potentially enhancing snowpack water yield in the short term (Varhola et al. 2010). However, these effects may be offset by elevated evapotranspiration from exposed soils and regrowth. Postfire reductions in canopy cover and albedo can accelerate melt for over a decade (Gleason et al. 2019, Koshkin et al. 2022), potentially lengthening fire seasons in burned areas. Recent work confirms that postfire snowmelt occurs earlier across the majority of snow-dominated watersheds, with the strongest shifts in lower-elevation and warmer sites, reinforcing the potential for fire-driven modifications to snow dynamics (Giovando and Niemann 2022, Koshkin et al. 2025). These feedbacks could further reinforce climate-driven changes in snowmelt timing and fire regimes. Replanting strategies that restore canopy cover and promote snow retention may be increasingly important for future fire and water resource resilience.

Conclusions

Our regional-scale analyses suggest that as snowpack declines throughout the western US, we should anticipate broad trends of amplified fire activity and increased burn severity. Reduced snow water storage and early melt precondition landscapes for severe fire by decreasing early spring soil and foliar moisture, which may promote greater fuel aridity throughout the fire season. These effects are compounded by warming temperatures and modulated by climate patterns such as ENSO that can offset or exacerbate snowpack decline at regional scales. Southwestern watersheds, where snowpack decline is most pronounced and fire seasons are closely tied to spring conditions, appear particularly vulnerable. Our findings underscore the importance of adaptive forest management strategies that respond to snowpack conditions, such as leveraging high-snow years for proactive forest treatment to help reduce burn severity during low-snow years. Future research at the level of individual fires and across different forest types or elevations could provide more targeted guidance for managing increasingly early and severe fire seasons.

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Data Availability Statement

The annual snowpack and fire season data that support the findings of this study are included in Appendix S4.

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