

Microclimate and environmental change decades following repeat wildfire and vegetation type conversion in a central Arizona ponderosa pine forest

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ABSTRACT

Wildfire is altering forested landscapes across the southwestern United States. There is opportunity to better understand regional landscape change by comparing more and less wildfire-affected forest areas at local scales. We evaluated meteorological and above- and belowground environmental variables in less-disturbed (PIPO: 2016 low-severity wildfire) and more-disturbed (PIPO-burned: 2000 stand-replacing, 2016 low-severity) ponderosa pine forest in central Arizona, USA. PIPO-burned experienced low conifer recovery and extensive woody plant type conversion following the 2000 wildfire. Using ground-based instrumentation and snow transect data, we found considerable abiotic differences between PIPO and PIPO-burned during a recent period (2022–2025 water years) with near-average air temperatures and precipitation, and one very low precipitation season (2025). These included significantly higher warm season (April–September) and cool season (October–March) solar radiation, wind speed, surface and soil temperature, and reference evapotranspiration. Although average snow depth was significantly higher at PIPO-burned, its snow often melted earlier in the spring. Near surface soil moisture (10, 20, 40 cm depth) at PIPO-burned was significantly lower than PIPO in both the warm and cool seasons. Indeed, we found that the density distributions of soil temperature and moisture were often dissimilar between PIPO and PIPO-burned. Underscoring the severity of these changes, we found that many meteorological and environmental variables at PIPO-burned (2168 m) were on average more similar to those of a lower elevation piñon pine–juniper woodland (1605 m) than they were to the adjacent PIPO (2190 m). These local abiotic changes, here associated with repeat wildfire and woody plant type conversion over the past 25 years, illustrate the considerable transformation of forested landscapes in the southwestern US.

1. Introduction

Increasingly arid climate conditions and the legacy of human wildfire and forest management have led to an increase in the frequency and geographic extent of severe, stand-replacing wildfire in the western United States (Calkin et al., 2015; Singleton et al., 2019; Parks et al., 2023). Wildfire is predicted to continue to expand across the region, including an increase in repeat wildfire events in previously burned locations (Stevens-Rumann and Morgan, 2016; Abatzoglou et al., 2021). Wildfire increases – alongside other disturbances including heat and drought – are driving declines in coniferous forest cover in the western US, and the long term persistence of many forested areas is uncertain (van Mantgem et al., 2009; Williams et al., 2013; Stevens-Rumann et al., 2017). Following stand-replacing wildfire events, many locations

throughout the region are experiencing type conversion of coniferous forest towards non-forest vegetation communities, in many cases dominated by woody species (Coop et al., 2020; Guiterman et al., 2022). These type conversions often occur in conjunction with limited conifer reestablishment due to loss of seed source and/or less favorable environmental conditions such as increased soil temperature and reduced soil moisture (Korb et al., 2019; Marsh et al., 2022; Stevens-Rumann et al., 2022). Yet, natural conifer recovery and type conversion towards non-forest are inconsistent and influenced by complex combinations of factors including wildfire extent and severity, regional climate conditions, meteorological variation, vegetation community attributes, and landscape–topographic factors such as aspect, slope, and soil characteristics (Parks et al., 2019; Coop et al., 2020; Hill and Field, 2021).

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As wildfire impacts expand across the western US, it is imperative to develop greater understanding of how stand-replacing wildfire alters forested landscapes, and better constrain understanding of divergent trajectories of forest recovery and type conversion to non-forest.

The way that stand-replacing disturbances – including wildfire and other disturbances such as insect-induced tree mortality – alter local microclimate and above- and belowground environmental conditions offers insights for understanding wildfire impacts to coniferous forests. General expectations are for burned landscapes to experience higher solar radiation, air temperatures, and evaporative demand than intact forest with higher canopy cover, although actual evapotranspiration may decrease due to greater water runoff (Ma et al., 2020; Wolf et al., 2021; Marsh et al., 2022). Snowpack is expected to be higher in burned landscapes due to lower canopy interception, but may be more spatially variable and melt at a higher rate (Harpold et al., 2015; Maxwell et al., 2019; Moeser et al., 2020). Similarly, soil moisture may also be higher immediately following precipitation events and snowmelt, but may be lower on average and during low precipitation periods due to greater snowpack sublimation, surface water runoff, and bare soil evaporation (Ebel, 2013; Biederman et al., 2014b,a; Wooten et al., 2022). Ground surface and belowground, near-surface soil temperatures are expected to be higher in burned landscapes due to higher incident solar radiation and lower latent heat flux (Montes-Helu et al., 2009; Ma et al., 2010; Wooten et al., 2022). The utility of these generalizations is supported by the different settings, fire and management histories, and meteorological conditions of the studies from which they were derived, and suggest the potential for substantial change to microclimate and environment following stand-replacing wildfire across the western US.

Despite the apparent consensus on stand-replacing wildfire impacts to microclimate and environment, key limitations restrict the broad application of these findings. First, the majority of present studies were conducted in higher elevation mixed conifer forests and in northern latitudes of the western US (see Montes-Helu et al., 2009 for an exception), and due to their differing foci many report only a subset of microclimate and environmental variables, which complicates comparison of results across multiple studies. It is therefore unclear how applicable generalized effects are to less studied subregions, such as dry ponderosa pine (*Pinus ponderosa*)-dominated forests in the southwestern US (SWUS), where combinations of novel climate conditions and wildfire may strongly restrict forest recovery and promote woody plant dominance (Barton and Poulos, 2018; Davis et al., 2019; Singleton et al., 2021). Second, we lack comprehensive documentation of microclimate and environmental change over longer time periods following stand-replacing wildfire (multiple decades) and across variation in post-wildfire recovery, which limits our ability to determine the conditions under which long term conifer recovery can occur naturally or via active restoration (Brown and Wu, 2005; Wasserman et al., 2022). Finally, and perhaps most importantly, we often lack a suitable reference for determining the severity of post-wildfire changes. That is, although there may be statistically significant differences in microclimate and environmental variables between burned and unburned landscapes, do these differences indicate meaningful change to the physical processes that govern ecosystem function?

The Workman Creek watershed of the United States Department of Agriculture (USDA) Forest Service, Sierra Ancha Experimental Forest (SAEF) in central Arizona, USA, has experienced repeat wildfires that mirror the increase of wildfire-affected forest landscapes across the SWUS. The 2000 Coon Creek fire was stand-replacing and burned 3700 ha of ponderosa pine-dominated forest. A dense stand of New Mexico locust (*Robinia neomexicana*) established in the most severely burned portion of the watershed, slowing conifer recovery. A repeat low-severity, non-stand-replacing wildfire in 2016, the Juniper fire, burned 12,400 ha, and following this wildfire New Mexico locust came to dominate vegetation structure and transform the burned landscape to woody plant dominance. Burned areas were not reseeded or planted

with conifer species following either wildfire. This post-wildfire transformation of vegetation dominance at the SAEF resembles documented type conversion towards woody plant dominance throughout the SWUS and the western United States (McIntyre et al., 2015; Coop et al., 2020; Hurteau et al., 2025). The SAEF is located near the southern latitude boundary of the Mogollon Highlands Ecoregion, which includes a unique and biodiverse confluence of desert, woodland, and forest vegetation communities (Fleischner et al., 2017), and is a trailing edge boundary of ponderosa pine distribution that has experienced considerable vegetation type conversion over the past 40 years (Rodman et al., 2022). Wildfire-affected landscapes of the Workman Creek watershed therefore provide an opportunity to expand understanding of stand-replacing wildfire effects to microclimate and environment at a warmer and often more water-limited southern boundary of ponderosa pine, and can provide insight on longer-term transitions towards woody plant dominance in wildfire-affected SWUS landscapes.

We used long term (1990s–present) remote sensing imagery to characterize less wildfire-impacted (PIPO: 2016 low-severity wildfire) and more impacted (PIPO-burned: 2000 stand-replacing wildfire; 2016 low-severity) ponderosa pine forest areas at the SAEF, and used ground based field instrumentation and snow depth transect data from Snow-tography (automated snow photography) to compare the microclimate and above- and belowground environmental characteristics of PIPO and PIPO-burned over a more recent time period (2022–2025 water years). We compared the mean and distribution of meteorological and environmental variables between PIPO and PIPO-burned, and also compared similarity in the mean and distribution of these variables at PIPO-burned to those of PIPO and a lower elevation piñon pine–juniper woodland (PJ) at the SAEF. Our objectives were to: (1) Determine significant differences in microclimate and environmental variables between PIPO and PIPO-burned in the warm season (April–September) and cool season (October–March); (2) Assess the severity of meteorological and environmental change at PIPO-burned by comparing the mean and distribution of warm season and cool season variables at PIPO-burned to those of PIPO and lower elevation PJ; and (3) Characterize post-wildfire meteorology and broad vegetation cover classes in PIPO and PIPO-burned, providing context between our SAEF study area and post-wildfire changes occurring in the SWUS. Together, these objectives quantify sustained abiotic changes in a formerly ponderosa pine-dominated landscape following stand-replacing and repeat wildfire, with an overarching goal of developing new insight on stand-replacing wildfire impacts in dry coniferous forests of the SWUS.

2. Methods

2.1. Site description

The SAEF was established in the Tonto National Forest in Arizona, USA, in 1938 to study water resources in natural and managed ecosystems (Gottfried and Neary, 2015; Fig. 1). Reflecting its location near the southern boundary of the Mogollon Highlands Ecoregion, the SAEF includes ecosystems from low elevation desert and Arizona chaparral (1100–1400 m) to high elevation mixed conifer forest (1800–2300 m; Pase and Johnson, 1968). SAEF ponderosa pine forests are located at elevations > 1500 m, and co-occur with subdominant species including New Mexico locust, Gambel oak (*Quercus gambelii*), and Douglas fir (*Pseudotsuga menziesii*). Using Daymet gridded meteorological estimates and 2025 data from a nearby (~1 km distance) USDA Natural Resources Conservation Service (NRCS) SNOTEL station (Thornton et al., 2022; Fleming et al., 2023), water year precipitation at our SAEF ponderosa pine study area was 781 mm, with 65% occurring during the cool season (October to March; 1981–2025). Mean daily air temperature was 15.5°C in the warm season and 5.4°C in the cool season. Piñon pine–juniper woodlands at the SAEF are dominated by piñon pine (*Pinus edulis*), one-seed juniper (*Juniperus monosperma*),

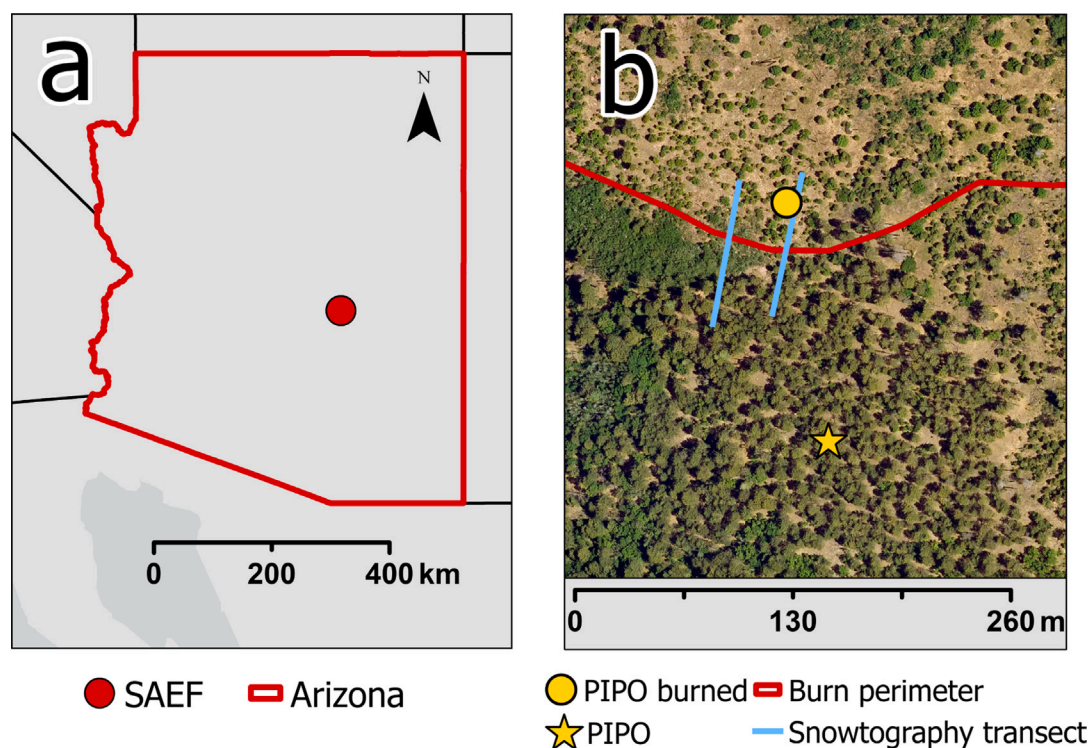


Fig. 1. Map illustrating the location of the Sierra Ancha Experimental Forest (SAEF; red dot) in Arizona, USA (red outline; Panel a), and a National Agriculture Imagery Program (NAIP) image from 2023 illustrating the burn perimeter of the Coon Creek fire (red), locations of snowtopography transects (blue), and locations of instrumented stations (yellow; Panel b).

and shrub live oak (*Quercus turbinella*), with understory vegetation that is characteristic of Arizona chaparral (Pase and Johnson, 1968). Using Daymet gridded meteorological estimates, water year precipitation at our SAEF piñon pine–juniper woodland study area was 655 mm, with 64% occurring during the cool season (1981–2024; Thornton et al., 2022). Mean daily air temperature was 21.3°C in the warm season and 9.0°C in the cool season (Thornton et al., 2022).

Our ponderosa pine study area was located in the SAEF Workman Creek watershed, with adjacent instrumented monitoring stations (PIPO, PIPO-burned) located on either side of the 2000 Coon Creek fire boundary (Fig. 1b; Supplementary Figure S1). Both PIPO and PIPO-burned experienced the 2016 low-severity Juniper wildfire. A third wildfire in August, 2025, the Billy fire, destroyed the PIPO instrumented station and was potentially stand-replacing in most of the PIPO area, but is not included in this study. Characterizations of the immediate area surrounding instrumented stations illustrate differences in the overstory and understory of PIPO, PIPO-burned, and PJ (single 5.0 m² plots centered on instrumented stations; located on shallow slopes in vegetation interspaces; conducted in 2022; see Pirtel et al., 2021 for methodology). Although these characterizations do not fully capture vegetation differences or variation between burned and unburned areas (they were conducted for computational water balance model parametrization of instrument location), they illustrate general differences between them. PIPO had higher basal area, larger mean diameter at breast height (DBH) of adult trees, and higher canopy cover than PIPO-burned and PJ (Table 1). PIPO burned had higher herbaceous cover than PIPO and PJ, and PJ had higher shrub cover than PIPO and PIPO-burned (Table 1). PIPO had higher litter cover than PIPO-burned and PJ, and PIPO and PIPO-burned had similar coarse woody debris (CWD) cover that was higher than that of PJ (Table 1). All three areas had loam or silty loam soils from 0–20 cm soil depth, and silt loam (PIPO and PIPO-burned) or clay loam (PJ) soils from 20–40 cm depth (Table 1).

Recognizing potential slope and aspect effects to solar radiation between PIPO (slope: 1.0°; aspect: 310°) and PIPO-burned (slope: 4.8°;

aspect: 330°; Table 1), we conducted a top-of-atmosphere, geometric projection of direct and diffuse solar radiation for the surface of each station location as a plane (i.e., no vegetation or topographic sky view shading; Campbell and Norman, 1998). On an annual scale, PIPO-burned was estimated to receive 3.8% less direct and 0.2% less diffuse solar radiation than PIPO, primarily due to differences in aspect. Differences in slope and aspect are unlikely to have resulted in meaningful differences in evaporative demand and soil surface heating potential between PIPO and PIPO-burned.

Physical soil properties differed slightly between PIPO and PIPO-burned, with PIPO having lower sand content and higher clay content compared to PIPO-burned (Table 1; measured at the Soil, Water and Forage Analytical Laboratory (SWFAL) at Oklahoma State University [www.soiltesting.okstate.edu]). We used the Rosetta 3 model to estimate differences in soil saturated hydraulic conductivity [K_s ; cm d⁻¹] between PIPO and PIPO-burned (Zhang and Schaap, 2017). K_s was estimated to be slightly lower at PIPO compared to PIPO-burned at 0–20 cm soil depth (PIPO: 5.5 cm d⁻¹; PIPO-burned: 5.9 cm d⁻¹; Table 1). Calculation of the effective saturated hydraulic conductivity normal to the slope ($K_s \cos \gamma$), where γ is % slope, resulted in no meaningful change to K_s values. Differences in physical soil properties and slope were therefore unlikely to have resulted in meaningful differences in water infiltration between PIPO and PIPO-burned.

2.2. Landcover and vegetation

We utilized USDA National Agriculture Imagery Program (NAIP) imagery at 0.3 m² spatial resolution to classify land cover in PIPO (~19.7 ha) and PIPO-burned (~97.6 ha) areas in 2023 (23 years after the 2000 wildfire, 7 years after the 2016 wildfire; see Supplementary Figure S1 for areas classified). We classified land cover into 4 broad classes (bare soil/rock, conifer vegetation, non-conifer vegetation, shadow). We performed a supervised object-based image analysis (OBIA) classification for each NAIP image in ArcGIS Pro (ESRI, ArcGIS desktop: Release

Table 1

Single plot site characterizations of a 5.0 m² area surrounding instrumented stations located in ponderosa pine forest (PIPO), burned ponderosa pine forest (PIPO-burned), and piñon pine-juniper woodland (PJ) at the Sierra Ancha Experimental Forest. Characterizations include wildfire history, elevation [m], slope [°], aspect [°], basal area [m² ha⁻¹], mean diameter at breast height of adult trees [DBH: cm], overstory canopy cover [%], herbaceous cover [%], shrub cover [%], coarse woody debris cover [CWD: %], litter cover [%], soil texture classification at 0–20 cm and 20–40 cm depth, soil sand, clay, and organic matter content at 0–20 cm and 20–40 cm depth [%], and estimated soil saturated hydraulic conductivity at 0–20 cm depth [K_s: cm d⁻¹].

Variable	Units	PIPO	PIPO-burned	PJ
Wildfire history	–	2016 low-severity	2000 stand-replacing 2016 low-severity	–
Elevation	m	2190	2168	1605
Slope	°	1.0	4.8	11.0
Aspect	°	310	330	10
Basal area	m ² ha ⁻¹	30	0	0
DBH	cm	44.6	11.5	0
Canopy	%	74.0	3.2	2.5
Herbaceous	%	2.3	15.0	5.0
Shrub	%	0	0	30.0
Litter	%	85.8	19.2	15.0
CWD	%	7.5	28.0	28.0
Soil classification	0–20 cm 20–40 cm	Loam Silt Loam	Silt Loam Silt Loam	Loam Clay Loam
Sand	%, 0–20 cm %, 20–40 cm	30.0 27.5	35.0 32.5	40.0 37.5
Clay	%, 0–20 cm %, 20–40 cm	20.0 17.5	12.5 15.0	22.5 27.5
Organic	%, 0–20 cm %, 20–40 cm	3.1 1.3	5.7 2.8	3.5 2.4
K _s	cm d ⁻¹ , 0–20 cm	5.5	5.9	3.3

3.4.2, Redlands, CA, USA), with a minimum of 50 training samples of each land cover class to train the model. We used the Support Vector Machine algorithm to delineate images into the four land cover classes (Cortes and Vapnik, 1995). Following the supervised OBIA classification, we conducted an accuracy assessment for each image in ArcGIS Pro. To evaluate the classification, we generated one hundred accuracy assessment points using a stratified random sample, and then determined the land cover class for each point (reference data). We calculated the Kappa coefficient to quantify agreement between the supervised OBIA classification and the reference data (Cohen, 1960).

To provide perspective on pre- and post-wildfire vegetation at PIPO and PIPO-burned, we used Landsat imagery to calculate mean Normalized Difference Vegetation Index (NDVI) values for PIPO and PIPO-burned areas from 1992–2023 (Rouse et al., 1974). Using Google Earth Engine (Gorelick et al., 2017), we acquired top-of-atmosphere imagery from Landsat 5 (1992–2013) and Landsat 7 (1999–2023), both Collection 2, Tier 1, with a 30 m² resolution. We used all images in our analyses, excepting those with >10% cloud cover. To address systematic data gaps in Landsat 7 imagery resulting from the Scan Line Corrector failure in May, 2003, we implemented a gapfilling procedure that applied a focal mean filter with a 1-pixel radius, a square kernel, and two iterations to interpolate missing pixel values based on their neighboring pixels. We blended the resulting smoothed image with the original image, preserving valid pixels and interpolating the missing data (Chen et al., 2011). For each image, we calculated the spatial mean of NDVI values separately for the PIPO and PIPO-burned areas. To ensure temporal consistency between Landsat 5 and Landsat 7, we compared their mean NDVI values during the 1999–2013 overlap period using two-tailed t-tests ($p < 0.05$). We found no significant difference between Landsat 5 and Landsat 7 for warm season (April–September; $p = 0.09$) or cool season (October–March; $p = 0.07$) images, and therefore used both Landsat 5 and 7 imagery during the overlap period. We note that our evaluations of land cover and NDVI are not the primary analytical focus of the study, and are instead intended to provide perspective on pre- and post-wildfire landscape change between PIPO and PIPO-burned areas.

2.3. Long-term meteorology and snow water equivalent

We obtained mean daily air temperature [Ta: °C] and total daily precipitation [P: mm] data for our ponderosa pine study area at 1.0 km² resolution from Daymet (Thornton et al., 2022). PIPO and PIPO-burned stations were located 140 m apart from one another, in the same 1.0 km² Daymet cell. We obtained 2025 Ta, P, and 1980–2024 mean daily snow water equivalent [SWE: mm] data from a USDA NRCS SNOTEL station, located in a forest interspace approximately 1 km from the PIPO and PIPO-burned stations (Fleming et al., 2023). We used Daymet P and Ta data due to large data gaps in the historical SNOTEL data. We evaluated interannual variation in warm season and cool season mean daily Ta and total P for 1981–2025 water years in the context of the long-term mean and standard deviation of Ta and P. We evaluated maximum observed SWE in each water year in the context of the long-term mean and standard deviation of maximum SWE.

2.4. 2021–2025 snow depth

We obtained snow depth measurements from snowtopography transects located in the PIPO and PIPO-burned areas from 2021–2025. Snowtopography employs graduated stakes and repeat photography from automated cameras to collect images of snow depth across linear transects, capturing snow depth variation across space and time (Payton et al., 2021; Dwivedi et al., 2023a). We derived daily measurements of snow depth from images collected across two parallel, 84 m long transects, each located from PIPO into PIPO-burned areas (see Fig. 1b–d for transect locations). We calculated daily mean snow depth for PIPO and PIPO-burned areas, only using images from stakes located in the PIPO (7 total stakes; stakes 1–4 and 19–21, for reference) and PIPO-burned (17 total; stakes 11–18 and 28–36) areas. We did not include stakes located in the burn perimeter, and selected PIPO-burned stakes that were close in proximity to the PIPO-burned instrumented station. We evaluated the density distributions of daily snow depth between PIPO and PIPO-burned areas in 2022–2025 water years using two-tailed Welch's t-tests, with significance determined at $p < 0.05$. Our statistical analysis only included days with snow cover at one or more transect stakes.

2.5. Basic comparison of microclimate and above- and belowground environment

We installed identical instrumented microclimate and environmental monitoring stations in the PIPO and PIPO-burned areas in May, 2022, and in the PJ area in October, 2022 (see Fig. 1b–d for PIPO and PIPO-burned station locations). Microclimate measurements included P, Ta, solar radiation [S: $\text{W m}^{-2} \text{ s}^{-1}$], wind speed [u: m s^{-1}], and relative humidity [RH: %] (Campbell Scientific ClimaVue50, Logan, UT, USA; 1.0 m height). We calculated vapor pressure deficit [VPD: kPa] and reference evapotranspiration [ET_0 : mm d^{-1}] from these measurements. Above- and belowground environmental measurements included soil surface temperature [Tsfc: $^{\circ}\text{C}$] (Apogee SI-111, Logan, UT, USA), soil temperature [Ts: $^{\circ}\text{C}$; 0–15 cm depth] (Campbell Scientific TCAV, Logan, UT, USA), soil heat flux [SHF: $\text{W m}^{-2} \text{ s}^{-1}$; 16 cm depth] (Hukseflux HFP01, Delft, Netherlands) and soil volumetric water content [VWC: $\text{m}^3 \text{ m}^{-3}$] (Meter TEROS10, Pullman, WA, USA; 10, 20, 40 cm depth). We calculated daily mean ground heat flux [G: W m^{-2}] from Ts and SHF measurements. Data were collected at 1-minute intervals, stored as 15-minute values (Campbell Scientific CR1000X, Logan, UT, USA), and mean daily values for each variable were calculated using R statistical computing software (R Development Core Team, 2023). Missing or erroneous values constituted less than 0.1% of daily data. Data gaps ≤ 3 days in length were gapfilled using a moving window average from the same variable at the same station, and gaps > 3 days in length were gapfilled from linear relationships developed with nearby stations ($R^2 > 0.9$). Large data gaps (≥ 10 days) only occurred for Tsfc at PIPO-burned (2022: DOY 205–215; 2023: DOY 9–130).

We determined if there were significant differences in microclimate and temperature variables between PIPO and PIPO-burned in the warm season and cool season using two-tailed Welch's t-tests, with significance determined at $p < 0.05$. We present monthly boxplots of mean daily G for PIPO and PIPO-burned. We present results using 2022–2025 combined values when significant differences also occurred in each individual year and season. We evaluated the density distributions of warm season and cool season VWC between PIPO and PIPO-burned from 2022–2025 at each soil depth (10, 20, 40 cm) independently. Due to the large sample sizes (630 observations at each depth in the warm season, 547 in the cool season), we determined significant differences in VWC between PIPO and PIPO-burned in the warm season and cool season using two-tailed Welch's t-tests, with significance determined at $p < 0.05$.

2.6. Advanced comparison of microclimate and above- and belowground environment

We used Kullback–Leibler divergence [K–L: bits] to quantify shared information in the density distributions of meteorological and environmental variables (2022–2025 data combined) between PIPO and PIPO-burned in the warm season and cool season. K–L is a measure of 'surprise' in generating an unknown probability distribution (PIPO-burned in our analyses) of a variable from a second known distribution (PIPO), given prior expectation that the two distributions are identical. We calculated K–L using the R package *entropy* (Hausser and Strimmer, 2009). Higher K–L values indicate greater "surprise" or dissimilarity in the distributions of a variable between PIPO and PIPO-burned, providing an assessment of variable dynamics that is not influenced by differences in magnitude. Calculation of K–L divergence requires binning density distributions of each variable in histograms. We calculated K–L using the largest number of bins between 6 and 24 (determined for each variable and season independently), where each bin included at least one observation. All variables were evaluated using 7 to 24 bins. We visualized K–L using pie charts, where the length of each segment (nonlinear with segments of 0.1, 0.25, 0.5, 1.0, and 1.5 bits) illustrates greater dissimilarity of the distribution of a variable at PIPO-burned given the expectation that its distribution is identical to that of PIPO

(larger values indicate greater dissimilarity). Pie charts were intended to visualize differences in K–L across multiple variables, and calculated K–L values for each variable were included in a separate table.

In a final analysis, we used a scoring procedure to determine how similar the mean of meteorological and environmental variables in the warm season and cool season (2022–2025 data combined) at PIPO-burned were to those at PIPO versus PJ. Our scoring was scaled from 1.0 to 2.0, where a score of 1.0 indicated that the PIPO-burned value was identical to or directionally exceeded the PIPO value, 2.0 indicated that the PIPO-burned value was identical to or directionally exceeded the PJ value, and a score in between reflected the PIPO-burned value's proportion between the PIPO and PJ values. For PIPO-burned values between PIPO and PJ, we calculated scores as:

$$\text{Score} = 1 + \text{abs} \left| \frac{\text{PIPO} - \text{burned} - \text{PIPO}}{\text{PIPO} - \text{PJ}} \right| \quad (1)$$

For a simplified example, consider a hypothetical variable with a mean value of 2.0 at PIPO and 5.0 at PJ. If the PIPO-burned value was ≤ 2.0 , it would be scored 1.0 (identical to or directionally exceeding PIPO). If it was ≥ 5.0 , it would be scored 2.0 (identical to or directionally exceeding PJ). If it were 3.0, it would be scored 1.33 (proportion between PIPO and PJ). We visualized scores using pie charts, where the length of each segment (from 1.0 to 2.0) reflects the PIPO-burned score for the mean of different meteorological and environmental variables, and a score exceeding 1.5 indicates a PIPO-burned variable value more similar to PJ than PIPO. Pie charts were intended to visualize differences in mean variable values across multiple variables on a single, dimensionless scale. Mean dimensional values and standard deviations for each variable were included in a separate table.

3. Results

3.1. Long-term landcover, vegetation greenness, and meteorology

Land cover classification illustrates differences in vegetation cover between PIPO and PIPO-burned areas following the 2000 and 2016 wildfires (imagery in 2023). PIPO had a larger percentage of area classified as conifer vegetation and shadow (44.4%; likely shading by conifer trees of other conifers) compared to PIPO-burned (12.1%), whereas PIPO-burned had a larger area classified as non-conifer vegetation (84.8%) than PIPO (46.4%; Supplementary Table S1). NDVI values illustrate declines in vegetation greenness in PIPO and PIPO-burned areas following the 2000 wildfire, with more pronounced declines in PIPO-burned where the wildfire was stand-replacing. Sustained differences in cool season NDVI between PIPO and PIPO-burned following the 2000 wildfire correspond to type conversion of PIPO-burned to deciduous woody vegetation, although cool season NDVI declines in PIPO are also occurring due to ongoing woody plant expansion in this area as well (Supplementary Figure S2b,d). Both areas exhibited immediate, short-term (3–5 year) declines in warm season NDVI values following the 2016 low-severity wildfire, followed by recovery of warm-season NDVI values that resembled pre-wildfire values (Supplementary Figure S2).

Long-term meteorological data shows that seasonal precipitation (P) totals in the post-2000 period at the SAEF were near-average, with a greater number of low P cool seasons (below one standard deviation of the 1981–2024 mean; Fig. 2a,b). Warm season air temperature (Ta) was also near-average, whereas cool season Ta was higher post-2000 (Fig. 2c,d). Maximum snow water equivalent (SWE) was below-average post-2000, with the exception of two very high snow years in 2009 and 2010 water years (Fig. 2e). The 2022–2025 time period with instrumentation data experienced below-average warm season P and near-average warm season Ta (Fig. 2a,c). Cool season P and maximum SWE was below average (excepting a high P and SWE winter in WY 2023; Fig. 2b,e). Cool season Ta was more variable, with two near-average water years (2022, 2024), one below-average (2023), and one above-average (2025; Fig. 2d).

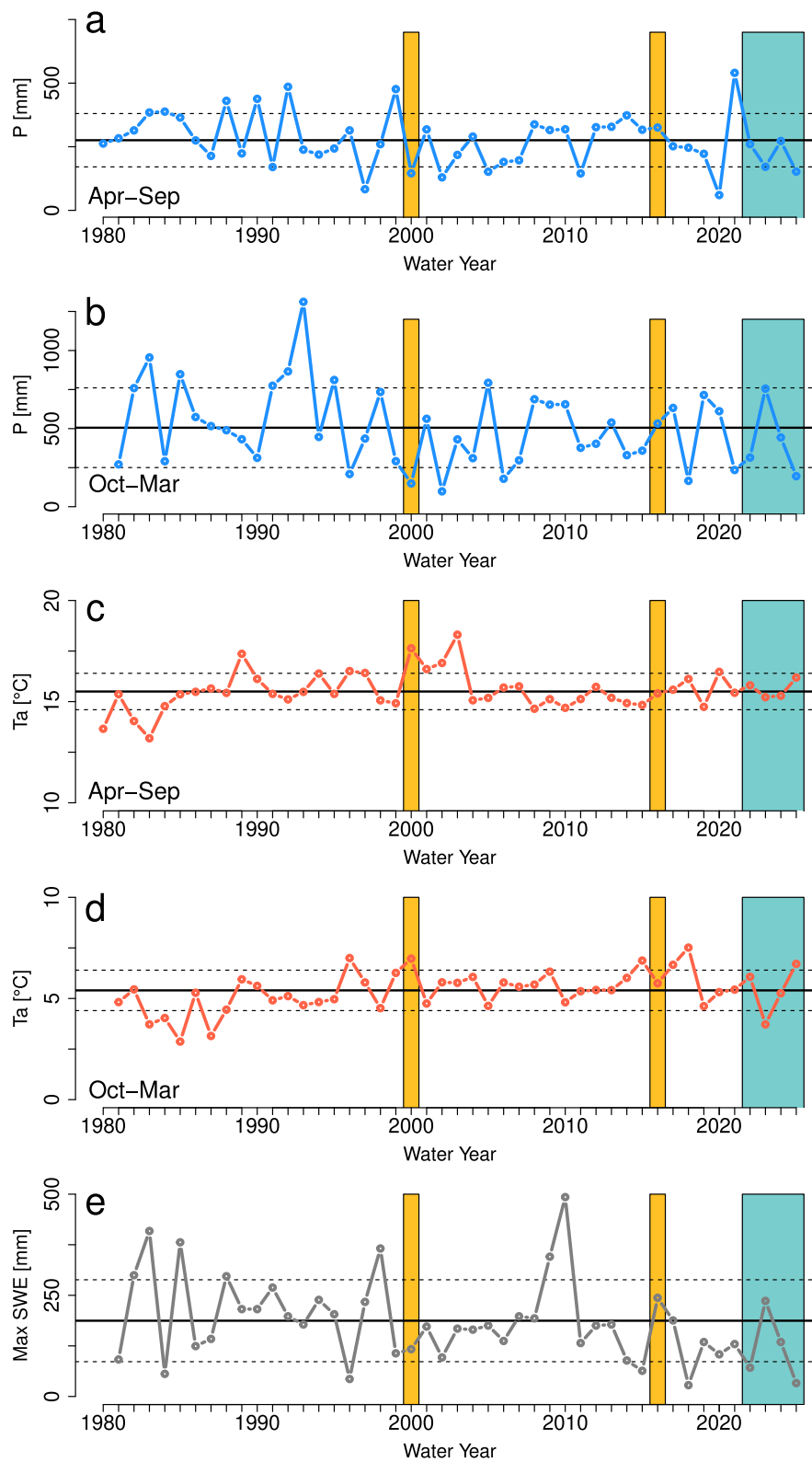


Fig. 2. Timeseries of warm season (April–September) and cool season (October–March) total precipitation [P: mm] (Panels a,b), mean daily air temperature [Ta: °C] (Panels c,d), and maximum snow water equivalent [SWE: mm] (Panel e) data for ponderosa pine forest areas during 1980–2025 water years. In each panel, ensemble mean values are illustrated by the black line, and the dotted lines illustrate ± 1 standard deviation from the mean. The 2000 Coon Creek and 2016 Juniper fires are highlighted in yellow, and the time period with instrumentation data is highlighted in blue (2022–2025).

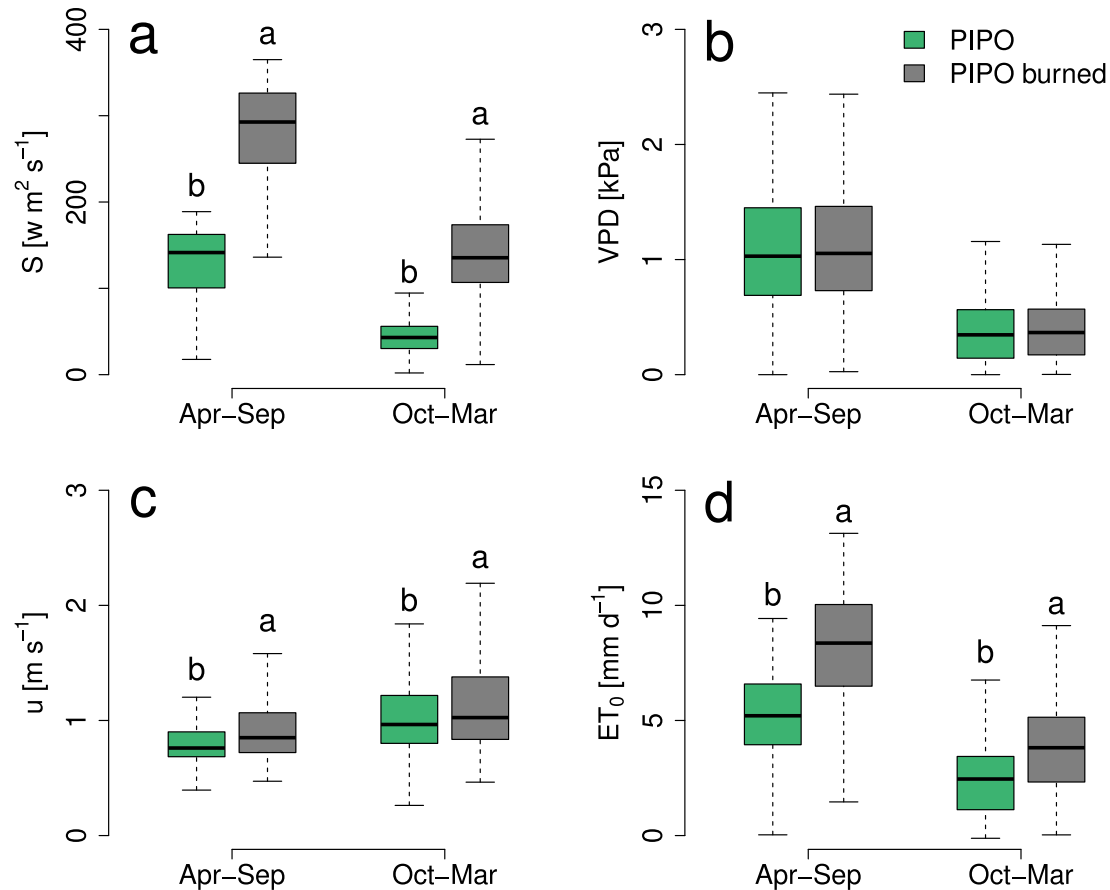


Fig. 3. Boxplots illustrating the mean and interquartile range of warm season (April–September) and cool season (October–March) solar radiation [S : $\text{W m}^{-2} \text{s}^{-1}$] (Panel a), vapor pressure deficit [VPD: kPa] (Panel b), wind speed [u : m s^{-1}] (Panel c), and reference evapotranspiration [ET_0 : mm d^{-1}] (Panel d) at ponderosa pine (PIPO) and burned ponderosa pine (PIPO-burned) stations from 2022–2025. Letters indicate significant differences in the mean, determined using two-tailed Welch's t-tests (seasons evaluated independently; $p < 0.05$). All significant differences using 2022–2025 combined data were also significant in each individual year.

3.2. Microclimate, above- and belowground temperature, snow depth, and VWC

From 2022–2025, solar radiation (S , warm and cool season: $p < 2.2\text{e}^{-16}$), wind speed (u , warm: $p < 1.04\text{e}^{-14}$; cool: $p < 2.78\text{e}^{-3}$), and reference evapotranspiration (ET_0 , warm and cool: $p < 2.2\text{e}^{-16}$) were significantly higher in PIPO-burned compared to PIPO (two-tailed Welch's t-tests; Fig. 3a,c,d). Surface temperature (T_{sfc} , warm: $p < 6.47\text{e}^{-15}$; cool: $p < 4.68\text{e}^{-4}$) and soil temperature (T_s , warm: $p < 2.2\text{e}^{-16}$; cool: $p < 3.83\text{e}^{-4}$) were also significantly higher in PIPO-burned compared to PIPO (two-tailed t-tests; Fig. 4b,c). On average, both PIPO and PIPO-burned lost energy as ground heat flux (G) during the cool season and gained energy during the warm season, with PIPO-burned experiencing slightly higher variation in G than PIPO in most months (Fig. 4d). Vapor pressure deficit (VPD) and T_a were not significantly different between PIPO and PIPO-burned (Figs. 3b, 4a).

Mean daily snow depth was significantly higher at PIPO-burned (218 ± 252 mm) compared to PIPO (174 ± 202 mm) across 2022–2025 water years ($p < 4.5\text{e}^{-3}$; two-tailed Welch's t-test; Fig. 5). Differences in snow depth between PIPO and PIPO-burned were largest when snow depth was higher (often in January–February), and were smaller when snow depth was lower (often in March–April; Supplementary Figure S3). Volumetric soil moisture (VWC) was significantly higher at PIPO than PIPO-burned at 10 cm (warm: $p < 2.2\text{e}^{-16}$; cool: $p < 1.52\text{e}^{-11}$), 20 cm (warm: $p < 2.2\text{e}^{-16}$; cool: $p < 1.08\text{e}^{-15}$), and 40 cm (warm and cool: $p < 2.2\text{e}^{-16}$) soil depths (two-tailed Welch's t-tests; Fig. 6).

At 10 cm, VWC at PIPO was consistently higher than that of PIPO-burned, with the exception of short duration time periods following P events in the warm season and early cool season (Supplementary Figure S4a). At 20 cm and 40 cm, VWC at PIPO was frequently higher than that of PIPO-burned, with the exception of short duration periods in the cool season when VWC was temporarily higher at PIPO-burned (Supplementary Figure S4b,c).

3.3. PIPO-burned compared to PIPO and PJ

With the exception of T_a and VPD, mean values of warm season microclimate and environmental variables at PIPO-burned were more similar to PJ than PIPO, especially S and VWC at 10, 20, and 40 cm depth (visualized by proportional values exceeding the red circle; Fig. 7a, Supplementary Table S2). In the cool season, mean values of S , ET_0 , and VWC at 10, 20, and 40 cm depth at PIPO-burned were more similar to PJ, whereas other variables were more similar to PIPO (Fig. 7b, Supplementary Table S2). In the warm season, K–L was high between PIPO and PIPO-burned for T_s (0.85 bits), and was moderately high for VWC at 40 cm (0.46 bits) and ET_0 (0.39 bits; Fig. 7c, Supplementary Table S3). In the cool season, K–L was high between PIPO and PIPO-burned for T_{sfc} (1.35 bits) and VWC at 10 cm and 20 cm (1.52 and 1.34 bits, respectively), and was moderately high for VWC at 40 cm (0.47 bits) and S (0.36 bits; Fig. 7d, Supplementary Table S3). Across all variables, average K–L across all evaluated variables was higher in the cool season (0.57 bits) than in the warm season (0.28 bits; not shown).

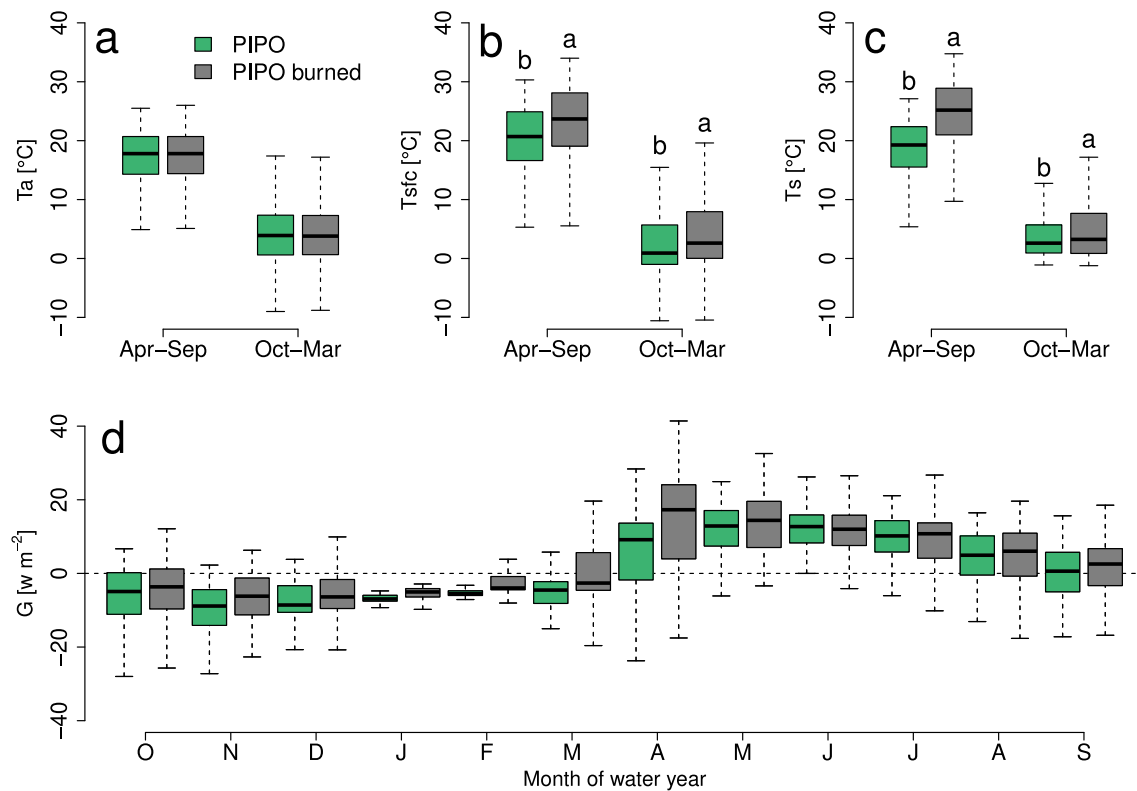


Fig. 4. Boxplots illustrating the mean and interquartile range of warm season (April–September) and cool season (October–March) air temperature [T_a : °C] (Panel a), soil surface temperature [T_{sfc} : °C] (Panel b), soil temperature from 0–15 cm depth [T_s : °C] (Panel c), and monthly ground heat flux [G : W m^{-2}] (Panel d) at ponderosa pine (PIPO) and burned ponderosa pine (PIPO-burned) stations from 2022–2025. Letters indicate significant differences in the mean, determined using two-tailed Welch's t-tests (seasons evaluated independently; $p < 0.05$). All significant differences using 2022–2025 combined data were also significant in each individual year. We did not evaluate statistical differences in G .

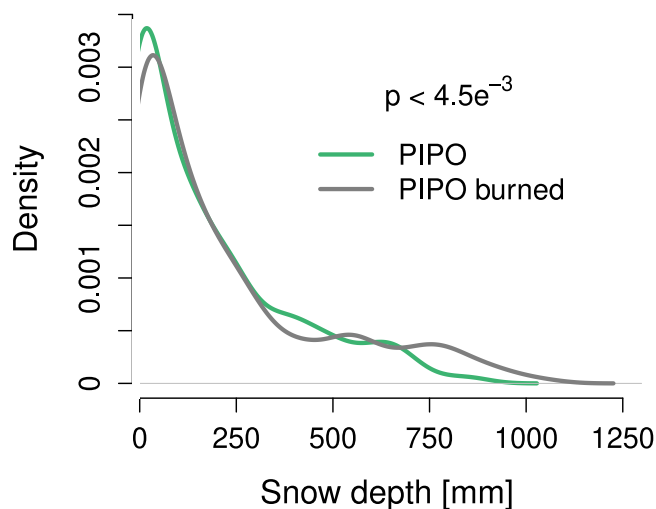


Fig. 5. Density plot of mean daily snow depth [mm] between the ponderosa pine (PIPO) and burned ponderosa pine (PIPO-burned) areas in 2022–2025 water years, calculated from snowtopography transect imagery. Density plots only include days when one or both areas had snow cover > 0.0 mm. Mean daily snow depth was significantly higher at PIPO-burned compared to PIPO ($p < 4.5e^{-3}$), determined using a two-tailed Welch's t-test.

4. Discussion

We explored microclimate and environmental differences between less- (PIPO) and more-wildfire impacted (PIPO-burned) ponderosa pine

areas at the Sierra Ancha Experimental Forest (SAEF) in central Arizona, USA. PIPO experienced a low-severity wildfire in 2016 and limited woody plant expansion. PIPO-burned experienced a stand-replacing wildfire in 2000, a low-severity wildfire in 2016, and extensive type conversion towards woody plant (New Mexico locust) dominance. Repeat wildfire and woody plant expansion at the SAEF over the past 25 years resembles landscape changes occurring throughout the SWUS and in temperate forests globally (Coop et al., 2020; Seidl and Turner, 2022; Hurteau et al., 2025).

Our period with ground-based transect and instrumentation data (2022–2025 water years) experienced slightly below-average warm and cool season precipitation (P) and cool season maximum snow water equivalent (SWE), and air temperatures (T_a) were near the long-term average. The 2025 cool season was especially dry, with the second lowest maximum SWE since WY 1981. Although studies conducted in northern latitude forests of western North America have found increased T_a following wildfire and loss of canopy cover (Wolf et al., 2021; Smith-Tripp et al., 2022), our results corroborate Montes-Helu et al. (2009), who found no significant difference in mean daily T_a between burned and unburned forest in northern Arizona. Additionally, although Wolf et al. (2021) found higher vapor pressure deficit (VPD) in a burned forest with low canopy cover in Montana, our results again corroborate Montes-Helu et al. (2009), who found no difference in VPD. Instead, we found that higher solar radiation (S) and wind speed (u) at PIPO-burned were the drivers of its significantly higher mean reference evapotranspiration (ET_0) in both the warm season and cool season. Based on these results, we postulate that the warmer temperatures and lower absolute humidity of SWUS dry coniferous forests may reduce land surface coupling to T_a and VPD compared to more northern latitude forests, potentially illuminating a key feature of how surface moisture fluxes in SWUS forests are reshaped by stand-replacing disturbance.

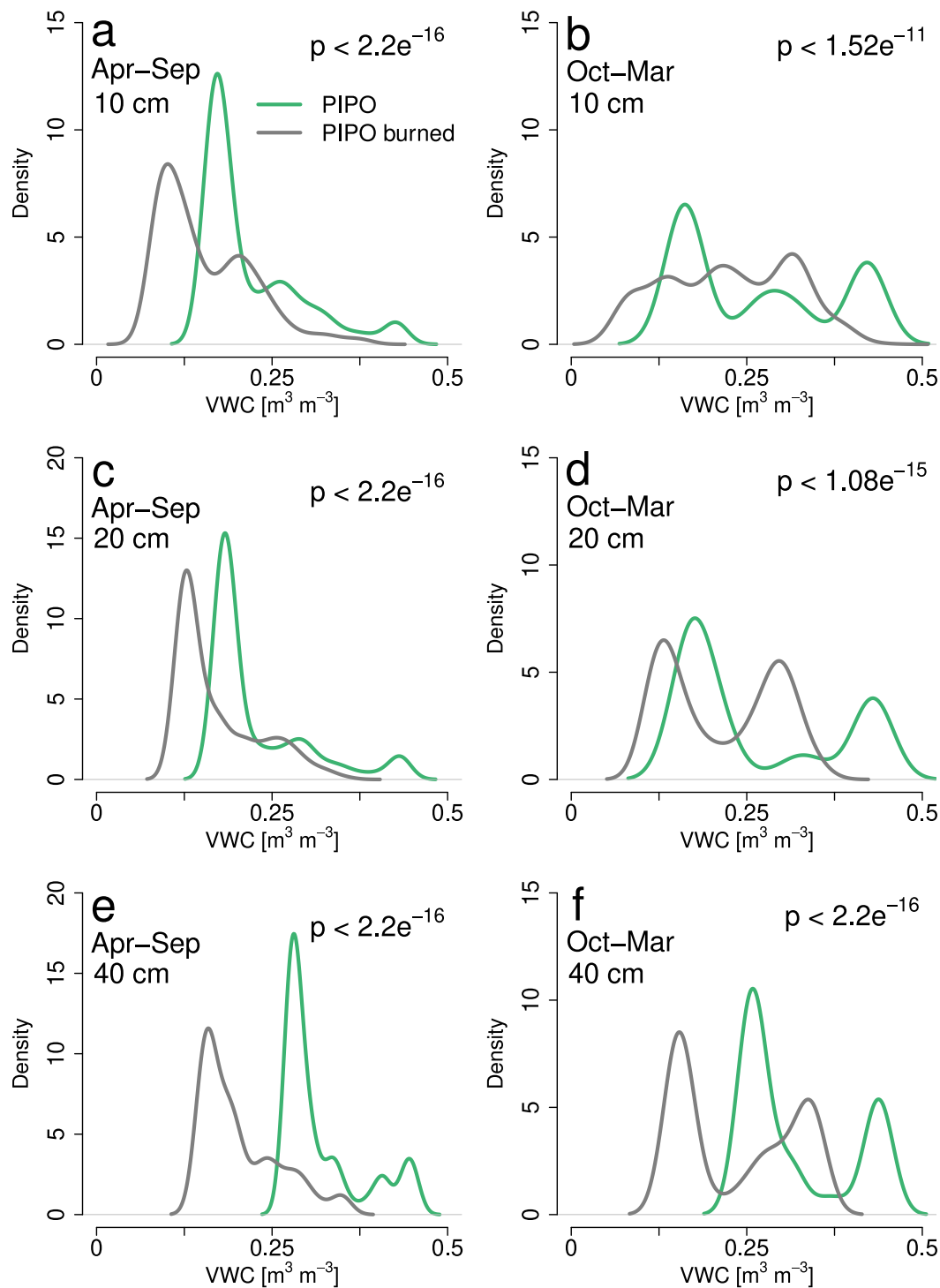


Fig. 6. Density plots of warm season (April–September) and cool season (October–March) daily soil volumetric water content [VWC: m³ m⁻³] at 10 cm (Panels a,b), 20 cm (Panels c,d), and 40 cm (Panels e,f) depth at ponderosa pine (PIPO) and burned ponderosa pine (PIPO-burned) stations from 2022–2025. The mean of VWC values were significantly higher at PIPO than PIPO-burned in all seasons and at all soil depths (p -values shown in each panel), with significance determined using two-tailed Welch's t -tests.

Many studies report higher surface (T_{sfc}) and soil temperatures (T_s) in canopy-disturbed forests (see Montes-Helu et al., 2009, Wooten et al., 2022, and Smith-Tripp et al., 2022 for examples), and we also found significantly higher warm season and cool season T_s and T_{sfc} at PIPO-burned compared to PIPO. We did not observe a change to the seasonality of ground heat flux (G) between PIPO and PIPO-burned, although variation in G was higher at PIPO-burned, which corresponds to its higher S , T_{sfc} , and lower near-surface volumetric soil moisture

(VWC). More ephemeral snowpack can reduce snow insulation and lower surface and soil temperatures (Wheeler et al., 2014). We found significantly lower cool season T_{sfc} and T_s at PIPO, potentially corresponding to its lower snow depth compared to PIPO-burned. Although studies in the western US report both lesser and greater snow depth following stand-replacing wildfire and other severe forest canopy reductions (Biederman et al., 2014a; Maxwell et al., 2019; Moeser et al., 2020), our results corroborate findings that canopy-disturbed areas

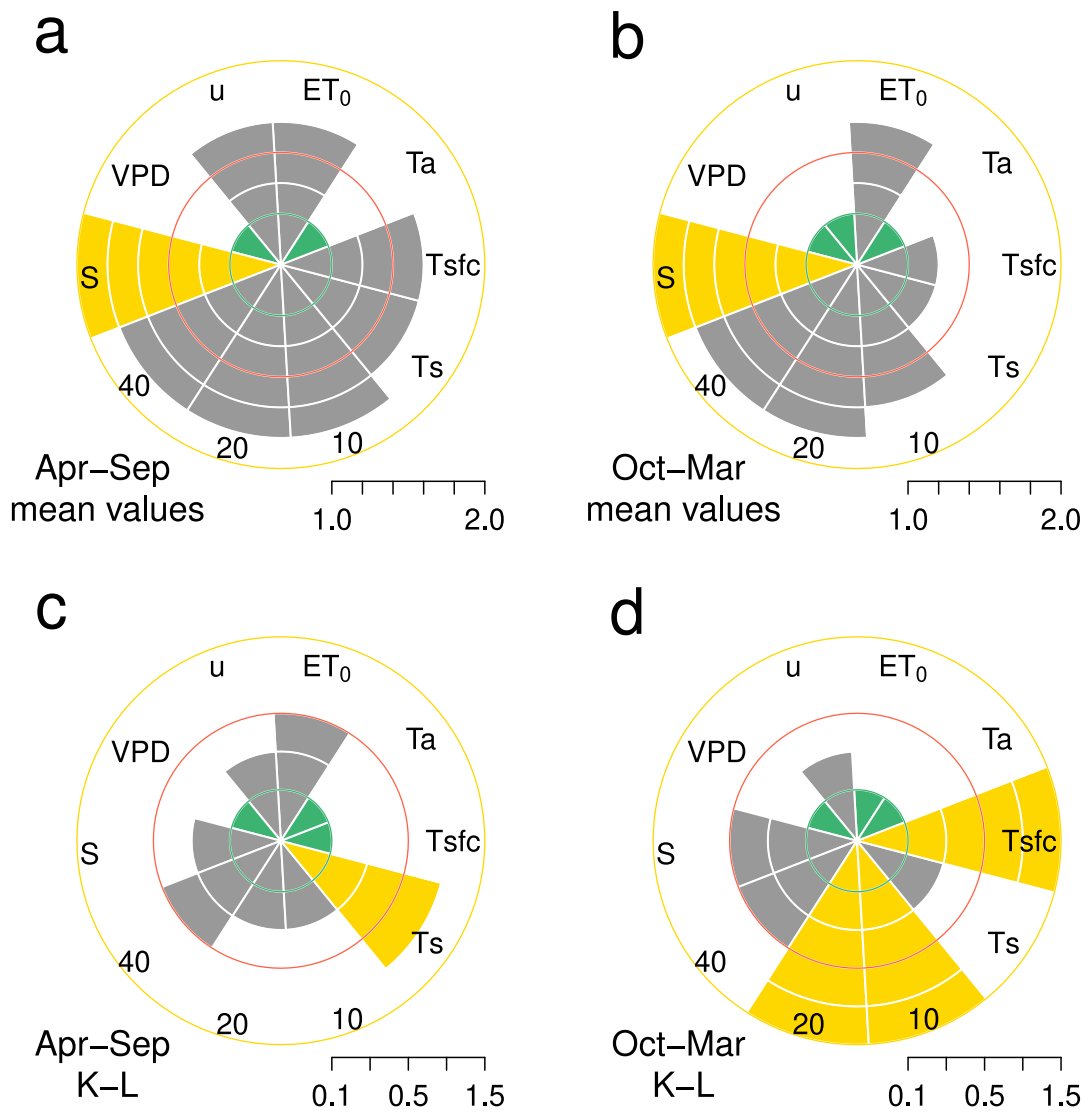


Fig. 7. Starplots illustrating similarities in the mean of meteorological and environmental variables between ponderosa pine (PIPO), burned ponderosa pine (PIPO-burned), and piñon pine-juniper woodland (PJ) stations during the warm season (April–September) and cool season (October–March; Panels a,b) from 2022–2025, and Kullback–Leibler divergence [K–L: bits] from PIPO to PIPO-burned in the warm and cool season (Panels c,d). For mean values, the length of each plot segment illustrates the proportional similarity of each variable at the PIPO-burned site to the same variable at PIPO and PJ. A value of 1.0 corresponds to a PIPO-burned variable with a value within 10% (0.1 proportion) of the variable value at the PIPO station (illustrated in green and within the green boundary), a value of 2.0 corresponds to a PIPO-burned variable with a value within 10% (0.1 proportion) of the variable value at the PJ station (illustrated in gold and exceeding the red boundary). Values from 1.2 to 1.8 (visualized in increments of 0.2) are illustrated in gray and correspond to PIPO-burned variable values between the PIPO and PJ variable value. Plot segments exceeding the red circle (1.4 proportion) indicate variables at PIPO-burned that are more similar to those of PJ than PIPO. For K–L, the length of each plot segment illustrates greater “surprise” in the dissimilarity of the distribution of a variable at PIPO-burned given the expectation that its distribution is identical to that of PIPO (larger values indicate greater dissimilarity). For visualization, the K–L scale is nonlinear with segments of 0.1, 0.25, 0.5, 1.0, and 1.5 bits. Low K–L values (~ 0.1 bits; within the green boundary) are illustrated in green, intermediate values (0.25 to 0.5 bits) are illustrated in gray, and high values (≥ 1.0 ; exceeding the red boundary) are illustrated in gold. In all panels, variables 10, 20, and 40 correspond to volumetric soil moisture at 10 cm, 20 cm, and 40 cm soil depth (abbreviated to fit the plot). Mean variable values are provided in Supplementary Table S2, and K–L values are provided in Supplementary Table S3.

experience earlier spring snowmelt and amplified near-surface soil water depletion in the warm season (Belmonte et al., 2022; Dwivedi et al., 2023b). We found significantly lower near-surface VWC at PIPO-burned (10 cm, 20 cm, and 40 cm depth), with greater mean differences in the warm season (0.05 to 0.11) and at 40 cm depth (0.08 to 0.11). Our results corroborate Ebel (2013) and Petrie (2025), who both report lower mean VWC in burned compared to unburned forest, and a tendency for VWC in burned forest to temporarily exceed that of unburned forest during snowmelt and following precipitation events. The interspace location of our PIPO station was influenced by canopy interception of precipitation (reducing water infiltration into the soil), but did not capture partitioning of precipitation as stemflow into the rooting zone

of adult conifer trees (Pinos et al., 2023). Thus, VWC differences in our data may actually underestimate differences in near-surface soil water availability between PIPO and PIPO-burned.

PIPO-burned experienced greater mean evaporative demand, higher mean surface and soil temperatures, and lower near-surface mean VWC than PIPO. Attesting to the severity of these changes, in the warm season the mean of all significantly different variables at PIPO-burned (T_{sfc} , T_s , VWC 10–40 cm, S , u , ET_0 ; 2168 m) were more similar in magnitude to those of lower elevation PJ (1605 m). In the cool season, VWC, S , and ET_0 were also more similar between PIPO and PJ. Information theory analyses illustrate that the dynamics of a subset

of these variables – including warm season T_s and cool season T_{sc} and VWC at 10 and 20 cm depth – were more dissimilar between PIPO and PIPO-burned compared to other variables (see Petrie et al., 2024 for additional discussion of Information Theory elucidation of ecosystem dynamics). In total, decades following repeat wildfire and woody plant type conversion, the mean of many microclimate and environmental variables at PIPO-burned more closely resembled those of lower elevation woodland than they did higher elevation, less wildfire-impacted forest, and the near-surface temperature and soil water dynamics of PIPO-burned were dissimilar from those of less wildfire-impacted forest as well.

In interpreting these results, it is important to consider the meteorological context of the 2022–2025 study period, which experienced near-average warm seasons, but warmer and lower precipitation cool seasons. It is unclear if differences between PIPO and PIPO-burned would increase or decrease in differing meteorological context, especially periods of higher precipitation. Furthermore, it is important to consider that PIPO-burned and PJ differ in mean annual precipitation (lower at PJ), vegetation composition (higher shrub cover at PJ), slope and aspect (greater slope, south facing aspect at PJ), and saturated hydraulic conductivity (lower K_s at PJ). Thus, although many meteorological and environmental variables were more similar between PIPO-burned and PJ during our study period, the precipitation, vegetation composition, and physiography of these sites was very different, and it is unclear if observations in our study would be maintained in differing meteorological context.

4.1. Water dynamics, regional climate, and woody plant expansion

Studies report considerable water balance transformation in forests following wildfire and other severe, stand-replacing disturbances, with changes to evaporation and runoff partitioning that may or may not increase basin water discharge (Biederman et al., 2015; Ma et al., 2020; Collar et al., 2022). Biederman et al. (2022) found short-term (1 yr) seasonal streamflow increases following stand-replacing wildfire in southern Colorado, and Collar et al. (2022) report that water balance changes persist beyond five years only in basins with a high proportion of area impacted by wildfire. Although we found lower near-surface soil moisture and higher reference evapotranspiration two decades following stand-replacing wildfire in the SAEF Workman Creek watershed, how these changes may have reduced water discharges over time is unknown (see Biederman et al., 2014b, 2015). Better understanding of linkages between landscape change and hydrology is important for forecasting future climate conditions. Stark et al. (2016) propose that deforestation in the western US has potential to reduce precipitation and vegetation productivity in eastern North America, the tropics, and northern Eurasia through alteration of ecoclimate teleconnections. Thus, although our work to quantify microclimate and environmental effects of stand-replacing wildfire is applicable to landscape change in the SWUS, there remains a great need to upscale fine-scale understanding to broader-scale processes.

The type conversion of coniferous forest to woody plant dominance is a small but growing area of research (see Guiterman et al., 2018; Krofcheck et al., 2019, and Crockett and Hurteau, 2022 for examples), and its potential to reshape basin hydrology, surface energy partitioning, and regional climate is a key unknown for SWUS landscapes. We identify opportunities to begin to better understand and upscale the effects of this specific type conversion. First, our instrumented station in PIPO-burned was located in a bare soil interspace, and although it was located near dense stands of New Mexico locust, it was not located in them. There is opportunity to quantify the microclimate and especially the ecophysiology of woody plant expansion in burned landscapes. We postulate that an important component of understanding woody plant expansion is the effect of phenology (inactive leaf-off versus active leaf-on periods) in shaping seasonal water and energy partitioning. Compared to in-tact coniferous forest,

less dense woody plant canopies in the cool season have the potential to alter snowpack, surface albedo, and snowmelt partitioning between evaporation, soil moisture, and basin discharge. Dwivedi et al. (2024) report that forest canopy loss can reduce snowpack duration by up to one month. During the warm season, differences in canopy interception and water use by woody plants – and how these differences align with precipitation seasonality – could reshape landscape water and energy fluxes. Finally, we also need to understand the timescales of woody plant type conversion, including how water and energy partitioning changes as they expand and densify, and how repeat wildfire may reshape partitioning until woody plants again reestablish. By doing so, we can begin to more comprehensively understand and upscale the effects of post-wildfire vegetation type conversion in the SWUS, improving the ability to plan and prepare for expanding wildfire impacts and regional vegetation change.

4.2. Considering the future of forest type conversion

Considerable research has documented and explored the mechanisms of failed conifer recovery following wildfire in the SWUS (Davis et al., 2019; Donovan et al., 2019; Singleton et al., 2021), and how vegetation type conversion towards non-forest is reinforced by climate change and repeat wildfire events (Coop et al., 2016; Stevens-Rumann and Morgan, 2016; Guiterman et al., 2022). Expanding transformation of forests in the SWUS towards non-forest requires flexible management of post-wildfire landscapes. To this end, Hurteau et al. (2025) propose a resist–accept–direct (RAD) framework for considering ecosystem restoration (resist), accepting ecosystem changes (accept), or promoting a desired new ecological state (direct). In the following sections, we explore how the RAD framework and its decisionmaking outcomes may be applied to our study findings at the SAEF.

We found that near-surface soil moisture and temperature changes at PIPO-burned resembled those reported by other studies to severely limit ponderosa pine seedling survival (Marsh et al., 2022; Petrie et al., 2023; Petrie, 2025; Crockett and Hurteau, 2024), and Crockett and Hurteau (2022) report that microclimates in New Mexico locust are generally unfavorable for conifer seedlings. Limited ponderosa pine recovery in the burned area at the SAEF coincided with two decades of cool seasons with near-average precipitation, lower than average snowpack, and warmer than average air temperatures. Conversely, warm season precipitation and air temperatures were near average. Combined with the expectation for increasing cool and warm season temperatures and water deficit in coming decades (Bradford et al., 2020), observation of failed recovery during a near-average meteorological period could support the determination that conifer restoration is unlikely at the SAEF, and “accept” is an appropriate determination. This determination would also require acceptance of vegetation type conversion towards woodlands dominated by New Mexico locust at the SAEF, which has been ongoing in both more and less wildfire-affected forest areas over the past two decades.

In a contrasting viewpoint, ponderosa pine is a long-lived species with reproduction that is often tied to infrequent and favorable periods of higher precipitation (League and Veblen, 2006), and it is plausible that the severity of the 2000 Coon Creek fire at the SAEF reduced the ponderosa pine seed bank from much of the landscape, limiting the potential for natural recovery. Much of the SWUS is experiencing the second decade of a regional megadrought (Cook et al., 2022), and although drought events are predicted to become more severe and frequent in the future (Bradford et al., 2020), intervening periods of higher precipitation may offer a window of opportunity for recovery. Therefore, observation of limited ponderosa pine recovery could also support a “resist” determination, where assisted conifer recovery (e.g., seeding and/or planting) is possible in a favorable microclimate and/or meteorological setting, and repeat wildfire may offer a window of opportunity for management interventions that reduce woody plant expansion. Following microclimate changes observed in

this study and in a location with even more severe warm season water deficit (Petrie, 2025), assisted conifer recovery may benefit from natural and constructed shade structures to reduce solar radiation, surface temperatures, and evaporative demand in planting locations.

Finally, if long term microclimate and environmental changes in a burned forest resemble those of lower elevation piñon pine–juniper woodland, then perhaps efforts to establish piñon pine, juniper, and shrub live oak are most feasible, and “direct” is an appropriate determination. Type conversion of coniferous forest to woodlands dominated by New Mexico locust has been strongly enhanced by repeat wildfire over the past 25 years at the SAEF. If coniferous forest restoration is not feasible in wildfire-altered landscapes of the SAEF, less desirable piñon pine–juniper woodland may be a preferable outcome to undesirable New Mexico locust woodland. Yet, it is again important to consider the meteorological and physiographic settings of our PIPO-burned and PJ comparisons — although some environmental variables were similar between these sites during near-average warm seasons and lower precipitation cool seasons, it is unclear if these similarities would be maintained during higher precipitation periods that provide greater support for conifer establishment (League and Veblen, 2006). We intend for future research at the SAEF to experimentally test “resist” and “direct” as alternative strategies for post-wildfire landscapes, with the goal of providing insight on management of vegetation type conversion.

5. Conclusions

We found considerable microclimate and environmental differences in the warm season and cool season between less (PIPO) and more wildfire-disturbed and woody plant-encroached (PIPO-burned) ponderosa pine forest areas in central Arizona, USA. These included higher evaporative demand, higher surface and soil temperatures, and lower near-surface soil moisture. In many cases, mean variable values at PIPO-burned were more similar to those of lower elevation piñon pine–juniper woodland than PIPO, and the dynamics of temperature and soil moisture variables in some cases were highly dissimilar between PIPO and PIPO-burned. This study provides one of the first fine-scale and SWUS-focused evaluations of sustained wildfire effects in mid-elevation coniferous forests, and the study's location near the southern latitude boundary of ponderosa pine may help inform changes occurring at more northern latitudes in the future. As wildfire continues to promote landscape and vegetation change, severely altered post-wildfire landscapes will become a growing feature of the SWUS, and are likely to be associated with considerable alteration to microclimate and environmental conditions.

CRedit authorship contribution statement

Matthew D. Petrie: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Keegan D. Hammond:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Joel A. Biederman:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Data curation. **Charles J. Devine:** Validation, Resources, Project administration, Data curation. **Jackson M. Leonard:** Writing – review & editing, Supervision, Resources, Project administration, Data curation. **Roger Tyler:** Writing – review & editing, Validation, Resources, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.agrformet.2026.111297>.

Data availability

Data will be made available on request.

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