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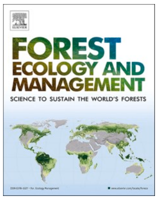

Trends in prescribed fire weather windows from 2000 to 2022 in California

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ABSTRACT

As increasing wildfire activity puts pressure on wildland fire suppression resources both nationally and within the state of California, further development of programs and infrastructure that emphasize preventative fuels treatments, e.g. prescribed burning, is critical for mitigating the impacts of wildfire at large spatial scales. Among many factors that limit the use of prescribed fire, weather and fuel moisture conditions are among the most critical. We analyzed a 2-km gridded hourly surface weather dataset over a 23-yr period to explore the relationship between climatological trends and prescribed fire weather windows. Pairing this dataset with burn prescription parameters provided by experienced regional fire practitioners, we seek to identify the timing and extent of changes in weather-related opportunities for prescribed fire in two distinct geographic regions within California. We found an increasing trend in opportunities for prescribed fire use in Sonoma County, a representative coastal Mediterranean region of CA, and a decreasing trend in Plumas County, a montane region that extends through the Northern Sierra Nevada. Seasonally, we see more nuances—increased winter opportunities in both counties, as well as increased summer opportunities in Sonoma. Most notably, we see great variation spatially in the occurrence of suitable weather windows for prescribed burning. Fire management resource availability and air quality regulations further constrain burn windows. We observed a greater influence of these factors in Sonoma County vs. Plumas. Resource availability is the greatest constraint in the Summer and Fall, during wildfire season, and air quality regulations are a greater constraint in the Winter. Our findings provide information to decision-makers and regulators at the county and other government levels to more effectively support use of prescribed fire to achieve land management and fuels reduction goals.

1. Introduction

Over 4.5% of California burned annually prior to European settlement, mostly at low-moderate severity, due in large part to widespread Indigenous burning (Stephens et al., 2007). While distinct from the Indigenous and cultural burning that once maintained California ecosystems, prescribed burning (Rx) is an imperative land management tool in fire-prone regions.

Today, annual burned area is still well below millennial averages, but the proportion burning at high severity has increased (Williams et al., 2023a, 2023b). This is reflected in recent unprecedented wildfire seasons that set new records for fire size as well as social and economic impacts (Safford et al., 2022). Atmospheric warming due to anthropogenic climate change, in combination with the legacy of fire suppression, has resulted in unnatural fuel accumulation and loss of ecosystem resilience across much of the state. These trends are likely to continue to influence increases in both frequency and severity of wildfires statewide (Westerling et al., 2006; Abatzoglou and Williams, 2016; Williams et al., 2019).

There is already a consensus in the literature that Rx fires are effective at increasing adult tree survival (Safford et al. 2012), reducing required suppression resources (Fernandes and Botelho, 2004), moderating severity and extent (Lydersen et al., 2017 & Fernandes, 2015) of subsequent wildfire (Davis and Cooper, 1963, Martin et al. 1989), as well as meeting our state carbon targets (Bernal et al., 2022). A recent study modeling the global effectiveness of Rx fires in mitigating wildfire impacts found a direct positive relationship between prescribed fire and reduction in wildfire in the state of California (Jose et al., 2023). Despite

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acknowledgement that the extensive proactive use of fire ought to be a greater management priority across California (Task Force, 2021), and recent state legislation calling to annually treat 400,000 acres with beneficial fire (Task Force, 2022), there are challenges with implementing targets for more frequent and extensive prescribed fires across California. It should be noted that prescribed fire has been used extensively for decades in the southeast US (Kobziar et al. 2015) and this provides useful experiences to increase fire use California although there are difference between the regions (Stephens et al., 2019).

Many impediments to widespread use of prescribed fire make it difficult to implement at the necessary scale. These include regulatory constraints such as air quality and endangered species concerns (Quinn-Davidson Lenya and Varner, 2012; Williams et al., 2023a, 2023b), and inadequate resources to conduct burns (Stephens et al., 2016) that stem from a mismatch in burn window occurrence and resource availability (York et al. 2020). Due to its prolonged annual dry season, California has limited opportunities for large-scale prescribed burning (Miller et al. 2020). Often these opportunities are limited to the “shoulder” seasons, where fuels are dry enough to ignite and carry fire, but not so dry that fires spread rapidly and threaten containment lines. However, reduced winter snowpack in higher elevation regions (Casirati et al., 2023) may create more winter and spring burn windows (York et al., 2021). Having a better understanding of the spatial and temporal variation in Rx burn windows across the state, and how they may be changing, could help overcome some of these barriers by enabling planning and implementation at the regional or local level, as well as prioritization of statewide resources.

Previously, Ryan (1984) derived an atlas of potential fire characteristics across California, with the application to assist land managers target appropriate RX windows (Ryan, 1984). However, the influence of climate change on the seasonality and regional patterns of Rx windows in California is not well understood, particularly at finer spatial and temporal scales. This study takes advantage of a recently developed weather dataset consisting of hourly, 2-km gridded data (Brown, 2020) over a 23-year period from 2000 to 2022. We investigated how Rx windows changed over this period for two counties located in distinct geographic and climatic regions within California: Sonoma County, which has more coastal influence, and Plumas County, which has a montane influence (Fig. 1). The areas capture contrasting land ownership types, climate, and vegetation communities, which together represent a large portion of the diversity in prescribed fire considerations across the state (Fig. 1). While these counties do not comprehensively encompass the broad set of climates and ecosystems across California, they do represent diverse conditions in areas where recent fire activity has heightened interest in land management.

This information provides fire practitioners with a better framework around which to plan prescribed burns to best meet wildfire management and ecosystem restoration goals.

2. Materials and methods

2.1. *Study areas*

This study included analyses of Sonoma and Plumas counties. Sonoma County is located within the North Coast California Bioregion (Stuart and Stephens, 2006), bordering the Pacific Ocean to the west, and the Central Valley to the east (Fig. 1). Climate consists of cool, wet winters, and cool-to-warm, dry summers; the degree of climate-moderating effect from the Pacific Ocean decreases west to east. The presence of summer fog and distance from the coast largely drives summer relative humidity and temperature (Pillers, 1989). Topography is diverse; elevations range from sea level to over 1000 m in the North Coast Ranges (Miles and Goudey, 1998).

Moving inland, dominant plant communities include North Coast Scrub/ Prairie, Redwood *(Sequoia sempervirens)* forests, Douglas-Fir *(Pseudotsuga menziesii)* / Tanoak *(Notholithocarpus densiflorus)* forests, Blue Oak *(Quercus douglasii)* Woodlands, and to a lesser extent, chaparral, and valley grasslands (Stuart and Stephens, 2006; Sawyer et al., 2000). Historically, grasslands and oak woodlands burned quite frequently in this area. Native American cultivation of food and basketry

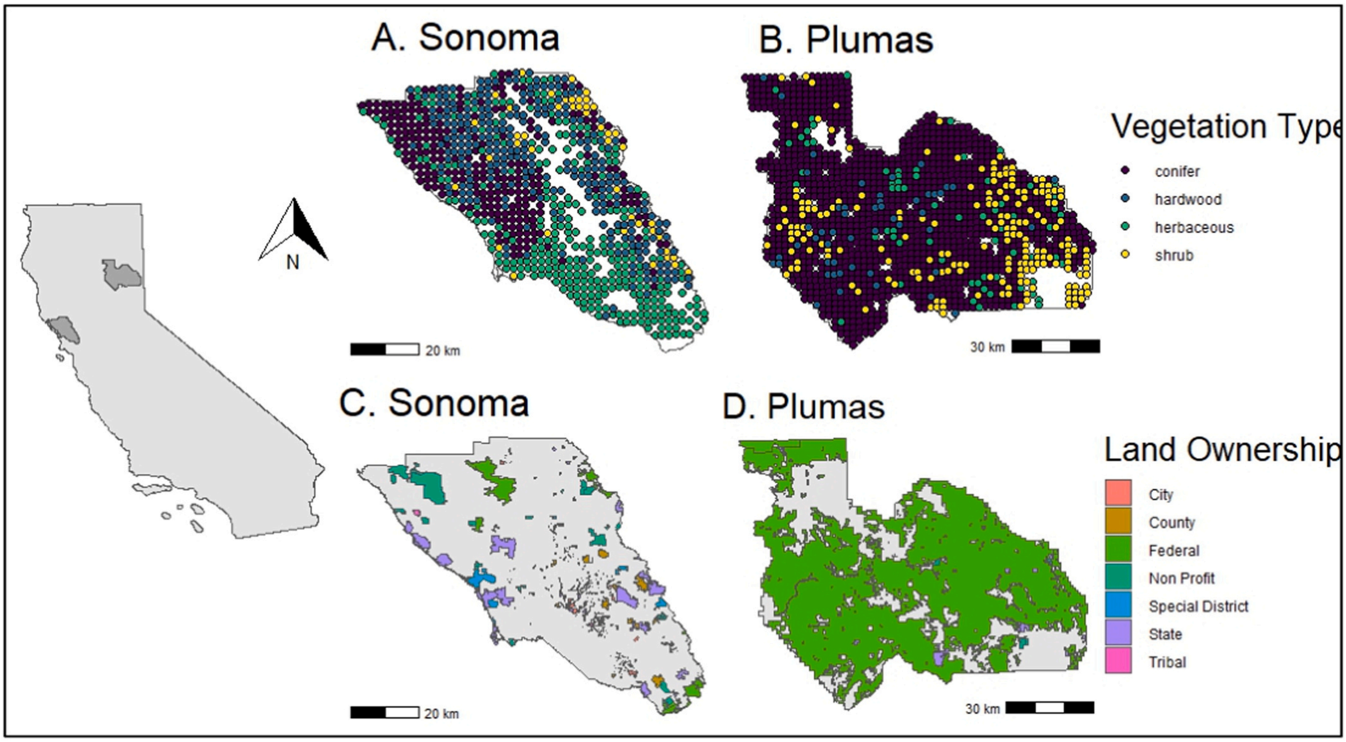

Fig. 1. Map of geographical locations of Sonoma and Plumas Counties within the state of California, distribution of vegetation types analyzed in this study (A, B) and land ownership (C, D), privately owned land is indicated by gray background color.

materials resulted in nearly annual fire return intervals near population centers (Lewis, 1993, Keter, 1995). The use of fire has declined as a management tool for the last 150 years due to European colonization and fire suppression. As a result, there are significant increases to tree density and surface fuels, and livestock grazing is now widespread in areas with adequate forage (Stuart and Stephens, 2006; Marks-Block et al., 2021; Huntsinger et al., 2007).

Sonoma County is comprised of a heterogeneous mix of wildland vegetation cover: 24% conifer forest, 26% hardwood forest, 30% herbaceous, and 4% shrub; the remaining area is about evenly split between agricultural and developed (U.S. Forest Service, 2018). Most of the land is privately owned, 3% federal, 3% non-profit, and <7% state and local (California, 2023).

Plumas County is located at the northern end of the Sierra Nevada, and the southern end of the Southern Cascades (Skinner & Taylor, 2006). Elevation ranges from 350 m in the Sierra Valley to over 2500 m in the Sierra Nevada (Plumas County, 2024). Climate is characterized by warm dry summers and cool winters. Most of the precipitation falls in the winter as snow, with precipitation increasing and temperatures decreasing with latitude and elevation (van Wagtendonk and Fites-Kaufman, 2006).

The dominant vegetation type in Plumas County is Sierra mixed-conifer forest with conifer forest accounting for 79% of the vegetated land cover, hardwood forest 3%, herbaceous forest 4%, and shrubland 13% (U.S. Forest Service, 2018). Land ownership is mostly federal, with over 70% managed by Plumas National Forest (California, 2023). Fire scar studies conducted in the area estimate a historic fire interval of 15–44 years, with fires on south-facing lower elevation slopes occurring more frequently, and on north-facing higher elevation slopes occurring less frequently (Moody et al., 2006; Beaty and Taylor, 2001). Federally organized fire exclusion began in the late 1890's and characterized the Sierra Nevada through at least the 1960's (van Wagtendonk, 1991; Debruin, 1974). The legacy of fire suppression and past timber harvesting practices have resulted in high fuel accumulation and forest compositional shifts across much of the Sierra Nevada (Parsons and Debenedetti, 1979, Collins et al. 2017; Stephens et al., 2023).

2.2. *Data development and sourcing*

We used windspeed, temperature, relative humidity, and 100-hr fuel moisture data parameters to write our initial burn prescriptions. The specific prescription parameters were derived from prescribed burn plans developed by prescribed fire professionals in the focal regions. We referenced multiple burn plans in defining prescription parameters to ensure differences between our four focal vegetation types were represented. We produced weather data using the Weather Research and Forecasting (WRF) mesoscale meteorology model (Skamarock et al., 2008), and bias corrected using RAWS data. The weather data was processed by the Desert Research Institute (Brown et al., 2016) California and Nevada Smoke and Air Committee (CANSAC) at a 2-km gridded and hourly resolution for the years 2000–2022. We used daily 100-hr fuel moisture data from the gridMET dataset (Abatzoglou, 2013), resampled to the same 2-km grid as the WRF variables. We delineated burn prescription parameters according to four broad vegetation types—conifer forest, hardwood forest, herbaceous, and shrubland— by overlaying weather and fuels data with the CALVEG (Classification and Assessment with LANDSAT of Visible Ecological Groupings) vegetation polygons (U.S. Forest Service, 2018).

To assess operational and regulatory constraints on prescribed fire windows, we included daily records of National Interagency Fire Center (NIFC) Preparedness Levels for the Northern California region, and California Air Resource Board (CARB) “burn” and “no burn” decisions from 2018–2022. Preparedness Levels are established by the National Multi-Agency Coordination Group and updated throughout the calendar year to ensure there is sufficient availability of suppression resources to respond to potential wildfire incidences (U.S.D.A. Forest Service, 2016). Preparedness Levels range from PL1 (minimal wildfire activity) to PL5 (extremely high wildfire activity); higher preparedness levels correspond to greater national and/or regional need for suppression resources (i.e. fire crews). We used daily PL records from the Northern California Geographic Area Coordinating Center (ONCC) to capture operational capacity specific to our study area (U.S.D.A. Forest Service, 2016).

CARB Air Quality Planning and Science Division provides state air management districts with daily agricultural and prescribed burning control notices based on air quality projections (California, 2001). We used daily decision records for “San Francisco Bay North” and “North Coast” air basins to capture air quality constraints on Sonoma County, and the “Mountain Counties—North” air basin to capture air quality constraints on Plumas County.

2.3. *Burn prescriptions*

We determined Rx windows individually for each 2-km cell by processing the gridded WRF weather data through a series of filter steps. First, we established weather-based criteria, classifying a cell “in prescription” for a given hour when the following conditions were met concurrently for 5 consecutive hours: for all vegetation types, requirements of (1) temperature between 50 and 90 degrees F and (2) windspeed <10 mph, and differing among vegetation types, requirements of (3) relative humidity between 20% and 80% for conifer, 20–70% for hardwood, 40–70% for herbaceous, and 30–70% for shrub.

Next, we further filtered out instances of “marginal” weather conditions. We defined marginal conditions as concurrent instances of (1) temperature > 85 degrees and RH within 5% of the low end of our acceptable range, and (2) RH within 5% of the low end of our acceptable range and windspeed > 5 mph. Additionally, we required temperature < 100 degrees F, RH > 20%, and windspeed < 15 mph for the 24-hour period following the initial window to account for suitable weather conditions in the “burn down” period after prescribed burn operations. Then, we filtered out days where 100-hr fuel moisture was < 10% or > 20%. 100-hr fuel moisture greater than 20% is too high to reliably ignite under appropriate weather conditions, and less than 10% is low enough that fire intensity and rate of spread would likely exceed the parameters outlined in the burn prescription. Finally, we restricted windows to reasonable operation hours (0600–2400) and classified any remaining day containing at least 1 Rx window as a “burn day”.

While we calculated most of our subsequent analyses on this weather and fuels-based definition of a “burn day”, we also considered a more holistic definition to capture operational and regulatory constraints on Rx implementation (Fig. 2). For this, we added two additional filters to our calculated burn days: (1) exclusion of ONCC preparedness level > 3, and (2) exclusion of CARB “no-burn” days.

2.4. *Data analyses*

All analyses were performed in R (R Core Team, 2023). The occurrence of burn days was calculated individually for each spatial cell. We tested for county-level differences in the average annual number of burn days per season (Spring, Summer, Fall, Winter) by averaging cell-level burn day counts within season and applying a protected Dunn test to these annualized data. We then applied the Holm-Bonferroni p-value correction to the results of each Dunn test to reduce false detections resulting from multiple comparisons. We chose to use non-parametric tests for this analysis to account for potential non-normality and heterogeneity in data variance among groups caused by small sample sizes. We tested for trends in annual and seasonal burn day occurrence, as well as effects of latitude, longitude, and elevation, using the R package, “remotePARTS” (Morrow & Ives, 2023). This methodology allowed us to test for county-level trends in burn day occurrence while accounting for spatial and temporal autocorrelation intrinsic to gridded datasets (Ives et al., 2021). We analyzed annual trends separately for Plumas and Sonoma Counties; summing the number of burn days per cell per year

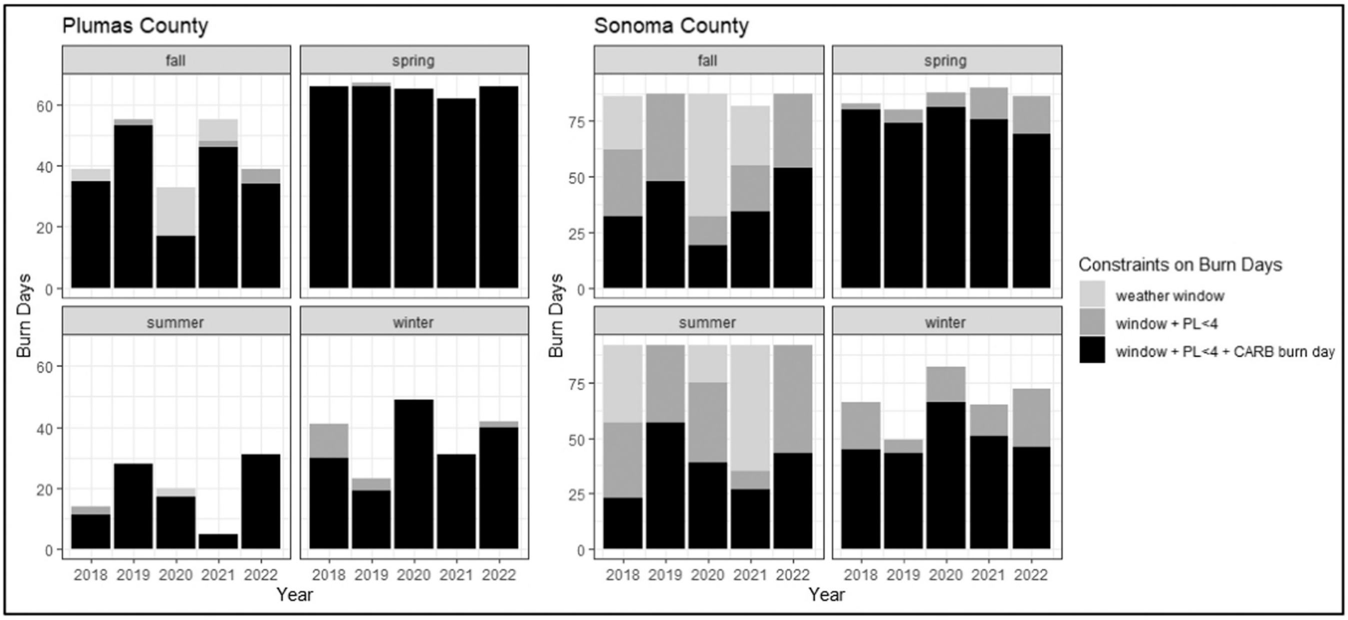

Fig. 2. Bar plots represent number of seasonal burn days over the last 5 years of the study period: 2018–2022. Light gray bars, “weather window”, represent number of burn days calculated strictly from weather prescriptions. Dark gray bars, “window + PL<4”, represent those same weather windows, with the added requirement that NOPS PL < 4. Black bars represent the most constrained burn windows, with the added requirement of California Air Resources Board “burn day” designation.

and applying a first order moving average model to estimate interannual change in burn days at the cell level (Eq. 1).

$$\boldsymbol{x_i(t)} = \boldsymbol{\alpha_{\rm i}} + \boldsymbol{c_i t} + \boldsymbol{\epsilon_i(t)} \tag{1}$$

Where $\boldsymbol{x_i(t)}$ represents the number of burn days at location $\boldsymbol{i}$ for year t, $\boldsymbol{\alpha_{\rm i}}$ represents a fitted intercept at location $\boldsymbol{i}$, $\boldsymbol{c_i}$ represents the fitted time trend at location $\boldsymbol{i}$, $\boldsymbol{t}$ represents year, and $\epsilon_i(\boldsymbol{t})$represents AR(1) temporally autocorrelated observational errors where $\epsilon_i(\boldsymbol{t}) = \rho\epsilon_{t-1} + \omega_t$, $\omega_t \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\sigma^2})$.

We evaluated timeseries model performance by applying a Breusch-Pagan test to each cell timeseries model to evaluate for residual heteroskedasticity. To evaluate the prevalence of residual heteroskedasticity within our timeseries models, we calculated the percentage of cell timeseries which exhibited significant (alpha = 0.1) residual heteroskedasticity and compared this to what would be expected at this alpha level due to commission errors from multiple comparisons (10%). Results of these Breusch-Pagan tests showed that four out of five temporal aggregations (annual, spring, summer, and fall) in both Plumas and Sonoma counties showed expected (<= 10%) levels heteroskedasticity. However, the winter season showed heteroskedasticity in 10% and 16% more cell timeseries than expected in Plumas and Sonoma counties respectively (Table S1).

We used a spatial error model to test for a significant trend in annual burn days as well as to assess effects of latitude, longitude, and elevation at the county scale (Eq. 2).

$$\boldsymbol{c_i} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1 X_{i1}} + \boldsymbol{\beta_2 X_{i2}} + \quad \dots \quad + \boldsymbol{\beta_p X_{ip}} + \boldsymbol{\gamma_i} \tag{2}$$

Where $\boldsymbol{c_i}$ represents the pixel-level burn day time trend value at location $\boldsymbol{i}$, $\boldsymbol{\beta_0}$ represents a fitted intercept, $\boldsymbol{\beta_1 X_i} + \boldsymbol{\beta_2 X_i} + \dots + \boldsymbol{\beta_p X_i}$ represents selected explanatory variables and associated observations corresponding to value $\boldsymbol{y_i}$, and $\boldsymbol{\gamma_i}$ represents spatially correlated observational error which follows a multivariate Gaussian distribution with correlation matrix $\boldsymbol{N}\left(\boldsymbol{0},\ \boldsymbol{\sigma_\gamma^2}\mathbf{V}\right)$ where $\mathbf{V}$ represents a correlation matrix with $\mathbf{N}$ elements.

Similarly, we summed the number of burn days per cell per season prior to seasonal trend analysis. We used three different spatial error model configurations to conduct hypothesis testing; an intercept-only model to test for county-level change, a model with cell latitude, longitude, and elevation as predictor variables to evaluate for geographic dependence in trends, and a model which treats each vegetation type as a factor to test for trends based on vegetation type. We applied these three models to each county and seasonal dataset individually. Additionally, we also applied the model evaluating the influence of elevation, latitude, and longitude to each pair of season and vegetation type individually resulting in 40 models overall (Table 2A & 2B, S2). To reduce false detections caused by multiple comparisons, we specified an alpha value of 0.01 for these analyses.

Table 1
Average, minimum, and maximum annual median number of burn days in Plumas and Sonoma Counties. *Avg (min – max)*.

Season	Vegetation	# Burn Days – Plumas County	# Burn Days – Sonoma County
Annual	**County-wide**	**28.1** ***(14–40)***	**125.2** ***(100–156)***
Fall	**County-wide**	**9.9 (1–16)**	**36.7 (25–46)**
Fall	Conifer	10.1 *(1–17)*	48.5 *(37–58)*
Fall	Hardwood	10.5 *(1–18.5)*	38.7 *(25–48)*
Fall	Herbaceous	4.2 *(1–8)*	21.6 *(14–27)*
Fall	Shrub	9.4 *(1–16)*	36 *(28–43)*
Winter	**County-wide**	**3.2 (1–7)**	**19 (6–29)**
Winter	Conifer	3.4 *(2–7)*	27.2 *(13–42)*
Winter	Hardwood	2.5 *(1–8.5)*	19.8 *(5–36.5)*
Winter	Herbaceous	1.5 *(1–3)*	15.2 *(4–24)*
Winter	Shrub	2.6 *(1–6)*	18 *(4.5–31)*
Spring	**County-wide**	**12.2 (3–24)**	**25 (16–36)**
Spring	Conifer	13.2 *(3–25)*	35 *(25–49)*
Spring	Hardwood	13.8 *(2–26)*	26 (16–37)
Spring	Herbaceous	3.9 *(1–10)*	17.2 *(11–23)*
Spring	Shrub	9.5 *(2–21)*	25.8 *(15–36.5)*
Summer	**County-wide**	**4.2** ***(1–15)***	**45 (34–55)**
Summer	Conifer	4.4 *(1–16)*	58.6 *(47–71)*
Summer	Hardwood	4.0 *(1–14)*	48.4 *(35.5–62)*
Summer	Herbaceous	2.4 *(1–9)*	19.5 *(14–27)*
Summer	Shrub	4.0 *(1–15)*	44.9 *(33.5–53.5)*

Table 2A
23-year trends in annual number of burn days. Asterisk (*) indicates $p < 0.01$. Pixels refer to the number of spatial points included in analysis.

Season	Vegetation	# Pixels (Plumas)	Trend	# Pixels (Sonoma)	Trend
Annual	***County-wide***	***1484***	**- 8.5***	***830***	**+8.6***
Annual	Conifer	1172	- 9.0*	*233*	+12.1*
Annual	Hardwood	50	- 6.6*	*256*	+ 19.1*
Annual	Herbaceous	66	- 5.2*	*297*	- 0.9
Annual	Shrub	196	- 7.2*	*44*	+12.4

3. Results and discussion

This study illuminates fine-scale regional and land cover-specific patterns and trends in prescribed burn windows within two distinct regions in California, Plumas, and Sonoma Counties (Fig. 1). We observed a greater number of burn days annually in Sonoma than in Plumas County (Table 1), implying greater flexibility in this more mesic, coastal region of California. However, we also observed a greater overall influence from insufficient wildland firefighting resources (defined by ONCC PL 4 or 5) and air quality concerns (defined by CARB "no burn" day for respective air basins) on potential burn days in Sonoma County than on Plumas (Fig. 2). In other words, we found opportunities for prescribed burning in Sonoma County to be more constrained by non-weather-related indices than in Plumas County.

Seasonally, we observed important distinctions in the number of burn days between the two counties (Table S3). In Sonoma, the greatest number of burn days occurs in summer ($p < 0.01$), followed by fall ($p < 0.01$), spring and winter ($p = 0.05$). In Plumas, most burn days occur in spring and fall ($p < 0.01$). However, the number of burn days does not differ between spring and fall ($p = 0.49$) or between summer and winter ($p = 0.79$). (Table 1 & S2, Fig. 3).

Although Rx weather windows were common in summer and fall in Sonoma, these windows frequently occurred alongside elevated wildfire preparedness levels (PL 4 and 5) (Fig. 2), indicating a potential mismatch in burn windows and resource availability.

These observed patterns support both increasing flexibility in both decision making workforce capacity to take advantage of these previously under-utilized burn windows. However, this type of structural shift would require expanding Rx infrastructure, e.g. greater inter-agency collaboration and sharing of resources, increasing the number of dedicated prescribed fire crews, and streamlining regulatory frameworks (Schultz et al., 2019). Additionally, in an area as climatically diverse as northern California adhering to single metric of wildfire activity (i.e., PL) throughout, let alone a common "prescribed fire season", is far too coarse in scale and restrictive to allow the burning needed to achieve stated fuel reduction and ecological restoration goals (Task Force, 2021, 2022). We expect such a shift to expand Rx capabilities outside of traditional burn windows would most directly benefit regions like Sonoma County that have frequent occurrence of burn windows that go unused due to constraints at a larger geographic scale (Fig. 2). However, the complexity in Sonoma County's land ownership, and a greater overall proportion of privately owned land (Fig. 1), presents different challenges related to risk, economic incentives, and cooperation. In regions where weather conditions alone are the main driver of limited burn windows, such as Plumas County, expanded Rx infrastructure will afford greater flexibility to take advantage of infrequent windows.

Within each county, the seasonal distribution of burn days is generally consistent across vegetation types (Fig. 3). However, there tended to be high variability between locations and years in the number of burn days per year (Fig. 3). It is essential that future prescribed fire policy is flexible enough to facilitate the implementation of Rx treatments, particularly where windows are infrequent or inconsistent.

In Plumas County, we found a decrease of 8.5 ($p < 0.01$) burn days over the 23-year study period (Table 2A); this trend is strongest in the southwest part of the county ($p < 0.01$), although we did not detect an effect of elevation ($p = 0.82$) (Fig. 4A).

This is substantial given the overall number of burn days annually in

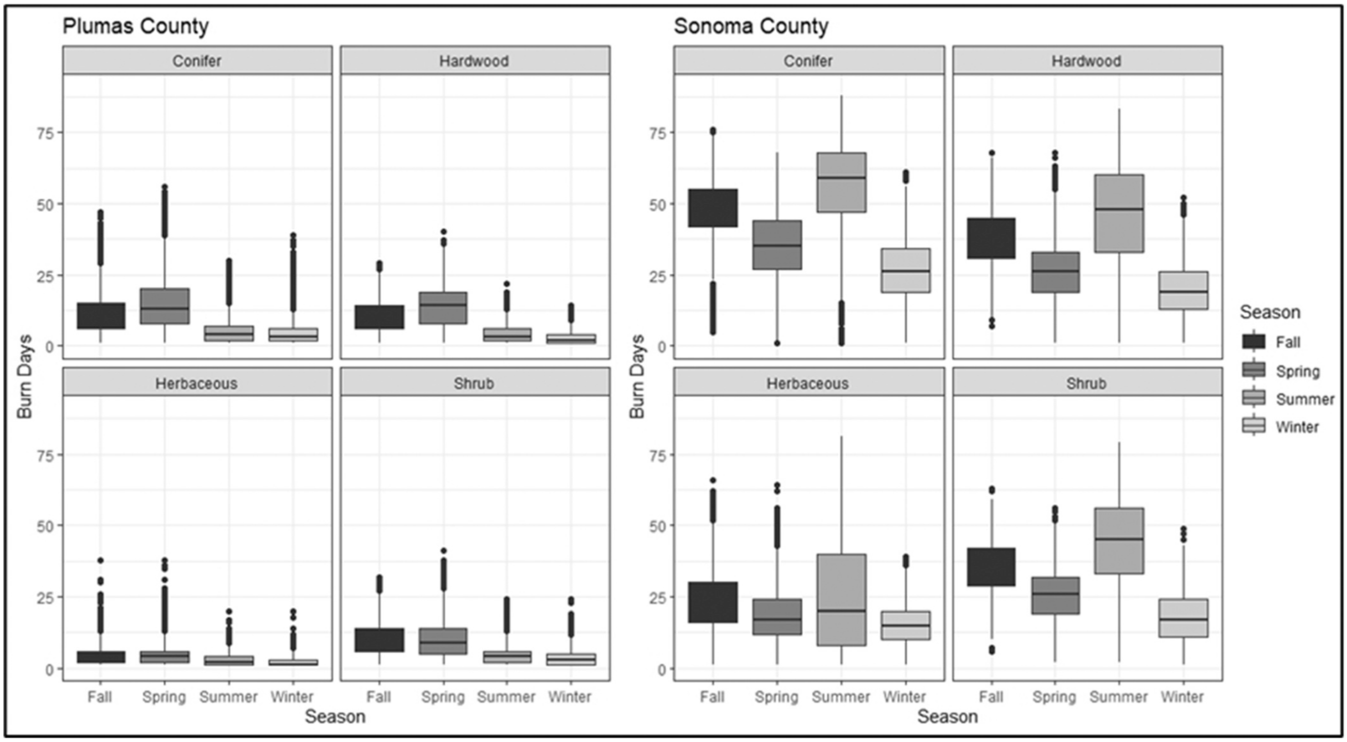

Fig. 3. Distribution of burn days (Median of each year and spatial point) for Plumas and Sonoma counties per season (x-axis) and separated by vegetation type (Conifer, Hardwood, Herbaceous, and Shrub).

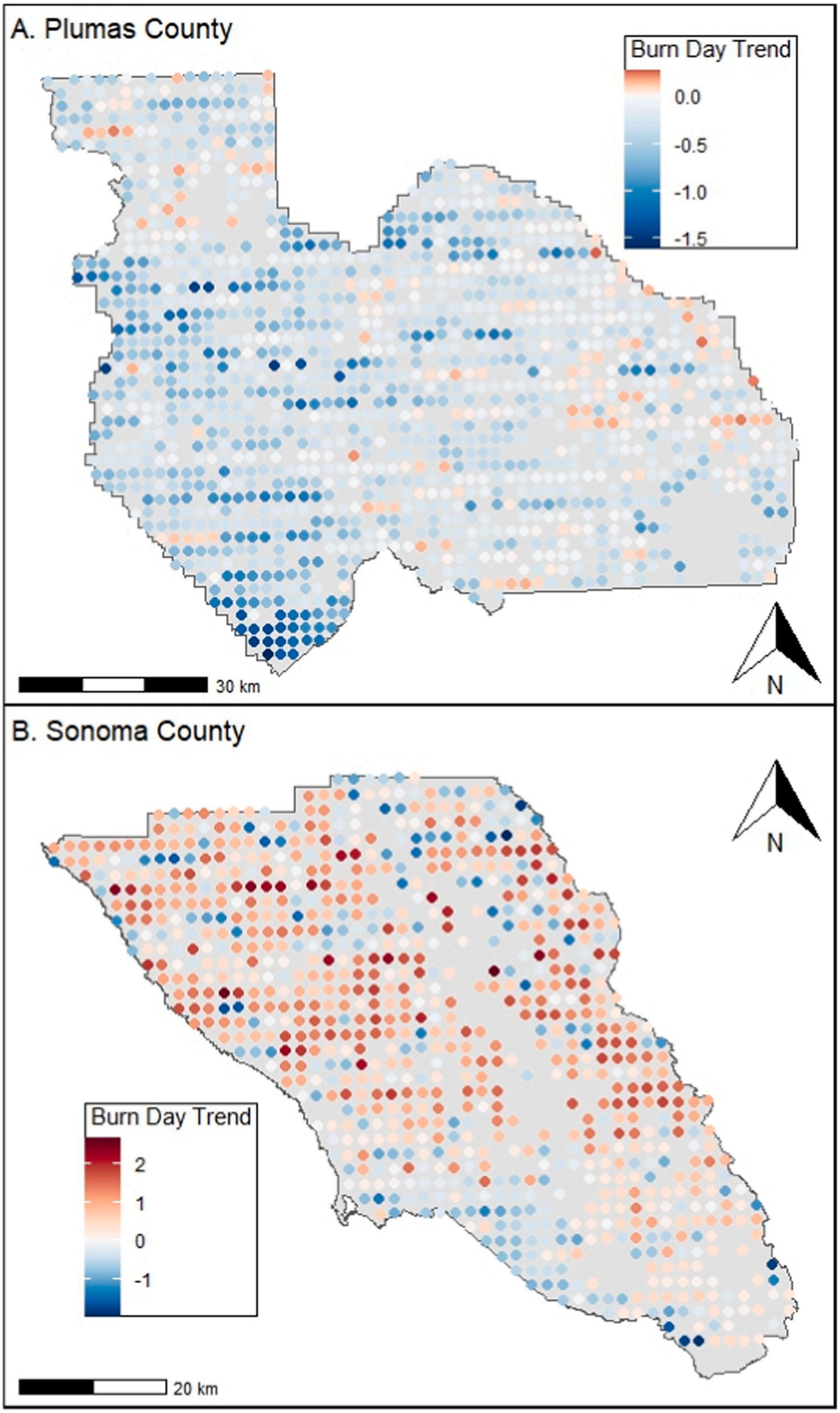

Fig. 4. Trends in annual burn days across Plumas (A) and Sonoma (B) counties. Points with increasing trends represented by red color, decreasing trends represented by blue.

Plumas County (averaged across geographic extent) is 28.1 (Table 1) and reflects the challenge and urgency for meeting prescribed fire needs in parts of California under a changing climate. Over the study period, we measured a decrease of 9.0 ($p < 0.01$) days for conifer, 6.6 ($p < 0.01$) days for hardwood, 5.2 ($p < 0.01$) days for herbaceous, and 7.2 ($p < 0.01$) days for shrublands (Table 2A). In conifer systems, the greatest decreases occurred in southern ($p = 0.01$) and western ($p < 0.01$) areas and were not related to elevation ($p = 0.78$). Likewise, the greatest decreases for shrublands ($p < 0.01$) and potentially herbaceous ($p = 0.02$) systems also occurred in southern areas and were likewise unaffected by elevation ($p > 0.26$). We observed no trends based on location or elevation in hardwood systems at the annual level ($p > 0.21$). This observed decrease in burn days aligns with the findings from Swain et al., 2023, that projected reductions in suitable weather windows over the next several decades throughout the western United States. Such a reduction will present another barrier land managers must overcome to successfully implement prescribed fire treatments at the necessary spatial scale to achieve ecological and fuels reduction targets (Lydersen et al., 2019; Knight et al., 2022).

This is amplified by recent state policy calling to increase total area treated annually with prescribed fire (Task Force, 2022). The prioritization of prescribed fire in regions where we observe greater reductions in burn windows may be necessary to both restore vulnerable ecosystems and protect nearby communities before it becomes more difficult to do so. A willingness to accept generally more severe fire effects from prescribed burning may more closely simulate the effects of historic wildfire (Striplin et al., 2020) and restore a less dense, more climate-resilient forest structure (Bernal et al., 2022). New regulations loosening certain restrictions on implementing Rx fire, such as considering increasing night operations in Summer, could help facilitate a new paradigm of burning in different/more flexible burn windows.

Across Sonoma County, we found an increase of 8.6 ($p < 0.01$) burn days over the 23-year study period, with the greatest increases potentially occurring in northern ($p = 0.02$) regions of the county (Fig. 4B). Per vegetation type, we measured increases of 12.1 ($p < 0.01$) days for conifer 19.1 ($p < 0.01$) days for hardwood, and 12.4 days ($p < 0.07$) for shrubland systems (Table 2A). Finally, we detected a non-significant decrease in burn days in herbaceous systems (-0.9 days, $p = 0.59$).

The increase in burn days we observed in Sonoma County (Fig. 4B) suggests that weather windows could continue to increase in some areas. Reduced humidity along the coast resulting from changes in marine layer dynamics could introduce new weather windows throughout coastal California (Johnstone and Dawson, 2010). Our findings of increasing burn day trends in non-herbaceous areas suggest that while vegetation type-change throughout coastal California is a major concern (Fertel et al., 2023), there is also ample opportunity for increasing prescribed burning in forests and shrublands as a tool to restore coastal grasslands, e.g. coastal prairie, and desired wildlife habitat (Keeley et al., 2023; Bartolome et al., 2004).

Seasonal burn windows in Plumas County decreased by 2.3days ($p < 0.01$) in the fall, 5.6 days ($p < 0.01$) in the spring, and 1.5 days ($p < 0.01$) in the summer but increased by 1.1 days ($p < 0.01$) in the winter (Table 2B, Fig. 5A).

The decreasing summer, spring, and fall trends were strongest in the west ($p < 0.01$), with spring ($p < 0.01$) and potentially fall ($p = 0.02$) also decreasing in the western regions of the county (Fig. 5A). Within individual vegetation types, decreases in spring burn days were consistently greater than decreases in fall burn days (Table 2B), suggesting greater stability in future fall windows vs. spring. While this stability in fall windows bodes well for achieving greater fuel consumption, which is a common objective for Rx fires in forested areas of the western U.S., Striplin et al. (2020) demonstrated that multi-day burn windows (i.e., on consecutive days) occurred less frequently in the fall than in the spring. This suggests spring would be more conducive for planning larger burns (>400 ha), which require multiple consecutive days. However, our results indicating a decreasing trend in spring burn days imply a reduced likelihood of these multi-day windows in the spring. Furthermore, practitioners are increasingly deterred from burning in areas with high surface fuel concentrations during spring out of concern that they might have to patrol those projects for months into extreme summer conditions to prevent escape.

Table 2B

23-year trends in seasonal number of burn days. Asterisk (*) indicates $p < 0.01$.

Season	Vegetation	Plumas County Trend	Sonoma County Trend
Fall	***County-wide***	−***2.3****	−***0.8***
Fall	Conifer	−2.4*	−0.3
Fall	Hardwood	−2.0*	+ 2.0*
Fall	Herbaceous	−0.8	−2.9*
Fall	Shrub	−2.0*	+ 0.7
Winter	***County-wide***	+***1.1****	+***6.6****
Winter	Conifer	+ 1.0*	+ 9.1*
Winter	Hardwood	+ 2.5*	+ 9.8*
Winter	Herbaceous	−0.2	+ 4.7*
Winter	Shrub	+ 1.8*	+ 8.9*
Spring	***County-wide***	−***5.6****	−***1.9****
Spring	Conifer	- 5.9*	- 2.3*
Spring	Hardwood	- 5.6*	+ 0.5
Spring	Herbaceous	- 2.9*	- 3.4*
Spring	Shrub	- 5.5*	- 1.7
Summer	***County-wide***	−***1.5****	+***2.7****
Summer	Conifer	−1.6*	+ 3.5*
Summer	Hardwood	−1.3*	+ 5.1*
Summer	Herbaceous	−1.0*	+ 0.3
Summer	Shrub	−1.2 *	+ 3.4

Additional concerns with spring Rx burning relate to potentially detrimental effects on vegetation (Kauffman and Martin, 1990) and wildlife species during key life stages (Thompson and Purcell, 2016), though this is likely limited by the fact that spring burns often result in lower fire intensity and fuel consumption compared to dryer fall Rx burns (Knapp et al. 2009). Patchy, lower-severity fire effects with spring Rx burns often produce a greater degree of heterogenous fire effects within burn units (i.e. unburned islands) (Knapp and Keeley, 2006), creating a range of structural habitat characteristics that emulate pre-suppression conditions (Bagne and Purcell, 2011) and promote biodiversity over the long-term. To mitigate some of these potential escape and wildlife concerns, suitable single-day burn windows in spring months could be utilized for smaller-scale pile burning operations, which generally allow more flexibility in treatment timing and extent and may limit short-term negative effects on vegetation and wildlife (i.e. nesting locations and food availability), compared to broadcast Rx burns. Future Rx planning will require greater flexibility so that land managers can take advantage of appropriate windows when they occur, regardless of the time of year.

The increase in winter burn days in Plumas County was greatest in the northeastern ($p = 0.01$) part of the county (Fig. 5A) and was detected within conifer (1.0 days, $p < 0.01$), (hardwood (2.5 days, $p < 0.01$), and shrubland (1.8 days, $p < 0.01$) but not hardwood ($p = 0.44$) vegetation types (Table 2B). Warmer and drier winter conditions may reveal new potential weather windows (Swain et al., 2023). More ephemeral winter snowpack (Casirati et al., 2023) and accelerated snowmelt in areas recently burned by wildfire (Kampf et al., 2022) will result in both shorter periods that fuels are inaccessible due to snow coverage, and earlier and more frequent snowmelt resulting in drier fuels (i.e. higher fuel consumption). Since 2018 in Plumas County, we observed the greatest incongruity between suitable weather windows, and CARB “burn day” decisions in the winter (Fig. 2). Atmospheric inversions that trap smoke at low altitudes are common in the winter (Striplin et al., 2020), contributing to these “no-burn” decisions. However, potential public health benefits of reduced wildfire smoke exposure with increased prescribed fire (Long et al., 2019; Schollaert et al., 2023; Jones et al., 2022) warrant a re-evaluation of current smoke and air quality constraints on Rx burning (Stephens et al., 2016). Expansion of winter Rx resources could allow land managers to bypass certain challenges of

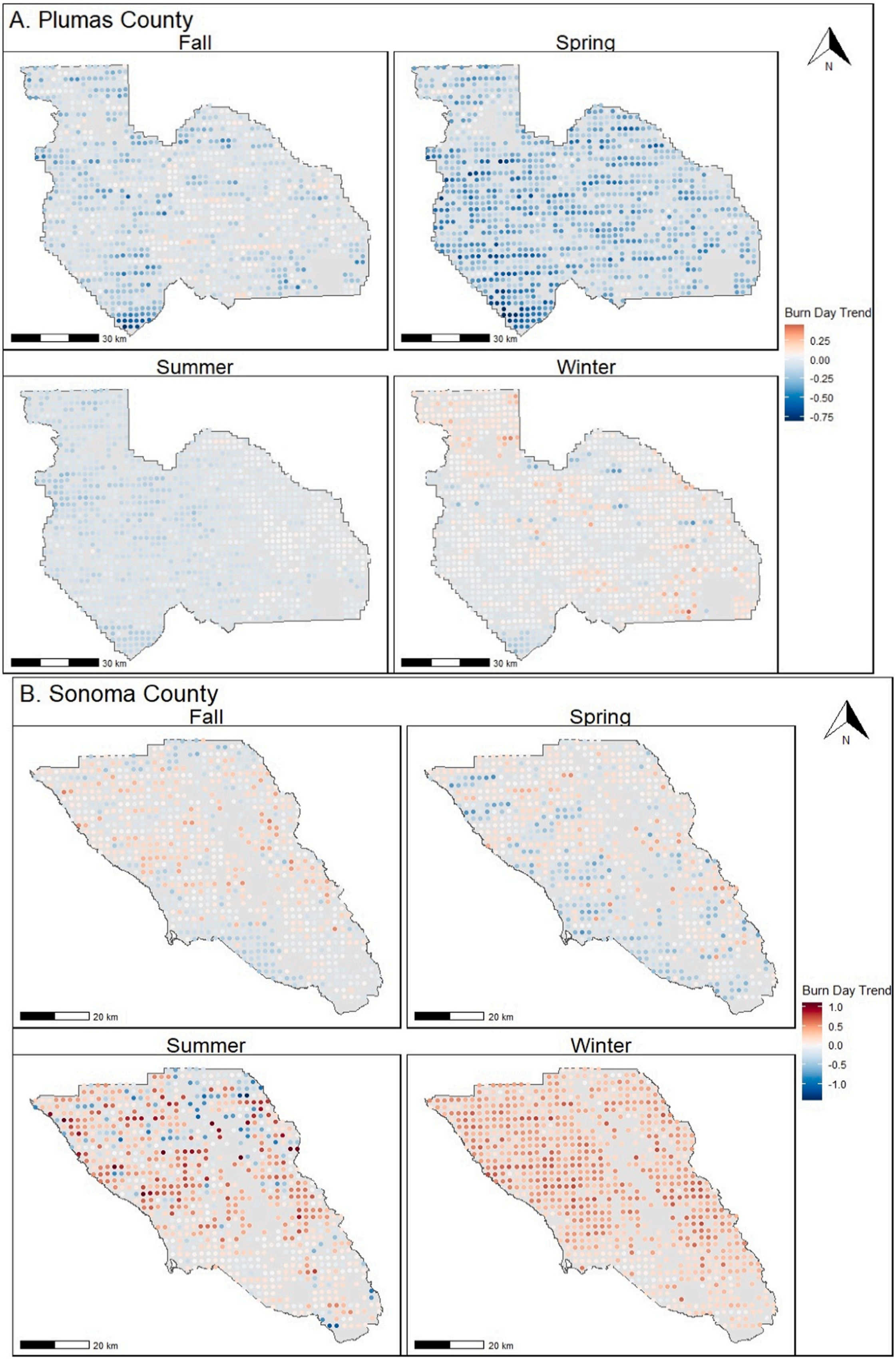

Fig. 5. Trends in seasonal burn days across Plumas (A) and Sonoma (B) counties. Points with increasing trends represented by red color, decreasing trends represented by blue.

fall and spring burning—riskier conditions on the hotter and drier end of desired weather windows and overlapping with recently increasing wildfire seasons (Stephens et al., 2023). Following a legacy of fire suppression and increased tree mortality, fuel loads remain uncharacteristically high throughout the state, particularly in forested areas with historic mixed-to-frequent fire regimes (Vilanova et al., 2023). As such, winter Rx burning while fuels are moist may result in more natural fire effects (Knapp et al., 2009); and would optimally be conducted with mechanical treatments in areas of particularly high fuel accumulation (York et al., 2021). Pile burning after mechanical treatments also provides practitioners a means to reduce surface fuels during winter months and prepare units for safer broadcast Rx burns under dried conditions.

Seasonal burn windows in Sonoma County increased by 6.6 days ($p < 0.01$) in the winter and 2.7 days ($p < 0.01$) in the summer, decreased by 1.8 days ($p < 0.01$) in the spring, and did not change in fall ($p = 0.14$) (Table 2B, Fig. 5B). In forested vegetation types, we observe particularly large burn day increases in the summer and winter, with an increase of 9.1-conifer and 9.8-hardwood days ($p < 0.01$) in the winter and 3.4-conifer and 5.1-hardwood days in the summer ($p < 0.01$) (Table 2B). We measured a decrease in fall windows for herbaceous (-2.9 days, $p < 0.01$), and a decrease in spring windows for herbaceous (-3.4 days, $p < 0.01$), and conifer (-2.3 days, $p < 0.01$) vegetation types. Winter windows increased between 4 and 10 days for each individual vegetation type ($p < 0.01$), and summer windows increased between 3 and 5 days for each non-herbaceous vegetation type ($p < 0.01$) (Table 2B). The management objective of many grassland-burns in coastal parts of California such as Sonoma County is to enhance native plant diversity or reduce invasive cover. Burns must target the appropriate phenological stage of plant development to achieve desired outcomes (Knapp et al., 2009). Strategically planning Rx treatments to utilize new windows while still achieving desired ecological effects will be a major challenge for land managers as the effects of climate change continue to re-shape opportunities for prescribed burning.

4. Conclusion

This study identifies trends in burn days across contrasting land ownership types, climates, and vegetation communities that describe much of the diversity in landscape-level challenges to expanding the use of Rx fire in California. Evidence that Rx fire weather windows are changing justifies the implementation of long-overdue reforms to current wildland fire infrastructure. Strengthening the role of beneficial fire in managing California's wildlands will require some changes to the current status quo, specifically restructuring operational capacity (Miller et al., 2020), increasing flexibility afforded to fire practitioners by regulators and decision makers, and empowering the authority of local and Indigenous knowledge to steward landscapes (Task Force, 2021).

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CRediT authorship contribution statement

Scott L. Stephens: Writing – review & editing, Resources, Funding acquisition. **Brandon M. Collins:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Christina Fossum:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Jamie M. Lydersen:** Writing – review & editing, Methodology, Conceptualization. **Connor Stephens:** Writing – review & editing, Validation, Formal analysis. **Taj Katuna:** Writing – review & editing, Methodology, Conceptualization. **Joe Restaino:** Writing – review & editing, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christina Fossum reports financial support was provided by California Department of Forestry and Fire Protection. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.121966.

References

Abatzoglou, J.T., 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33 (1), 121–131. https://doi.org/10.1002/joc.3413.

Abatzoglou, J., Williams, A.P., 2016. Impact o9f anthropogenic climate change on wildfire across western US forests. Proc. Natl. Acad. Sci. 113 (42) https://doi.org/10.1073/pnas.

Bagne, Karen E., Purcell, Kathryn L., 2011. "Short-term responses of birds to prescribed fire in fire-suppressed forests of California". J. Wildl. Manag. 75 (5), 1051–1060. https://doi.org/10.1002/jwmg.128.

Bartolome, J.W., Fehmi, J.S., Jackson, R.D., Allen-Diaz, B., 2004. Response of native perennial grass stand to disturbance in California's coast range Grassland. Restor. Ecol. 12 (2), 279–289. https://doi.org/10.1111/j.1061-2971.2004.00355.x.

Beaty, R.M., Taylor, A.H., 2001. Spatial and Temporal variation in fire regimes in a mixed conifer forested landscape, southern Cascades, California, USA. J. Biogeogr. 28 (8), 955–966.

Bernal, A.A., Stephens, S.L., Collins, B.M., Battles, J.J., 2022. Biomass stocks in California's fire-prone forests: mismatch in ecology and policy. Environ. Res. Lett. 17 (4) https://doi.org/10.1088/1748-9326/ac576a.

Brown, T.J., Mills, G., Harris, S., Podnar, D., Reinbold, H.J., Fearon, M.G., 2016. A bias corrected WRF mesoscale fire weather dataset for Victoria, Australia 1972-2012. J. South. Hemisph. Earth Syst. Sci. 66 (3), 281–313. https://doi.org/10.22499/3.6003.00004.

California department of forestry and fire protection, 2023. California Land Ownership 2023. Fire Resour. Assess. Program (assessed Jan. 2024).

California Air Resources Board, 2001. Title 17 of the California Code of Regulations, Article 2. District Smoke Management Program. California Environmental Protection Agency.

Casirati, S., Conklin, M.H., Safeeq, M., 2023. Influence of snowpack on forest water stress in the Sierra Nevada. Front. For. Glob. Change 6. https://doi.org/10.3389/ffgc.2023.1181819.

Collins, B.M., Fry, D.L., Lydersen, J.M., Everett, R., Stephens, S.L., 2017. Impacts of different land management histories on forest change. Ecol. Appl. 27 (8), 2475–2486. https://doi.org/10.1002/eap.1622.

Davis, L.S., Cooper, R.W., 1963. How prescribed burning affects wildfire occurrence. J. For. 61 (12), 915–917.

Debruin, H.W., 1974. From fire control to fire management: a major policy change in the Forest Service. Proc. Tall Timbers Fire Ecol. Conf. 14, 11–17.

Fernandes, P.M., 2015. Empirical support for the use of prescribed burning as a fuel treatment. Curr. For. Rep. 1, 118–127. https://doi.org/10.1007/s40725-015-0010-z.

Fernandes, P., Botelho, H., 2004. Analysis of the prescribed burning practice in the pine forest of northwestern Portugal. J. Environ. Manag. 70 (1), 15–26. https://doi.org/10.1016/j.jenvman.2003.10.001.

Fertel, H.M., Collins, B.M., Lydersen, J.M., Stephens, S.L., 2023. Vegetation type change in California's Northern Bay Area: a comparison of contemporary and historical aerial imagery. For. Ecol. Manag. 542 (15) https://doi.org/10.1016/j.foreco.2023.121102.

Force, T. 2021. California's wildfire & forest resilience action plan. A comprehensive strategy of the Governor's forest management task force, available from: ⟨https://wildfiretaskforce.org/action-plan/⟩ (accessed Jan. 2024).

Force, T. 2022. California's strategic plan for expanding the use of beneficial fire. Wildfire and forest resiliency task force & prescribed fire work group. Available from: / ⟨https://wildfiretaskforce.org/about/action-areas/prescribed-fire/⟩ (accessed Jan. 2024).

Huntsinger, L., Bartolome, J.W., D'antonio, C.M., 2007. Grazing Management on California's Mediterranean Grasslands. In: Stromberg, Mark (Ed.), California Grasslands: Ecology and Management. The University of California Press. https://doi.org/10.1525/california/9780520252202.003.0020.

Ives, A.R., Zhu, L., Wang, F., Zhu, J., Morrow, C.J., Radeloff, V.C., 2021. Statistical inference for trends in spatiotemporal data. Remote Sens. Environ. 266 https://doi.org/10.1016/j.rse.2021.112678.

Johnstone, J.A., Dawson, T.E., 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. Proc. Natl. Acad. Sci. 107 (10), 4533–4538. https://doi.org/10.1073/pnas.0915062107.

Jones, B.A., Mcdermott, S., Champ, P.A., Berrens, R.P., 2022. More smoke today for less smoke tomorrow? We need to better understand the public health benefits and costs of prescribed fire. Int. J. Wildland Fire 31 (10), 918–926. https://doi.org/10.1071/WF22025.

Jose, E., Agarwal, P., Zhuang, J., 2023. A data-driven analysis and optimization of the impact of prescribed fire programs on wildfire risk in different regions of the USA. Nat. Hazards 118, 181–207. https://doi.org/10.1007/s11069-023-05997-w.

Kampf, S.K., McGrath, D., Sears, M.G., Hammond, J.C., 2022. Increasing wildfire impacts on snowpack in the western U.S. Proc. Natl. Acad. Sci. 119 (39) https://doi.org/10.1073/pnas.2200333119.

Kauffman, J.B., Martin, R.E., 1990. Sprouting shrub response to different seasons and fuel consumption levels of prescribed fire in Sierra Nevada mixed conifer ecosystems. For. Sci. 36 (3), 748–764.

Keeley, J.E., Klinger, R.C., Brennan, T.J., Lawson, D.M., La Grange, J., Berg, K.N., 2023. A decade-long study of repeated prescription burning in California native grassland restoration. Restor. Ecol. https://doi.org/10.1111/rec.13939.

Keter, T.S., 1995. Environmental history and cultural ecology of the North Fork and Eel River Basin, California. U.S. Department of Agriculture Forest Service, Pacific Southwest Region, R5-EM-TP-002, Eureka, CA.

Knapp, Eric, E., Estes, B.L., Skinner, C.N., 2009. Ecological effects of prescribed fire season: a literature review and synthesis for managers. U. S. Dep. Agric., For. Serv., Pac. Southwest Res. Station. https://doi.org/10.2737/PSW-GTR-224.

Knapp, E.E., Keeley, J.E., 2006. Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest. Int. J. Wildland Fire 15, 37–45.

Knight, C.A., Tompkins, R.E., Wang, J.A., York, R., Goulden, M.L., Battles, J.J., 2022. Accurate tracking of forest activity key to multi-jurisdictional management goals: A case study in California. J. Environ. Manag. 302 (B) https://doi.org/10.1016/j.jenvman.2021.114083.

Kobziar, L.N., Godwin, D., Taylor, L., Watts, A.C., 2015. Perspectives on trends, effectiveness, and impediments to prescribed burning in the southern US. Forests 6 (3), 561–580.

Lewis, H.T., 1993. Patterns of Indian burning in California: ecology and ethnohistory. In: Blackburn, T.C., Anderson, K. (Eds.), Before the wilderness: environmental management by Native Californians. Ballena Press, Menlo Park, CA, pp. 55–116.

Long, J.W., Tarnay, L.W., North, M.P., 2019. Aligning Smoke Management with Ecological and Public Health Goals. J. For. 116 (1), 76–86.

Lydersen, J.M., Collins, B.M., Brooks, M.L., Matchett, J.R., Shive, K.L., Povak, N.A., Kane, V.R., Smith, D.F., 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecol. Appl. 27, 2013–2030. https://doi.org/10.1002/eap.1586.

Lydersen, J.M., Collins, B.M., Hunsaker, C.T., 2019. Implementation constraints limit benefits of restoration treatments in mixed-conifer forests. Int. J. Wildland Fire 28, 495–511. https://doi.org/10.1071/WF18141.

Marks-Block, T., Lake, F.K., Bird, R.B., Curran, L.M., 2021. Revitalizing Karuk and Yurok cultural burning to enhance California Hazelnut for basketweaving in northwestern California, USA. Fire Ecol. 17, 6. https://doi.org/10.1186/s42408-021-00092-6.

Martin, Robert, E., Boone Kauffman, J., Landsberg, Joan D., 1989. "Use of prescribed fire to reduce wildfire potential". In: Berg [Tech. Coord.], N.H. (Ed.), Proceedings: Symposium on fire and watershed management. PSW-GTR-109. USDA. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, pp. 17–22.

Miles, S.R., Goudey, C.B., 1998. Ecological subregions of California: section and subsection descriptions. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, San Francisco, CA. ⟨https://purl.fdlp.gov/GPO/LPS95404⟩.

Miller, R.K., Field, C.B., Mach, K.J., 2020. Barriers and enablers for prescribed burns for wildfire management in California. Nat. Sustain. 3, 101–109. https://doi.org/10.1038/s41893-019-0451-7.

Moody, T.J., Fites-Kaufman, J., Stephens, S.L., 2006. Fire history and climate influences from forests in the northern Sierra Nevada, USA. Fire Ecol. 2, 115–141.

Morrow, C., Ives, A., 2023. _remotePARTS: Spatiotemporal Autoregression Analyses for Large Data Sets_. R. Package Version 1. 0. 4. ⟨https://CRAN.R-project.org/package=remotePARTS⟩.

Pillers, M.D., 1989. Fine Fuel Dynamics of old-growth redwood forests. M. S. Humboldt State University, Arcata, CA.

Parsons, D.J., Debenedetti, S.H., 1979. Impact of fire suppression on a mixed-conifer forest. For. Ecol. Manag. 2, 21–33.

Plumas County, 2024. CA – Official Website | County Maps (Accessed Jan.). CivicPlus. ⟨https://www.plumascounty.us/482/County-Maps⟩ (Accessed Jan.).

Quinn-Davidson Lenya, N., Varner, J.Morgan, 2012. Impediments to prescribed fire across agency, landscape, and manager: an example from northern California. Int. J. Wildland Fire 21 (3), 210–218. https://doi.org/10.1071/WF11017.

R Core Team, 2023. _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, *Vienna Austria*. ⟨https://www.R-project.org/⟩.

Ryan, B.C., 1984. Potential fire behavior in California: an atlas and guide for forest and brushland managers (General Technical Report No. PWS-77). USDA Forest Service Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. ⟨https://www.fs.usda.gov/psw/publications/documents/psw_gtr077/psw_gtr077.pdf⟩.

Safford, H.D., Stevens, J.T., Merriam, K., Meyer, M.D., Latimer, A.M., 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. For. Ecol. Manag. 274, 17–28. https://doi.org/10.1016/j.foreco.2012.02.013.

Safford, H.D., Paulson, A.K., Steel, Z.L., Young, D.J.N., Wayman, R.B., 2022. The 2020 California fire season: A year like no other, a return to the past or a harbinger of the future? Glob. Ecol. Biogeogr. 31, 2005–2025.

Sawyer, J.O., Gray, J., West, G.J., Thornburgh, D.A., Noss, R.F., Engbeck, J.H., Marcot, B. G., Raymond, R., 2000. History of redwood and redwood forests. In: Noss, R.F. (Ed.), The redwood forest: history, ecology, and conservation of the coast redwoods. Island Press, Washington, D.C., pp. 7–38

Schollaert, C.L., Jung, J., Wilkins, J., et al., 2023. Quantifying the smoke-related public health trade-offs of forest management. Nat. Sustain. https://doi.org/10.1038/s41893-023-01253-y.

Schultz, C.A., McCaffrey, S.M., Huber-Stearns, H.R., 2019. Policy barriers and opportunities for prescribed fire application in the western United States. Int. J. Wildland Fire 28, 874–884. https://doi.org/10.1071/WF19040.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Powers, J.G., 2008. A Description of the Advanced Research WRF Version 3. U.S. National Center for Atmospheric Research, Boulder, CO. https://doi.org/10.5065/D68S4MVH.

Skinner, C.N., Taylor, A.H., 2006. Southern Cascades Bioregion. In: Sugihara, N. (Ed.), Fire in California's Ecosystems. University of California Press, pp. 146–169.

Stephens, S.L., Martin, R.E., Clinton, N.E., 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. For. Ecol. Manag. 251, 205–216. https://doi.org/10.1016/j.foreco.2007.06.005.

Stephens, S.L., Collins, B.M., Biber, E., Fulé, P.Z., 2016. U.S. federal fire and forest policy: emphasizing resilience in dry forests. Ecosphere 7 (11). https://doi.org/10.1002/ecs2.1584.

Stephens, S.L., Kobziar, L.N., Collins, B.M., Davis, R., Fulé, P.Z., Gaines, W., Ganey, J., Guldin, J.M., Hessburg, P.F., Hiers, K., Hoagland, S., 2019. Is fire "for the birds"? How two rare species influence fire management across the US. Front. Ecol. Environ. 17 (7), 391–399.

Stephens, S.L., Hall, L., Stephens, C.W., Bernal, A.A., Collins, B.M., 2023. Degradation and restoration of Indigenous California black oak (*Quercus kelloggii)* stands in the northern Sierra Nevada. Fire Ecol. 19, 12. https://doi.org/10.1186/s42408-023-00172-9.

Striplin, R., McAfee, S.A., Safford, H.D., Papa, M.J., 2020. Retrospective analysis of burn windows for fire and fuels management: an example from the Lake Tahoe Basin, California, USA. *Fire* Ecol. 16, 13. https://doi.org/10.1186/s42408-020-00071-3.

Stuart, J.D., Stephens, S.L., 2006. North Coast Bioregion. In: Sugihara, N. (Ed.), Fire in California's Ecosystems. University of California Press, pp. 146–169.

Swain, D.L., Abatzoglou, J.T., Kolden, C., et al., 2023. Climate change is narrowing and shifting prescribed fire windows in western United States. Commun. Earth Environ. 4, 340. https://doi.org/10.1038/s43247-023-00993-1.

Thompson, Craig M., Purcell, Kathryn L., 2016. "Conditions inside Fisher Dens during Prescribed Fires; What Is the Risk Posed by Spring Underburns?". For. Ecol. Manag. 359, 156–161. https://doi.org/10.1016/j.foreco.2015.10.003.

van Wagtendonk, J.W., 1991. The evolution of National Park Service Fire Policy. West. Ecol. Res. Cent. Fire Manag. Notes 52 (4), 10–15. ⟨https://pubs.usgs.gov/publication/1008068⟩.

van Wagtendonk, J.W., Fites-Kaufman, J.A., 2006. Sierra Nevada Bioregion. In: Sugihara, N. (Ed.), Fire in California's Ecosystems. University of California Press, pp. 146–169.

Vilanova, E., Mortenson, L.A., Cox, L.E., Bulaon, B.M., Lydersen, J.M., Fettig, C.J., Battles, J.J., Axelson, J.N., 2023. Characterizing ground and surface fuels across Sierra Nevada forests shortly after the 2012-2016 drought. For. Ecol. Manag. 537 https://doi.org/10.1016/j.foreco.2023.120945.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940–943. https://doi.org/10.1126/science.1128834.

Williams, A.P., Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K., Lettenmaier, D.P., 2019. Observed Impacts of Anthropogenic Climate Change on Wildfire in California. Earths Future 7, 892–910. https://doi.org/10.1029/2019EF001210.

Williams, J., Quinn-Davidson, L., Safford, H., Grupenhoff, A., Middleton, B.R., Restaino, J., Smith, E., Adlam, C., Rivera-Huerta, H., 2023a. Overcoming obstacles to prescribed fire in the North American Mediterranean Climate Zone. Front. Ecol. Environ. https://doi.org/10.1002/fee.2687.

Williams, J.N., Safford, H.D., Enstice, N., Steel, Z.L., Paulson, A.K., 2023b. High-severity burned area and proportion exceed historic conditions in Sierra Nevada, California, and adjacent ranges. Ecosphere 14 (1). https://doi.org/10.1002/ecs2.4397.

York, R.A., Roughton, A., Tompkins, R.E., Kocher, S.D., 2020. Burn permits need to facilitate—not prevent— "good fire" in California. Calif. Agric. 74, 62–66.

York, R.A., Levine, J., Russell, K., et al., 2021. Opportunities for winter prescribed burning in mixed conifer plantations of the Sierra Nevada. Fire Ecol. 17, 33. https://doi.org/10.1186/s42408-021-00120-5.