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Historical seasonal changes in prescribed burn windows in California

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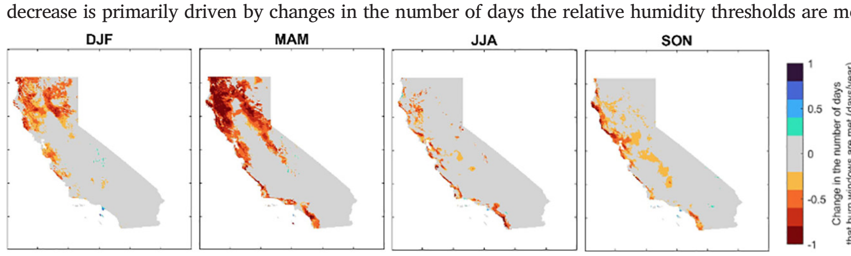
HIGHLIGHTS

- Can burn windows be extended to include other opportune seasons?
- Burn windows are one of the most important constraints for conducting Rx burns.
- Opportune windows are present (70–90% of the time) over forests in DJF and MAM.
- DJF and MAM windows are decreasing (1 day/yr) over larger areas than other months
- Relative humidity is the driving factor influencing the decrease in burn windows.

GRAPHICAL ABSTRACT

Prescribed (Rx) burns are conducted on days when the meteorological thresholds of maximum air temperature, relative humidity, and wind speeds are all met (burn window) in order to ensure safe Rx burn practices. Burn windows are identified as one of the most important constraints for conducting Rx burns in California. We investigate whether burn windows across California can be extended from the typical fall season to include other opportune seasons for facilitating specific management objectives. Note the seasons as defined by the first letter of each month: winter (DJF), spring (MAM), summer (JJA), fall (SON).We quantify the seasonal Rx burn efficiencies by assessing the frequency and burned areas using an aggregate of the California Department of Forestry and Fire Protection (Cal Fire), Prescribed Fires Incident Reporting System (PFIRS), and Monitoring Trends in Burn Severity (MTBS) datasets. Fall burns are most frequently executed (40% of the time), the spring (and to a lesser extent winter) seasons yield efficient Rx burns similar to fall, because greater acres are being consumed with less burns. In addition, winter and spring seasons experience burn window opportunities (70–90% of the time) over larger areas than the other seasons, and this is predominantly over forested regions in Northern California. Burn windows in the winter and spring are decreasing at a rate of one day per year over a larger spatial area than that of summer and fall. This decrease is primarily driven by changes in the number of days the relative humidity thresholds are met.



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ABSTRACT

Prescribed (Rx) burns are conducted on days when the meteorological thresholds of maximum air temperature, relative humidity, and wind speeds are all met (burn window) in order to ensure safe Rx burn practices. Limited burn windows have been consistently identified as one of the most important constraints for conducting Rx burns in California. We investigate whether burn windows across California can be extended from the typical fall season to include other opportune seasons for facilitating specific management objectives. We quantify the seasonal Rx burn efficiencies by assessing the frequency and burned areas using an aggregate of Rx datasets, and we compute the seasonal spatiotemporal trends in the number of days the set of meteorological parameters are met over thirty-five years (1984 to 2019), using the gridMET 4 km dataset. Our results indicate that while fall burns are most frequently executed (40% of the time), the spring (and to a lesser extent winter) seasons yield efficient Rx burns similar to fall because greater acres are being consumed with less burns. In addition, winter and spring seasons experience burn window opportunities (70–90% of the time) over larger areas than the other seasons, and this is predominantly over forested regions in Northern California. Our results also indicate that burn windows in the winter and spring are decreasing at a rate of

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one day per year over a larger spatial area than that of summer and fall. This decrease is primarily driven by changes in the number of days the relative humidity thresholds are met. Policymakers recognize the critical importance that Rx burns have on a multitude of ecosystem restoration factors, fire behavior dynamics, and firefighter safety. Therefore, there is a need to capitalize on these additional burn windows before these opportunities become less feasible in the future.

1. Introduction

California has one of the highest exposures (e.g., wildfire occurrence, extreme fire weather) and sensitivities (e.g., ignition causes and vulnerable demographics) to wildfires in the US, with wildfire conditions worsening each year (Baijnath-Rodino et al., 2021). Despite decades of investments in wildfire prevention education and an expansive fire suppression infrastructure, California has experienced a fivefold increase in annual burned area (Williams et al., 2019). Also, across the western and central regions of California, wildfire season has been expanding, and wildfire frequency has been increasing (predominantly for small wildfires less than 500 acres) (Li and Banerjee, 2021). The trends in wildfire activity in California and throughout the rest of Western North America have been associated with a changing climate and a century of fire suppression/exclusion, including past forest management that was not focused on reducing fire severity (Hessburg et al., 2021).

Currently, a treatment option that can be done either as an alternative to mechanical treatments or in conjunction with them is prescribed fire (Rx burns). Rx burns are intentionally ignited, typically low intensity fires that consume surface fuels on the forest floor while minimizing mortality of overstory trees (York et al., 2020). One beneficial example from an Rx burn includes the post-burn charred material and ash layer that can protect the soil and reduce its vulnerability to overland flow and erosion, in contrast to severe wildfires that normally consume the majority of litter, leaving the soil more vulnerable (Vega and Fernández, 2005; Úbeda et al., 2018). Generally, Rx burns can be favored because they restore ecosystem processes, reduce future extreme wildfires (by removing the accumulation of hazardous vegetation), and improve firefighter safety (by providing increased accessibility during emergency response) (Wade and Lunsford, 1989). Rx burns are often employed in addition to fuel treatment operations such as mastication to meet site-specific objectives, and they are used for a myriad of other ecological and cultural objectives (Kalies and Kent, 2016; Banerjee et al., 2020; Miller et al., 2020). Thus, there is a critical need to increase the use of Rx burn practices (Hiers et al., 2020).

In order for Rx burns to be executed, a multitude of conditions need to be met concurrently (National Wildfire Coordinating Group, 2017), including 1) having adequate personnel and equipment present, 2) confirming with local air pollution control districts that burning is allowable, 3) obtaining permission from landowners and/or fire suppression agencies as needed, and 4) ensuring that weather conditions are safe yet also hot and dry enough to facilitate effective fuel consumption (Striplin et al., 2020). Some of these conditions depend directly on sociological tolerances. For example, Rx burns could be allowed more often if permits for burning were granted more frequently. Other conditions can be facilitated financially, for example by hiring additional personnel with more equipment to do further burns. Meteorological and fuel conditions, however, are to a large extent beyond the control of humans yet are the dominant factor in whether or not a physical "burn window" exists (Kupfer et al., 2020). Regardless of landowner type or any number of social or economic factors, the observed meteorological conditions (primarily air temperature, wind speed, and relative humidity) must meet the required conditions set by a burn plan criterion in order to ensure that burn objectives are met (Striplin et al., 2020). It is important to note that burn window parameters vary depending on burn objectives, and they are determined as part of the burn planning process.

Given the infeasibility of conducting all desired burns within a short window in the fall, it has become increasingly necessary to identify all possible burn windows, regardless of the time of year in which they occur (Hiers et al., 2020). A changing climate, however, means that these Rx burn windows are moving targets, creating a further challenge for efforts to increase Rx d fire activity.

The objective of this study is to determine if historical changes in meteorological variables are changing the feasibility of conducting burns during typical burn seasons and whether other seasons offer additional windows of opportunities to execute safe yet effective Rx burns in various vegetation types (trees, shrubs, grassland). We, therefore, aim to determine the 1) historical seasonal frequency and acres burned with Rx fires, 2) efficiency (acres/project) of Rx burns for each season and 3) changes in historical burn windows and the limiting meteorological factors over various vegetation types. By ascertaining the availability of burn windows, this work may help agencies and landowners target ideal times to maximize the chances of successfully and safely meeting Rx burn objectives, in addition to addressing a backlog of Rx burns (Hiers et al., 2020; Striplin et al., 2020).

2. Data & methods

The data used in this study describe past Rx fire occurrences, meteorological conditions, and vegetation types. The data are extracted for California and for the seasons spanning 1984/1985 to 2018/2019. This study examines the Rx burns during the calendar seasons in California, which are represented by the months December, January, February (DJF) for the Boreal winter; March, April, May (MAM) for the Boreal spring; June, July, August (JJA) for the Boreal summer; September, October, November (SON) for the Boreal fall. The monthly and yearly temporal selections were available, comprehensive, and consistent among most datasets and provided sufficient climatological records for assessing spatiotemporal trends in burn windows throughout California. The seasonal scale is analyzed in this study because fire management practices and burn permit issuance are based on seasons, and many other studies have focused on this temporal period when examining Rx fire management practices. Furthermore, the meteorological conditions can also be best interpreted by using the seasons as a reference point.

2.1. Rx burns & historical seasonal frequencies

An Rx burn database for California was created by aggregating data from the California Department of Forestry and Fire Protection (CAL FIRE) [https://frap.fire.ca.gov/mapping/gis-data], the Prescribed Fire Incident Reporting System (PFIRS) [https://ssl.arb.ca.gov/pfirs/index.php], and the Monitoring Trends in Burn Severity (MTBS) [https://www.mtbs.gov/]. CAL FIRE provides Rx burn records dating back to the early 1900s and includes burns under different vegetation types that are larger than 10 acres for timber, 30 acres for brush, and 300 acres for grasslands (CAL FIRE, 2020). MTBS provides Rx burn data for fires that are greater than 1000 acres in California, commencing in 1984 (Finco et al., 2012). PFIRS comprises burn permit records from 22 of the 35 air districts in California with a minimum burned area of 0.01 acres in California between 2013 and 2019 (PFIRS, 2019).

These datasets provide information on the start date of the Rx burns as well as the number of acres burned. The aggregation of these datasets provide a comprehensive record of Rx fires. Even when combined, we acknowledge that our database does not capture all Rx fire activity. For example, small Rx fires with no government agency involvment could be vastly under-recorded. In some air districts, Rx fires need to emit more than 1 ton of particulate matter that is smaller than 10 μm (equivalent of ~3 ha) in order to require a smoke management plan that would be reported in PFIRS. Therefore, our database reflects larger burns that would be conducted by agencies such as CAL Fire and the US Forest Service but likely does not represent smaller Rx fires by individual landowners.

The frequency of yearly Rx burns for a given season is expressed as a percent and shown in Eq. (1).

$$F_{s,y} = \frac{Rx_{s,y}}{\sum_{i=1}^{35} Rx_{s,i}} \times (100) \tag{1}$$

$F_{s,\,y}$ is the frequency of Rx burns occurring for a particular season (s) and for one particular year (y) expressed as a percent. Note that $Rx_{s,\,y}$ is the number of Rx burn occurrences for a particular season and year and is divided by the sum of all Rx burns over the 35-year period for that particular season, where (i) represents the "ith" year.

We also plot the frequency (expressed as a percent) of total Rx burns for a particular season (F_s) over the 35 years, and it is determined by computing the sum of Rx burns for all year and for a particular season divided by the sum of Rx burns for all 35 years and all 4 seasons, where (n) represents the "nth" season Eq. (2).

$$F_s = \frac{\sum_{i=1}^{35} Rx_{s,i}}{\sum_{i=1}^{35}\sum_{n=1}^{4} Rx_{n,i}} \times (100) \tag{2}$$

The same method is applied for determining the percentage of total burn acres per season. Finally, burn efficiency over the 35-year period for each season is calculated as the ratio of the percentage of acres burned per season, divided by the percentage of Rx burns in that season. In this study, the burn efficiency provides an indication of how effective Rx burns are for a particular season. A higher burn efficiency indicates that less Rx burns are required to burn a larger area. This working definition follows the work by Buckley and Corkish (1991), and adopted by Fernandez and Botelho (2003) who describes the classification of Rx fire effectiveness, based on fuel reduction percentages. This burn efficiency metric is appropriately adopted for this study because it provides a first order approximation of Rx burn effectiveness, given the relatively large spatial and temporal scale of analysis.

2.2. Meteorology & burn windows

Meteorological datasets were acquired from gridMET, which offers daily (midnight to midnight) gridded 4 km resolution of meteorological variables for the contiguous United States from 1979 to present (Abatzoglou, 2011). It is a blend of gridded climate data from PRISM (climate observations from monitoring networks) (Daly et al., 2008) and North American land data assimilation, NLDAS-2 (integration of satellite and ground-based observation of land surface states) (Mitchell et al., 2004; Xia et al., 2012). The gridMet dataset offers primary climate variables, including maximum temperature, maximum relative humidity, and wind velocity that will be used to determine daily burn windows in this study. While meteorological variables that are used to define prescription parameters can vary considerably depending on management objectives and safety constraints, the most commonly observed variables are temperature, relative humidity and wind speed (Wade and Lunsford, 1989; Striplin et al., 2020).

In this study, a daily burn window is considered "open" when all meteorological conditions are met per grid cell. It is noted that Rx burn prescriptions may vary depending on the different fire regimes, vegetation types, and geographic locations. However, detailed prescription types for various vegetation cover and locations are not well documented in peer-reviewed literature, making it difficult to attain. The thresholds used in this study offer an approximation that can be applied across all of California and follows the prescription recommendations for southern forested ecosystems, as provided by the United States Department of Agriculture (Wade and Lunsford, 1989).

The meteorological burn window thresholds are as follows: air temperatures are between 0 and 32 °C; wind conditions between 2 m^{-s}–10 m^{-s}; relative humidity between 30 and 55% (Table 1). These ranges are from Wade and Lunsford (1989) and are in agreement with studies that have published their prescriptions in California (Biswell, 1989).The seasonal burn window frequency, expressed as a percentage, is calculated as the ratio between the number of burn windows for a particular season for all years (e.g., fall) divided by the total number of burn window days for all seasons during the 35-year period. In addition, the seasonal trends in burn windows are determined by performing the Mann-Kendall (MK) statistical test. MK estimates the linear regression of a time series nonparametrically and is ideal for determining climatological trend analysis because it is less sensitive to outlier data (Kendall, 1975; Gilbert, 1987). Only significant changes (with a confidence level of 95%) are plotted. Similarly, we examine the spatiotemporal trends in the number of days each meteorological condition is met (temperature, wind speed, and relative humidity) in order to determine which weather condition is the limiting factor, influencing the spatiotemporal changes in burn windows over California.

2.3. Vegetation types

The vegetation dataset was obtained from Landfire (Landscape Fire and Resource Management Planning Tools program uses) and produces geospatial data, describing vegetation, wildland fuel, and fire regimes for the United States. Landfire provides maps of existing vegetation type, using decision tree models, field data, Landsat imagery, elevation and biophysical gradient data for herbaceous, shrubs, and trees (Landfire, 2021). The fuel vegetation cover (FVC) data represents continuous estimates of canopy cover (ranging between 0 and 100%) for tree, shrub, and herbaceous plants, with the resolution of 30 × 30m.

To calculate the dominant fuel types (tree, shrub, herbaceous) in different burn window frequencies across California, we overlapped the FVC data the burn window layer for each season and determined the area of the different fuel vegetation type in each burn window interval. We extracted the

Table 1
Description of the meteorological variables and thresholds for prescription burns as outlined in Wade and Lunsford (1989).

Meteorological variable	Threshold	Description
Daily maximum temperature	0 °C–32 °C	When the objective is to control undesirable species, air temperatures above 27 °C are recommended. Temperatures below freezing, retard fire intensity because additional heat is required to convert ice to liquid water before it can be vaporized and driven off as steam. It does not take much moisture under these conditions to produce a slow-moving fire that will leave unacceptably large areas unburned (Wade and Lunsford, 1989).
Wind speed	2 m^{-s}–10 m^{-s}	During a backing fire high winds quickly dissipate heat, resulting in less crown scorch. Lower winds will allow less dissipation of heat, resulting in more crown scorching. During a heading fire, high winds will rapidly spread the fire becoming very intense (Banerjee et al., 2020). Higher winds are required for keeping the heat from rising directly to the tree crowns (Wade and Lunsford, 1989).
Relative humidity	30%–55%	When relative humidity falls below 30%, prescribed burning becomes dangerous. Fires arc more intensely under these conditions and spotting is much more likely. When the relative humidity is 60% or higher, a fire may leave unburned islands or may not burn hot enough to accomplish the desired result (Wade and Lunsford, 1989).

area covered by each burn window interval into separate layers from the burn window map in the four seasons. The areas occupied by different fuel vegetation in varying burn window frequencies were counted and the percentage of three types of fuel vegetation in different seasons and levels of burn windows were obtained. Considering that the FVC data indicates the percentage of the vegetation cover in each 30 × 30 m grid, the FVC percentage was also weighted in the area calculation.

3. Results and discussion

Over the past 35-years, Rx burns have been conducted in every season but with different frequencies (Fig. 1a). Burns were conducted most frequently (40% of the time) in the months of SON followed by DJF and MAM (each accounted for 25% of the burns). Rx burns are desirable in the SON (Taylor, 2004) because sustainable silviculture practices try to follow the ecosystem's natural fire disturbance regime, such as seasonality.

The JJA months accounted for only 10% of burns. Most notably, however, the number of acres burned in JJA were greater than the number of acres burned in the DJF and MAM months (Fig. 1b). Related to this pattern, the burn efficiency was much higher in JJA compared to burns in all the other seasons (Fig. 1c). Even though conducting Rx burns in JJA would also align with the disturbance regime in Mediterranean climates such as in California, summer is currently viewed as too risky (York et al., 2020; Li and Banerjee, 2021), with warmer and drier conditions (Hueso-González et al., 2018) and fire suppression resources that may be needed to contain infrequent escapes are committed to active wildfires (Striplin et al., 2020). It is noted that the MAM season has a similar burn efficiency to that of SON. This suggests that MAM, and to a lesser extent DJF, are efficient burn seasons because they burn larger acres with less numbers of Rx burns per season compared to that of SON. Despite the typical SON months being conducive for Rx burns, our results suggest that from a burn efficiency perspective, MAM and DJF also yield optimal burn windows to carry out efficient Rx burns in California.

Over the past eight seasons (2011/2012 to 2018/2019), Rx burn frequency records have been collected for all datasets (CAL FIRE, MTBS, and PFIRS). Fig. 2 presents an aggregation of these three datasets to determine the frequency of Rx burns for each season. Notably, DJF burns have been exceeding all other seasonal burns since the 2013/2014 season. In the past three years, (2016/2019 to 2018/2019) the MAM season has also experienced higher frequencies in Rx burns, in comparison to the traditional SON and JJA burns.

In Fig. 3(a–d) we show the percentage of vegetation type (tree, shrub, or herb) that are exposed to different occurrence in burn window opportunities. For example, Fig. 3a shows that during DJF, regions that exhibit only 0–10% of burn window days were likely to be predominantly shrublands, whereas for regions that experienced 70–80% of burn window opportunities were in regions that were dominated by trees. In comparison to the other seasons, during DJF, burn windows are met only a maximum of 80% of the time and dominated mainly by trees and herbaceous plants, and to a smaller extent, shrublands. These burn windows are mainly prevalent over the north and central regions of California (Fig. 4a). We note here that during DJF, higher elevation forests are exposed to snowfall, which may contribute to an over estimation of burn windows during the DJF season and for these locations.

For MAM, regions with the greatest burn windows are met between 80 and 90% of the time and are mostly dominated by trees, followed by shrubs and then herbs (Fig. 3b) for most of the northern California region (Fig. 4b). When just considering climatological factors, JJA has provided the greatest number of days that burn windows are met over the past 35-years (90–100% of the time), over the tree dominated vegetation type (Fig. 3c). However, these burn windows are narrowly distributed along California's coast in the JJA months (Fig. 4c). The burn windows that occur 80-90% of the time during SON are predominant over tree vegetation types (Fig. 3d) and also spatially dominant along the Pacific coast (Fig. 4d).

Therefore, among all seasons, MAM also has a relatively large number of days when burn windows are met, and for a larger spatial area of northern and Central California, with almost even distributions of vegetation types (trees, shrubs, and herbaceous plants). Thus, while SON burns were most frequently executed over the past 35-years, our results indicate that MAM and DJF seasons may be offering more frequent opportunities to conduct Rx burns. These burn windows were not actively capitalized over the past 35-years.

While burn window opportunities have been more prevalent (>60%) in MAM and DJF in Northern California (Fig. 4a and b), these regions have also exhibited significant decrease in burn windows during these seasons (Fig. 5a). Using temperature, humidity, and wind speed to define burn windows, Rx burn opportunities have been decreasing significantly at a rate of approximately one day per year across California for all seasons. During DJF, burn windows have been decreasing predominantly in Northern California's Sierra and Coastal Mountains, and North and Central Coasts (Fig. 5a). Similar spatiotemporal decreases are noticeable for MAM, which extends along the South Coast. In the JJA and SON months, however, the decrease in burn windows is constrained along the Central Valley, as well as the North, Central, and South Coasts. In order to determine what meteorological drivers are influencing the decrease in burn windows, we plot the change in the number of days each meteorological condition (maximum temperature, wind speed, and relative humidity) are met. Most months do not exhibit a significant change in maximum temperature except for the months of JJA that experience a decrease of approximately 0.5 days per year along the Central Valley and Central Coast. To a lesser extent, the

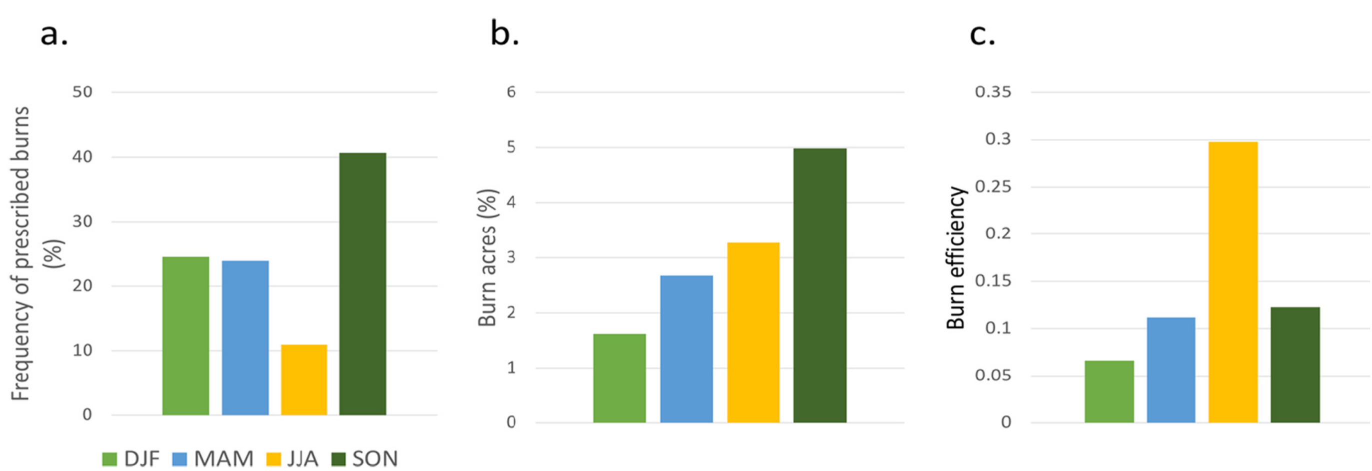

Fig. 1. The frequency, burnt acres, and burnt efficiency, of Rx burns for each season, DJF (winter), MAM (spring), JJA (summer), and SON (fall) over the 1984/1985 to 2018/2019 years are plotted as the percent of total Rx burns (a); the percent of total Rx burn acres (b) and as the ratio of the percent of acres burnt to the percent of burns per season (c).

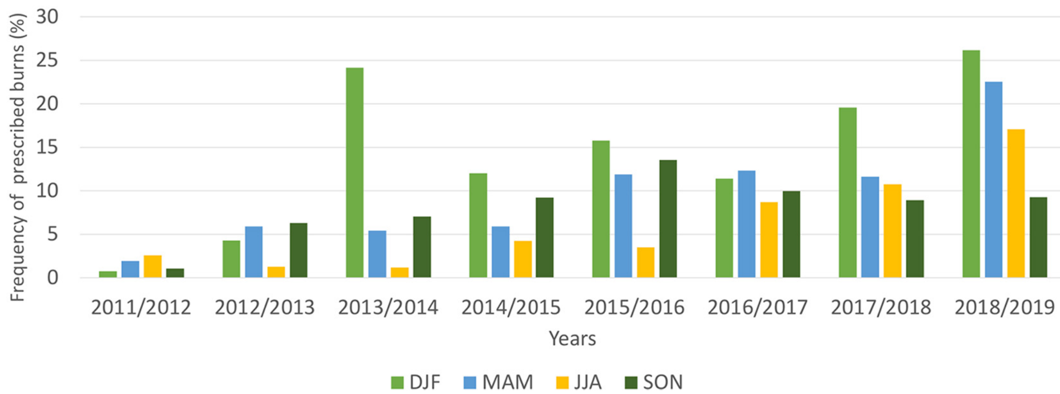

Fig. 2. Frequency of Rx burns (%) from 2010/2012 to 2018/2019 in California for each season winter (green), spring (blue), summer (yellow), fall (dark green) using CAL FIRE, MTBS, and PFIRS data.

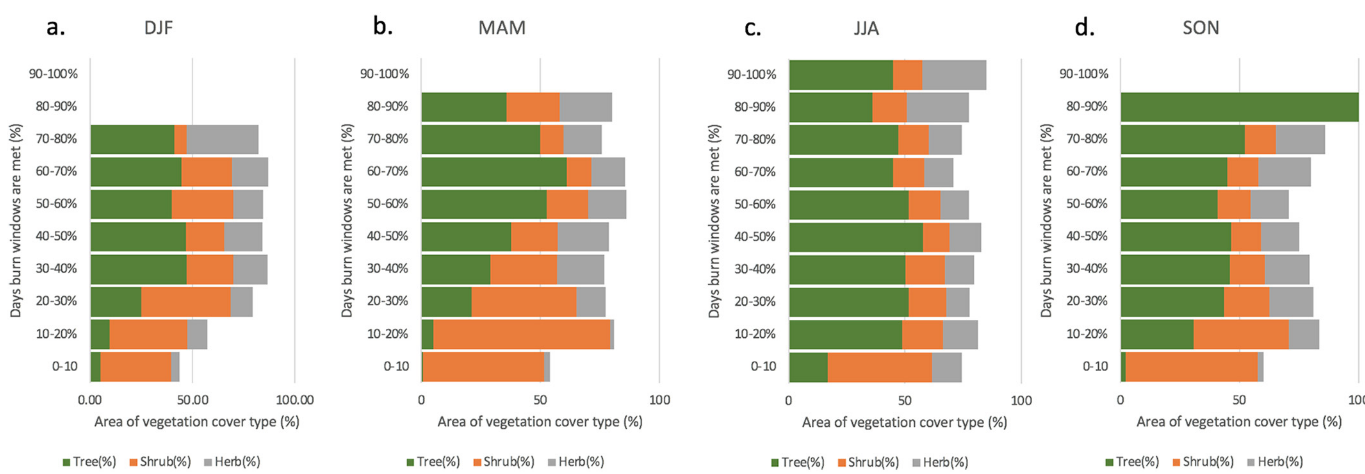

Fig. 3. The percent of fuel vegetation cover of trees (green), shrubs (orange), or and herbaceous plants (gray) that correspond to the frequency in burn windows for each season (JJA, SON, MAM, and DJF). Other land cover types (such as water, barren, quarries, agriculture areas, and sparse vegetation canopy (<10%) account for the remainder of land cover that is not considered).

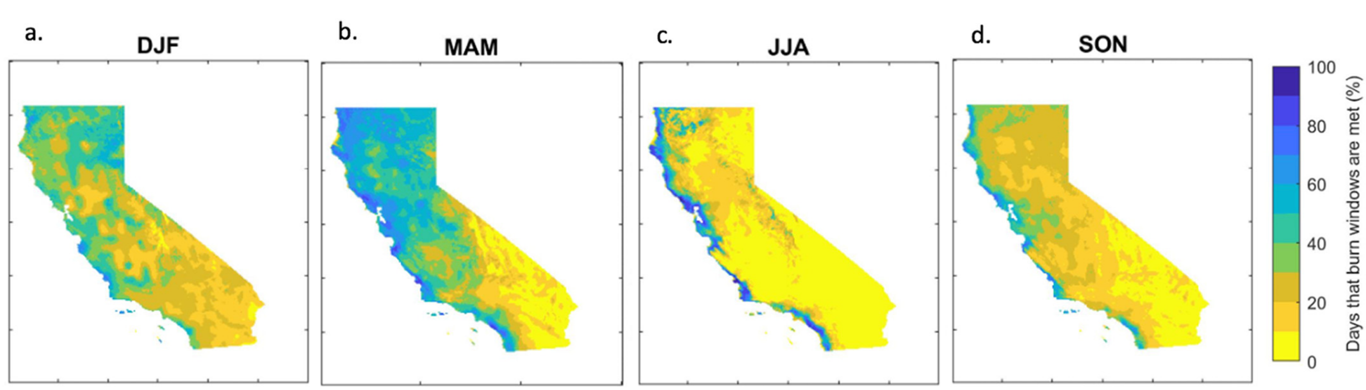

Fig. 4. The number of days (%) over the 35-year period that burn windows are met for each season across California (a) summer (June, July, August), (b) fall (September, October, November), (c) spring (March, April, May), (d) winter (December, January, February). With a total of approximately 3150 days for a given season, over all 35 years, a 10% burn window indicates that approximately 315 days were opportune time to burn in a given season, while a 100% burn window indicates that all 3150 days had opportune burn conditions.

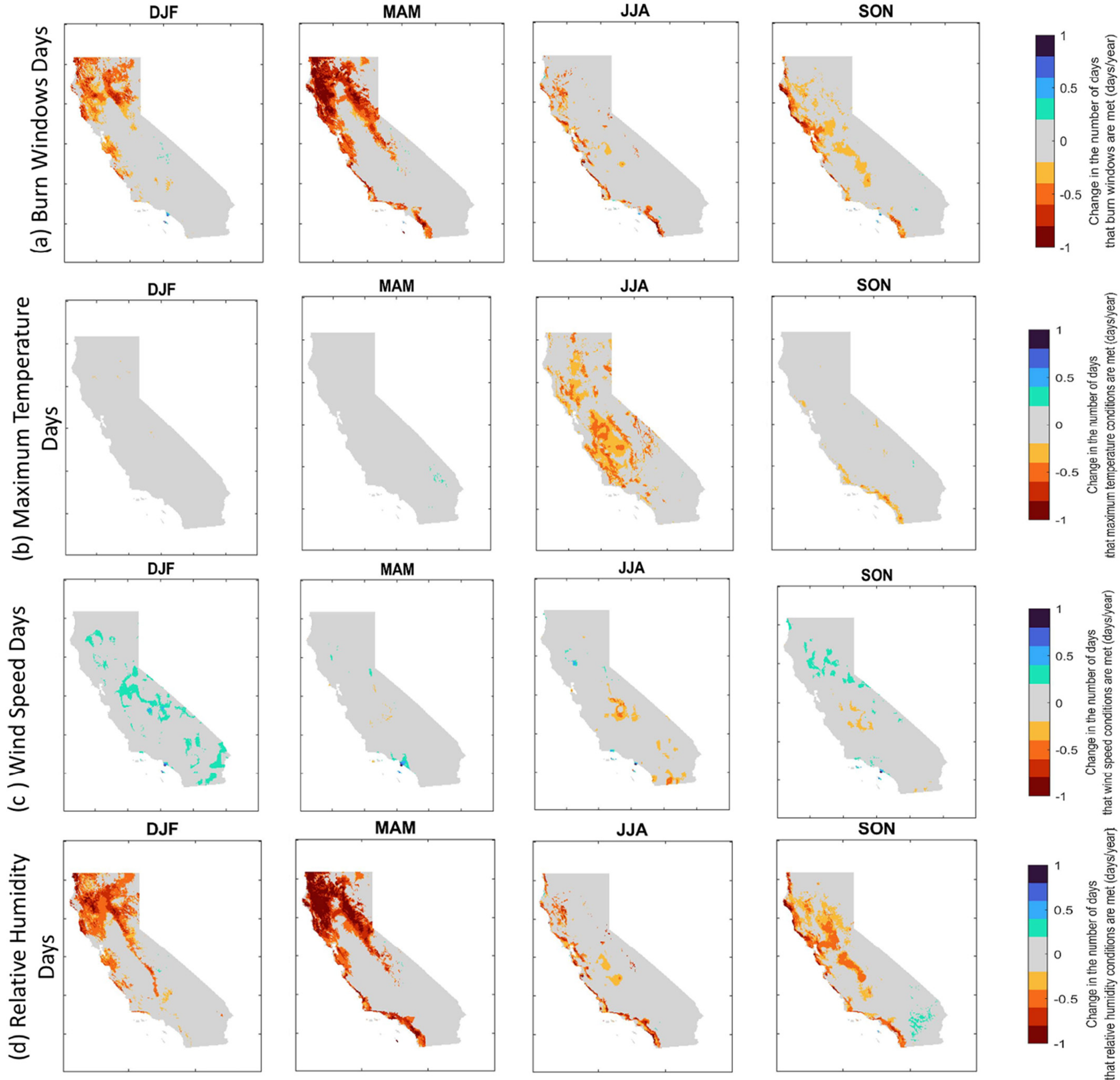

Fig. 5. The significant change (at the 95% confidence level) in the number of days that (a) burn windows, (b) maximum temperature, (c) wind speed, (d) relative humidity days are met (days/year) over the 1984/1985 to 2018/2019 seasons (DJF, MAM, JJA, SON) in California.

months of SON experience a slight decrease in the number of days the maximum daily temperatures are met (between 0 and 32 °C), and this is primarily along the Southern Coast (Fig. 5b). The decrease in the number of days that maximum air temperatures are met suggests daily maximum temperatures can be exceeding the 32 °C threshold. As a result, excessive maximum daily temperatures can lead to heat stress and mortality risk for personnel, increase risk in canopy damage, and elevate regional wildfire risk, thus limiting Rx burn opportunities (Wade and Johansen, 1986; Budd, 2001; Schultz et al., 2018; Kupfer et al., 2020).

The change in the number of days wind conditions is met (between 2 and 10 m^{-s}) are not spatially contiguous throughout California, but rather spatially dispersed. The months of DJF and SON show that the days in which wind conditions are met have been increasing across parts of California (Fig. 5c). This suggests that more days are exhibiting ideal wind conditions for Rx burns to be carried out. These ideal wind conditions can contribute well to smoke management and desired fire behavior when referring to Rx fire practices and management. However, determining safe smoke conditions also require analysis of additional meteorological variables, such as vertical mixing (Chiodi et al., 2018) that is beyond the variables explored in this study.

The spatiotemporal decrease in the relative humidty days, follows a similar spatial pattern to that of changes in the overall burn windows (Fig. 5d), at a rate of approximately one day per year. This decrease is predominant over the Sierra's and Coastal Mountains, and the North and Central Coasts during the months of DJF. The other months also exhibit a significant decrease in the number of days relative humidity conditions are met, which extends along the Coasts. Comparing the spatiotemporal changes in the number of days each meteorological parameter is met, the results indicate that spatiotemporal changes in relative humidity days

(Fig. 5d) are most similar to that of the burn windows (Fig. 5a). This suggests that of all the meteorological drivers analyzed, that relative humidity is the key meteorological limiting factor that influences the number of days the burn windows are met over the past 35-years. Relative humidity conditions are important for fuel moisture calculations that predict fire behavior throughout the diurnal cycle. Thus, the changes in the number of days that this variable is met will have direct implications on other Rx parameters (Striplin et al., 2020).

Our results show the opportune locations, vegetation cover, and months that Rx burns can be carried out, given the ideal meteorological burn windows. While burns conducted during the months of SON are most frequent, DJF and MAM currently offer opportune times for the execution of Rx burns. However, during these months, fewer seasonal fire personnel are available to conduct burns, despite optimal weather and atmospheric conditions (Striplin et al., 2020). Winter burns can be capitalized upon in order to mitigate and reduce wildfire severity, for example, in the Sierra Nevada (York et al., 2021). Thus, there is an incentive to develop innovative staffing solutions (staggering seasonal crew start and end dates; additional staffing in less active months; forming dedicated Rx fire crews) in order to actively benefit from the DJF and MAM burn window opportunities. Our results also indicate that DJF and MAM burn opportunities are decreasing at greater spatiotemporal rates than JJA and SON, and this decrease is primarily driven by changes in relative humidity. Therefore, there is a need to capitalize on these additional burn window months (DJF and MAM) before these burn window opportunities dwindle.

Despite these findings, it is noted that Rx fires are not always well accepted. A review by Úbeda et al., 2018 suggests that concerns still arise from smoke (Price et al., 2016), air pollution and greenhouse gas emissions (May et al., 2015; Aurell et al., 2017). In addition, there is the fear of escaped fires and the potential human impacts (health and livelihood) it may have for those living in close proximity to the fires (Twidwell et al., 2015). Furthermore, some studies show skepticism towards Rx burns with the public not wanting to pay for Rx management practices and would preferably invest in other fire suppression measures (Jacobson et al., 2001; Pereira et al., 2016).

However, a century-long fire deficit coupled with fuels and vegetation build-up have spawned intense megafires with parallel severe biophysical and socio-economic impacts, and Gov. Brown had issued an executive order on forest health to increase the opportunities of Rx burns in California (Brown, 2018). While unprecedented levels of funding have been aimed at reducing fire impacts to society (York et al., 2020), most of the work has been mechanical treatments such as thinning and chipping and actual work lags far behind targets (Knight et al., 2022). These treatments can be effective (Stephens et al., 2012) but are also relatively costly, sometimes by an order of magnitude compared with alternatives when they do not include revenues from the harvest of forest products (Hartsough et al., 2008). They are also operationally constrained by topography and wildlife protection laws constraints (North et al., 2012). Thus, a combination of both mechanical treatment and Rx burns are required. Others agree that Rx fires are appropriate for decreasing wildfire risk and reducing forest fuels (Toman et al., 2014). The acceptance of Rx burns increases with the familiarization and the gained knowledge of Rx burn practices, fire behavior dynamics, understanding the local ecology, and trust in local agencies (Úbeda et al., 2018).

4. Conclusions

This study examined the spatial and temporal changes in seasonal Rx burn activity, windows, and its meteorological drivers of maximum temperature, wind speed, and relative humidity over California during the past 35-years (1984/1985 to 2018/2019 seasons). Using three Rx fire datasets, we demonstrate the Rx fires have been recorded more robustly in the past six years, with more burns being conducted in DJF and MAM. While most burns have traditionally been conducted in the months of SON, the Rx burns are more efficiently conducted in the MAM months, and to a lesser extent, DJF. Thus, more Rx burns should be extended into the DJF and MAM months.

Using a set of meteorological and vegetation datasets we also find that Rx burns window opportunities are also dominant during the months of MAM and DJF, and this is prevalent over the fuel vegetation cover of trees, followed by shrubs, then herbaceous plants. Furthermore, burn windows have been decreasing significantly by approximately one day per year, and this is dominant over Northern California during the months of DJF and MAM. We also examined the spatial and temporal change in the number of days that each meteorological parameter thresholds were met. Compared to wind speed and maximum air temperature, relative humidity was found to be the limiting factor in influencing the spatiotemporal decrease in burn windows across California.

Identifying these changes in meteorological burn windows are imperative for establishing a foundation to facilitate more Rx burns, especially on private lands in California. This is because considerable adjustments to issuing permits are needed for Rx burns in order to make a difference in reducing wildfire risks across California (York et al., 2020). For example, the winter season permits are not required in many counties, but smoke emissions are still required. In spring, permit season begins at the start of the wildfire season and can last for several weeks. Summer season permits are often suspended, with the rare exceptions of permits being issued if appropriate levels of planning and resources are demonstrated. The fall season is noted as the optimal time for effective Rx burns (York et al., 2020). Thus, given the burn window opportunities as suggested by this study, further discussion at various scales among policymakers, practitioner, and stakeholder groups should be implemented in order to reassess how and when burn permits are issued and whether they should be refined based on local prescription objectives.

We acknowledge that the meteorological parameter thresholds are first order approximations and may vary depending on fire management practice objectives, resources, as well as the vegetation type being burned. However, since this study focuses on all of California with a very heterogeneous landscape, a relative approximation, as considered in this study, is appropriate. Future studies can be conducted with refined parameter thresholds for investigating specific locations and specific fire management objectives. In addition, projections in spatiotemporal changes in these Rx burn windows, and meteorological parameters will be helpful insights for informing future Rx burns and fire management practices across the State.

CRediT authorship contribution statement

Janine A. Baijnath-Rodino: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Roles/Writing – original draft; Writing – review & editing.

Shu Li: Data curation; Formal analysis; Investigation; Methodology; Resources; Software;; Visualization; Roles/Writing – original draft.

Alexandre Martinez Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Visualization.

Mukesh Kumar: Conceptualization; Data curation; Investigation; Methodology; Project administration; Resources; Software; Visualization.

Lenya N. Quinn-Davidson: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Supervision; Validation; Roles/Writing – original draft; Writing – review & editing.

Robert A. York: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Validation; Roles/Writing – original draft; Writing – review & editing.

Tirtha Banerjee: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing – original draft; Writing – review & editing.

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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