The threat of wildfire to cannabis agriculture in California

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Abstract

At the intersection of climate change and rural development, wildfire has emerged as a threat to agriculture in the western United States. This nexus is particularly problematic for the rapidly developing cannabis industry in California, which includes farms located outside of traditional agricultural zones and within landscapes potentially more prone to wildfire. Using fire hazard severity metrics, current and historical wildfire perimeter data, and future burn regime projections, we compared the location of licensed cannabis farms in California to other agricultural types, to determine if cannabis is uniquely vulnerable to wildfire. We found that cannabis farming was located closer to wildfire perimeters and more often in high fire hazard severity zones than other agriculture. Over the last 50 years, the distance between cannabis farm locations and fire perimeters decreased significantly, and projected burn regimes for the remainder of the century place cannabis farms at greater risk than other agricultural types. Our findings highlight cannabis' particular vulnerability to wildfire in California. In light of the sector's growing importance in the state, and given potentially direct and indirect consequences (e.g., human health risks, socioeconomic impacts), these risks should be considered for the development of future cannabis and rural development policies.

1. Introduction

Wildfire is becoming a global threat, compounded by climate change (Westerling et al, 2006) and the expansion of human development in fire prone areas (Radeloff et al., 2018). The threat of wildfire is particularly prominent in California, where the combination of prolonged drought, arid vegetation, climate change, historical fire suppression, and development in the wild-urban interface (WUI) is leading to more frequent and severe wildfires statewide (van Wagtendonk et al, 2021, Williams et al, 2019; Keeley & Syphard, 2018; Kramer et al., 2018; Parks et al., 2015; Radeloff et al., 2018; Syphard et al., 2007; Norgaard, 2014). Over the last five years, California has experienced its seven largest wildfires on record (CAL FIRE, 2020a) and current projections for the state suggest an increase in frequency and intensity of wildfires in the future (Westerling, 2018; Goss et al., 2020). As a result, wildfire is expected to continue to generate large social, economic, and ecological costs in the state (Jin et al., 2015; Kelly et al., 2020).

Wildfire has the strongest impacts on rural and agricultural communities that occupy fire-prone areas of the landscape. This is especially true for California's ranching communities that rely on arid rangelands, where wildfires disrupt operations and cause livestock losses each year (Bell 2015; Herskovitz 2017). Other agricultural activities, such as wine grape cultivation, also occur in areas of the landscape where wildfire may directly threaten vineyards, negatively impact wine quality through smoke damage, and discourage tourism (Thach and Eyler, 2017; Bauman et al., 2020). Cannabis cultivation, which is a rapidly growing segment of California's agricultural sector (Hudock 2019), may face similar risks as rangelands and vineyards. Cannabis has historically been grown in rugged terrain, in remote parts of the state away from population centers, as a result of its historical prohibition (Corva, 2014; Butsic et al., 2018). Additionally, the recent rapid expansion of cannabis in rural areas has followed patterns of low-density development in the WUI known to exacerbate fire risk (Butsic et al., 2018; Radeloff et al., 2018). Despite the potential for cannabis agriculture to be uniquely vulnerable to wildfire, to date, there has been no analysis of the spatial distribution of cannabis farms in relation to wildfire risk and no analysis of how the threat of wildfire to cannabis differs from other agriculture sectors.

The implementation of a regulated California cannabis industry in 2018 has created a pathway for small-scale legacy farms (i.e., previously unregulated), primarily located in the historical cannabis-farming epicenter of Northern California, to transition to licensed production (Dillis et al., 2021). Statewide expansion in production has lead to the establishment of new, larger farms outside of this region, especially along California's Central Coast, yet cannabis cultivation in the irrigated and less fire-prone agricultural lands of California's Central Valley remains largely prohibited under local ordinances (Dillis et al., 2021). Little attention has been given to how state and local policy is shaping the geography of the cannabis industry in relation to wildfire risk. Furthermore, the consequences of growing wildfire severity on cannabis agriculture from climate change has not been considered. To fill these information gaps, we addressed the following questions:

1) Does wildfire pose a greater threat to licensed cannabis than to other forms of agriculture on a statewide and county-level basis?
2) How does the threat of wildfire vary among licensed cannabis producing counties and has the threat increased in recent years?
3) What is the projected wildfire risk to cannabis agriculture under climate change and how does it compare to other agricultural sectors?

2. Methods

2.1. Data

License data for outdoor cannabis farms were obtained from the California Department of Food and Agriculture (CFDA) via a listserv distribution on May 27, 2020. License data included parcel numbers, which were matched to a county parcel layer obtained from the National Parcelmap Data Portal (Boundary Solutions, 2020). Multiple licenses on a single parcel were consolidated into a single observation and parcel centroids were used for all analyses. The locations of three other classes of agriculture were collected from the 2019 USDA Cropland Data Layer and the 2016 National Land Cover Database (USDA, 2019; Dewitz, 2019): pasture (excluding cultivated hay crops), grapes, and an aggregate of remaining crop types (referred to hereafter as *general crops*). Both the USDA Cropland Data Layer and the National Land Cover Database datasets feature nearly comprehensive mapping of agriculture in California at 30 meter resolution. For our statewide analysis, we took a random sample of points from within each agricultural class of interest from across the state, using an equal number of points for each crop (n=2228, the number of licensed cannabis farms in our dataset) in order to provide a balanced sample. For subsequent analyses restricted to cannabis producing counties, non-cannabis agricultural points were resampled to once again balance those of cannabis (n= 2228) with each agricultural type. Because agriculture is clustered in select counties statewide, and potentially clustered within these counties as well, we used county and subwatershed (HUC12) locations as predictors in mixed-effects models. County boundaries were downloaded from the California State Geoportal (State of California, 2019) and subwatershed boundaries were obtained from the National Hydrography Dataset (USGS 2019).

We assessed fire risk on the landscape by Fire Hazard Severity Zones (FHSZ), as well as historical fire perimeters, obtained from the California State Geoportal on December 7, 2020. FHSZs established by CAL FIRE classify terrain as moderate, high, or very high hazard severity based on factors including slope, fuel, and fire weather (CAL FIRE, 2020b). Although there is a small amount of missing data in Federal Responsibility Areas (e.g. National Forest) and Local Responsibility Areas (e.g. incorporated townships), zones with no data are most commonly those in areas of urban development or intensive irrigated agriculture, such as the Central Valley, in which wildfire is extremely unlikely. Fire perimeter data for the years 1950-2020 (CAL FIRE, 2020c; 2020d) were used as an additional risk metric and were screened for a minimum size of 400 ha, following Westerling (2018), to filter out small fires included in the database.

To analyze future projections of fire regimes we used a dataset from Moanga et al. (2020), which was derived from Westerling (2018) projections. The estimated number of hectares burned were calculated under the RCP4.5 greenhouse gas concentration pathway (a scenario in which emission levels peak around 2040 and then gradually decline; CalAdapt, 2018). The statewide modeled wildfire activity was analyzed using the ESRI space-time mining capabilities (Space-Time Cube and Emerging Hot Spot

Analysis functions). Areas likely to experience high levels of wildfire activity in both space and time were identified and classified into several different hot and cold spot categories based on the spatial and temporal progression of modeled wildfire activity (Table 1). The Space-Time Cube and Emerging Hot Spot Analysis functions were used to analyze the data in 3D across both space and time by aggregating the predicted number of hectares burned into space-time bins. Modeled wildfire data provided estimates of the number of hectares burned for each year between 2020 and 2100 across California (area divided into 10688 grid cells - one grid cell extending approximately 6 km^2). The initial wildfire projection data was aggregated into space time bins so that each bin incorporated one grid cell and contained modeled data for one time slice (temporal interval was set on a yearly basis to capture the gradual progression of wildfire activity). In total, our analysis included 4,950,973 hectares of hot-spots (76.90% of the study area) and 149,981 hectares of cold-spots (2.32% of the study area), which represent predicted fire dynamics for the period analyzed (2020-2100).

2.2. Does wildfire pose a greater threat to legal cannabis than to other forms of agriculture on a statewide basis?

To understand if cannabis farms were on average located closer to wildfires than other agricultural types across California, we compared distance to wildfires between agricultural types, using aggregated fire perimeters dating back to 1950. We used distance to fire perimeters as our main metric of comparison, because neither FHSZ data nor burn probability data (from Westerling, 2018) are comprehensive statewide. For each agricultural type, the distance was calculated between each data point and the nearest fire perimeter. Although the majority of agricultural data points (especially those of cannabis) were not contemporary with many of these fires, the perimeters instead are used herein as a proxy for measuring geospatial susceptibility to wildfire.

We fit a multilevel model, using the lme4 package in R Statistical Computing Software (Bates et al 2015, R Core Team, 2018), to establish whether there was a statistically reliable difference between cannabis and other agricultural types in terms of proximity to fire. Random effects were used for county and subwatershed to account for nested spatial clustering of data points. Because the distribution of distances was right-skewed and overdispersed, we opted to use a negative binomial model. Rather than log transforming the distances prior to model fitting, the generalized linear model (GLM) used a log link function, predicting the distance ($\boldsymbol{D}_i$) of each agricultural data point to the nearest wildfire perimeter, using the following equation:

Eq. 1

$$log(\boldsymbol{D}_i) = \boldsymbol{\alpha} + \boldsymbol{\alpha}_c + \boldsymbol{\alpha}_{wc} + \boldsymbol{\beta}_d d + \epsilon$$

A fixed-effects term for *Agricultural Type* ($\boldsymbol{\beta}_d$) is added to random intercepts for *County* ($\boldsymbol{\alpha}_c$) and *Watershed* (nested within County; $\boldsymbol{\alpha}_{wc}$) as well as the overall intercept ($\boldsymbol{\alpha}$). Cannabis was designated as the reference level for *Agricultural Type*, therefore producing coefficient estimates of the remaining agricultural types relative to cannabis (as the overall intercept). Model coefficients were considered reliable if 95% confidence intervals, constructed from the standard errors, did not overlap zero.

2.3. How does the threat of wildfire vary among legal cannabis producing counties and is the threat increasing?

We conducted a similar analysis focusing only on cannabis producing counties, restricted to those counties comprising at least 1% of all CDFA outdoor cultivation licenses statewide. These included: Humboldt, Lake, Mendocino, Monterey, Nevada, San Luis Obispo, Santa Barbara, Santa Cruz, Sonoma, Trinity, and Yolo Counties (Figure 1). In these counties, we compared the threat of wildfire to cannabis against the remaining agricultural types (pasture, grapes, general crops) using Fire Hazard Severity Zone (FHSZ) data. We also compared cannabis wildfire risk between counties using fire perimeter data.

In order to address whether the threat of wildfire to cannabis has changed over the preceding decade, we measured the distance of licensed cannabis farms to historic perimeters of wildfires that occurred between 1970 and 2020. We compared the proximity of cannabis farms to historic fire perimeters in two time periods, 1970-2015 (*Period: early*) and 2016-2020 (*Period: recent*), again using a multilevel negative binomial model. The model used a log link function, predicting the distance (D_i) of each cannabis data point to the nearest wildfire perimeter, using the following equation:

Eq. 2

$$log(D_i) = \alpha + \alpha_c + \alpha_{wc} + \beta_p p + + \epsilon$$

Fixed-effects terms for *Period* (β_p) were added to random intercepts for *County* (α_c) and *Watershed* (nested within County; α_{wc}) as well as the overall intercept (α). *Recent* was designated as the reference level for *Period*, therefore interpreting the coefficient estimate of *Period* as the difference observed in *Period: early* relative to *recent* (as the overall intercept). Model coefficients were exponentiated to produce estimates on the original scale of the response variable (km). The difference was considered reliable if 95% confidence intervals, constructed from the standard errors, did not overlap zero.

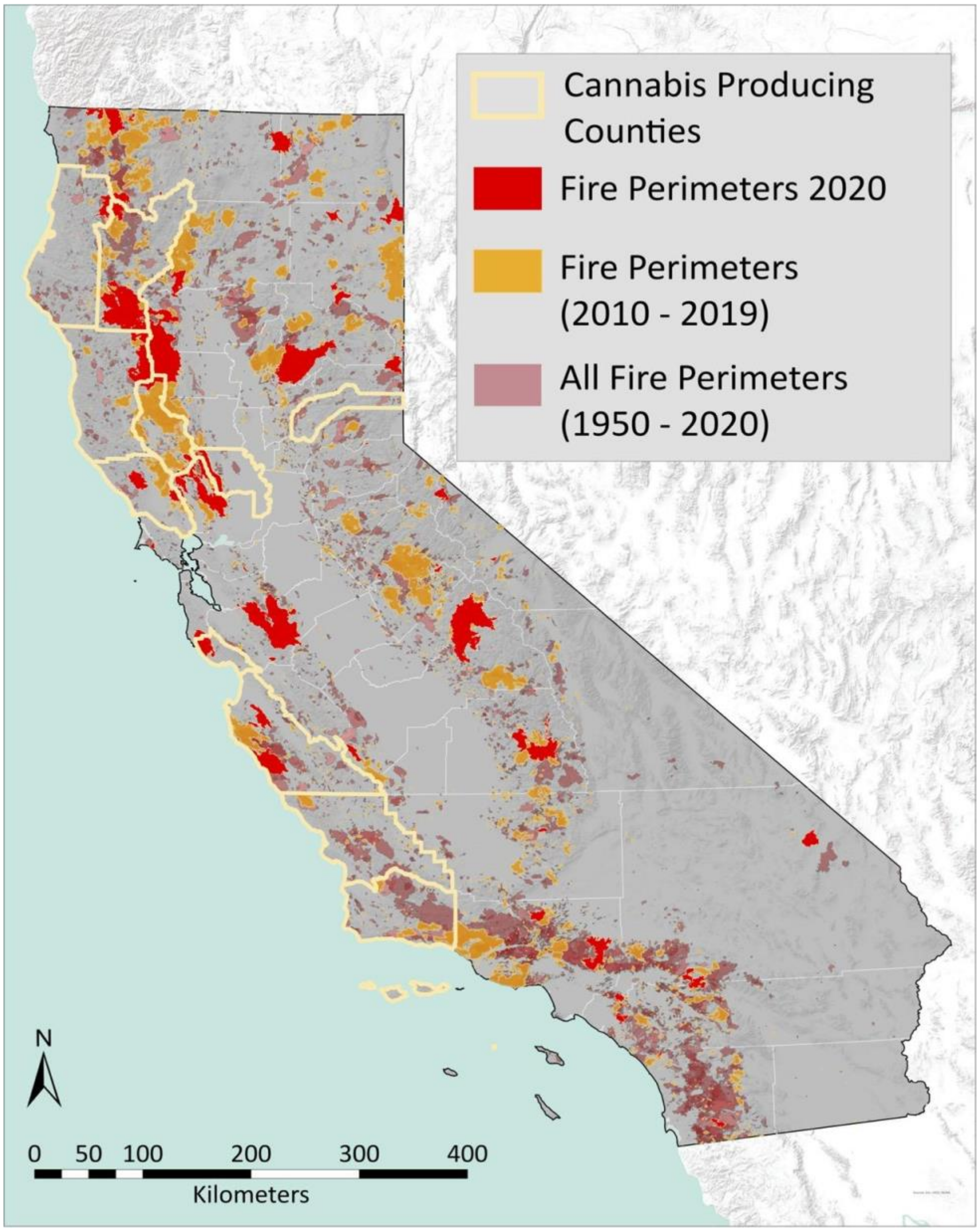

Figure 1. Study Area Map. Wildfire perimeters from 2020 are depicted, with the perimeters of the preceding decade and historical perimeters (since 1950) included for context. Cannabis producing counties included in this analysis are restricted to those comprising at least 1% of CDFA outdoor cannabis licenses.

2.4. What is the projected wildfire risk to cannabis agriculture under climate change and how does it compare to other agricultural sectors?

To assess the future threat of wildfire to licensed cannabis farms, we recorded the spatio-temporal burn pattern projections summarized by Moanga et al. (2020) for each agricultural data point from 2020-2100. Each point location was classified based on its projected burn pattern as: New/Intensifying Hot Spot, Historical/Persistent Hot Spot, Sporadic/Oscillating Hot Spot, Diminishing Hot Spot, No Pattern Detected, Diminishing Cold Spot, Sporadic/Oscillating Cold Spot, Historical/Persistent Cold Spot, New/Intensifying Cold Spot, or No Data (Table 1). Projected burn patterns were summarized between agricultural types in cannabis producing counties, as well as between cannabis producing counties, focusing exclusively on cannabis data points. Using a space-time approach in analyzing modeled wildfire activity throughout the twenty-first century allowed us to take into account not only the spatial, but also the temporal dynamic of predicted wildfire activity and helped identify areas likely to experience different wildfire threats through time. These distinctions are important in assessing not only the current wildfire risk of cannabis farms, but also evaluating how this risk is predicted to evolve in the future.

As a final metric of the threat to cannabis posed by wildfire, we calculated the proportion of cannabis farms within fire perimeters of the 2020 fire season. The proportion of cannabis farms within fire perimeters was calculated for each cannabis producing county. Cannabis was also compared to the remaining agricultural types, focused specifically within cannabis producing counties.

3. Results

3.1. Does wildfire pose a greater threat to legal cannabis than to other forms of agriculture on a statewide basis?

Cannabis farms were located closer to known wildfire perimeters than were any other type of agriculture (Figure 2), with a median distance of 2.81 km (IQR = 1.06,5.27) for cannabis, compared to 6.31 km for pasture (IQR= 2.96, 11.16), 11.10 km for grapes (IQR= 4.50, 21.48), and 13.28 km (IQR =

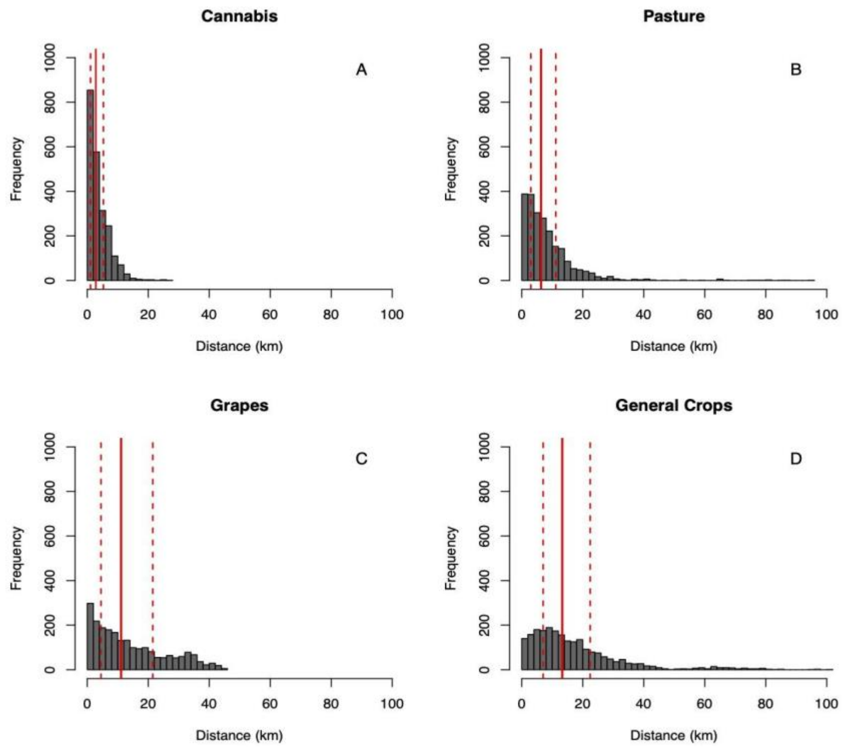

Figure 2. Farm Proximities to Known Wildfires. Perimeters for fires since 1950 are compared against the geospatial locations of (A) cannabis and sampled data points for (B) pasture, (C) grapes, and (D) general crops. Median distances for each agricultural type are indicated by a red line, with the interquartile range (IQR) represented with dashed lines on either side of the median.

7.00, 22.43) for general crops. Results of the negative binomial model confirmed that the distance for cannabis was significantly smaller than all other agricultural types, even after accounting for clustering of types within counties (Table 2). Coefficient estimates for *grapes* (MLE= 0.11; SE= 0.03, OSE= 4.82 km), *pasture* (MLE= 0.14, SE= 0.03, OSE= 4.96 km), and *general crops* (MLE= 0.14, SE= 0.03, OSE= 4.95 km) were all reliably positive, indicating larger distances than those of cannabis (Intercept MLE=1.46 , SE=0.11 , OSE= 4.30 km). Additionally, the percentage of cannabis farms that were located within historical fire perimeters (9.89%) was higher than grapes (2.91%), pasture (1.75%), and general crops (0.89%).

3.2. How does the threat of wildfire vary among legal cannabis producing counties and is the threat increasing?

The percentage of cannabis farming in high (43.88%) or very high FHSZs (35.25%) was also larger than any other type of agriculture found in cannabis producing counties (Figure 3). Grapes were the next most common type to occur in high (24.53%) or very high FHSZs (5.09%), followed by pasture (12.43%; 0.76%, respectively). General crops almost never occurred in high (6.83%) or very high FHSZs (0.45%). There was also a notable amount of variation in the percentage of cannabis farming within FHSZs between counties (Figure 4). For instance, Trinity (93.44%) and Nevada (53.33%) had over half of their cannabis farms in very high FHSZs, while Monterey and Yolo had almost no farms located in either high (6.82%; 0.00%, respectively) or very high FHSZs (0.00%; 2.33%, respectively).

For all counties, the proximity of cannabis farms to historic fire perimeters has decreased over time (Figure 5). The median reduction of average annual distance between early (1970-2015) and recent (2016-2020) was smallest in Santa Barbara County (-3.19 km), whereas Lake County recorded the largest median reduction in distance from (-43.81 km), and smallest average distance to (13.41km) wildfire within the recent period. The results of the negative binomial model indicated that, overall, the proximity cannabis farms to wildfire during the *recent* period has reliably decreased (Intercept MLE = 4.20, SE= 0.05; Coefficient MLE = -0.44, SE = 0.01), corresponding to a change in average annual distance from 66.37 km (95% CI = [60.43, 72.89]) to 42.94 km (95% CI = [38.82,47.51]).

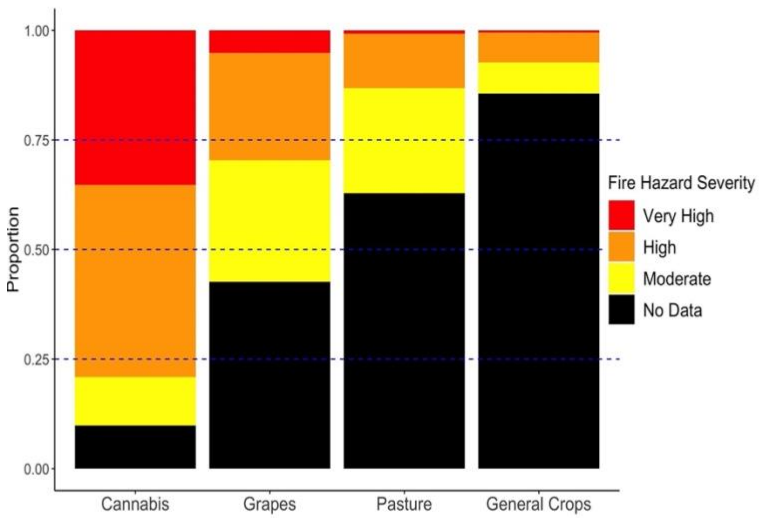

Figure 3. Fire Hazard Severity Zones by Agricultural Type. Proportions of farms of the four agricultural types within each FHSZ category are summarized, within cannabis producing counties only. FHSZs are categorized as moderate, high, and very high, with no data values resulting from areas not categorized either due to a lack of fire danger or Federal Fire Responsibility or Local Fire Responsibility zones.

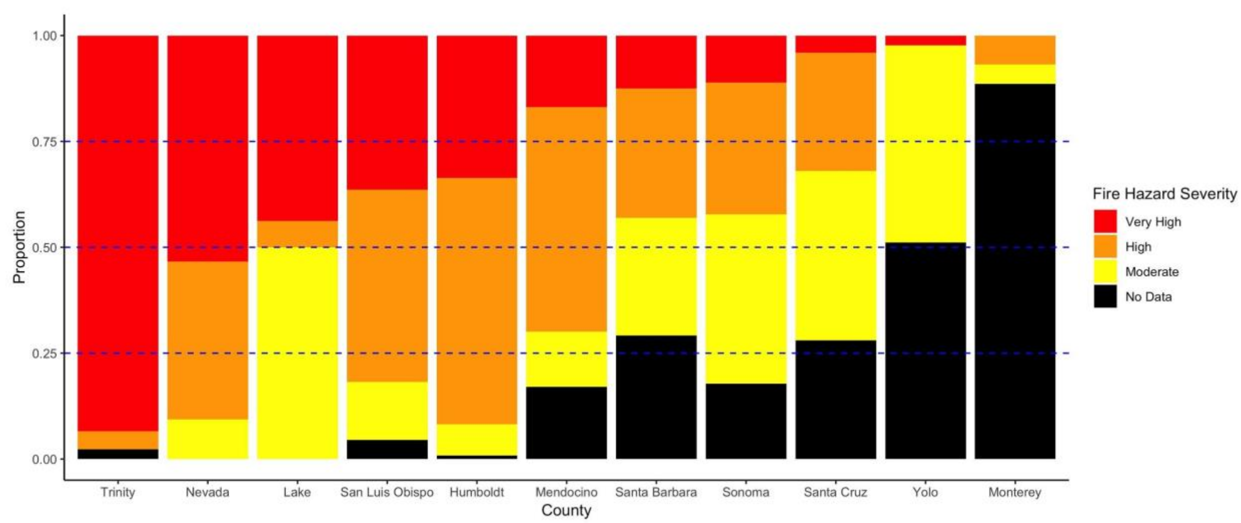

Figure 4. Fire Hazard Severity Zones by County. Proportions of cannabis farms (only) within each FHSZ category are summarized by county. FHSZs are categorized as moderate, high, and very high, with no data values resulting from areas not categorized either due to a lack of fire danger or Federal Fire Responsibility or Local Fire Responsibility zones.

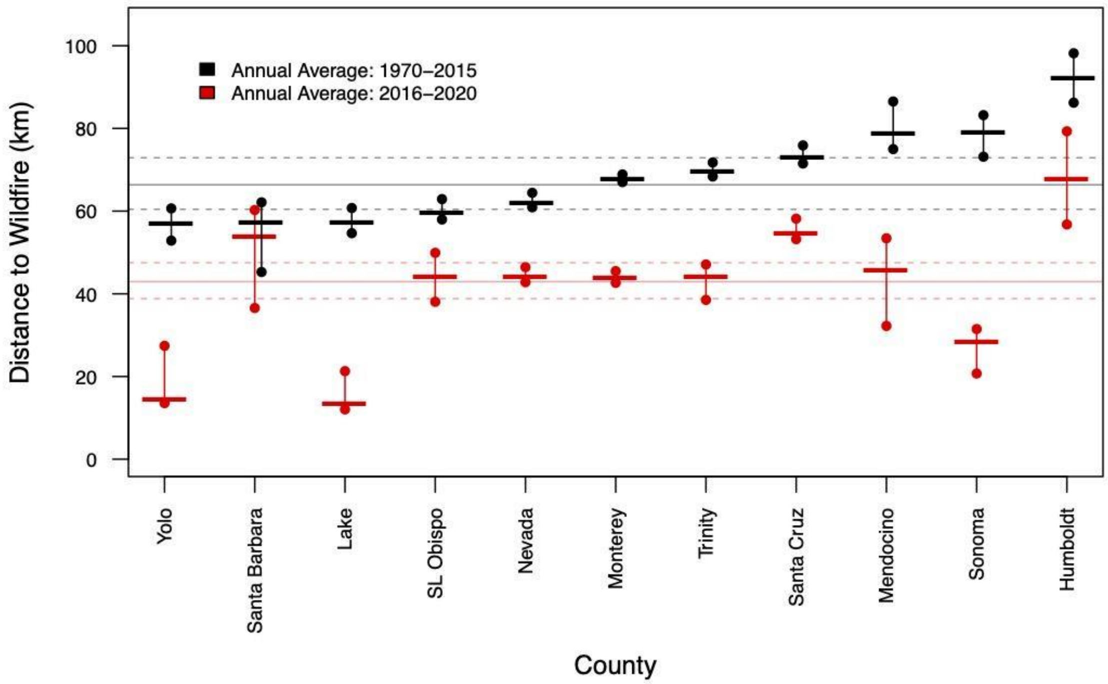

Figure 5. Annual Average Distance to Wildfire. The annual average distances between cannabis farms and wildfire perimeters recorded in each of the 11 cannabis producing counties in two five-year periods: *Early* (2010-2014) and *Recent* (2015-2019). Raw data are plotted as bars representing median values and dots representing the interquartile range. Results of the model predictions are overlaid in corresponding colors, with maximum likelihood estimates displayed as a horizontal line, bracketed by dashed lines depicting the 95% confidence interval of the MLE.

3.3. What is the projected wildfire risk to cannabis agriculture under climate change and how does it compare to other agricultural sectors?

Cannabis was the only agricultural type with over 75% of farms (84.67%) located in areas projected as New/Intensifying, Historical/Persistent, or Sporadic/Oscillating Hot Spots for the prediction period 2020-2100. The only other agricultural type to exceed 50% in these classifications was grapes (60.79%), while the occurrence of pasture (42.41%) and general crops (24.39%) in these areas was much lower. Among cannabis producing counties, seven of 11 had 75% or more of cannabis farms located in zones projected as New/Intensifying, Historical/Persistent, or Sporadic/Oscillating Hot Spots (Santa Barbara: 97.22%, San Luis Obispo: 77.27%, Trinity: 100%, Mendocino: 98.55%, Monterey: 75%, Lake: 100%, and Nevada: 97.33%). There were three counties in which over half of the cannabis farms were specifically within zones projected as New/Intensifying Hot Spots (Santa Barbara: 95.83%, Trinity: 61.64%, and San Luis Obispo: 63.64%).

The percentage of cannabis farms located within fire perimeters in 2020 was higher than those of any other agricultural crop: (0.63%) or 14 out of 2,228 CDFA licensed farms. The number of sampled grape data points was even lower (6 out of 2,228; 0.026%) and no sampled points for pasture or general crops were located within fire perimeters in 2020. Of the cannabis farms within 2020 fire perimeters, eight were in Mendocino County (1.29% of county farms), three were in Trinity County (0.98% of county farms), two were in Sonoma County (4.44% of county farms), and one was in Santa Cruz County (4.00% of farms).

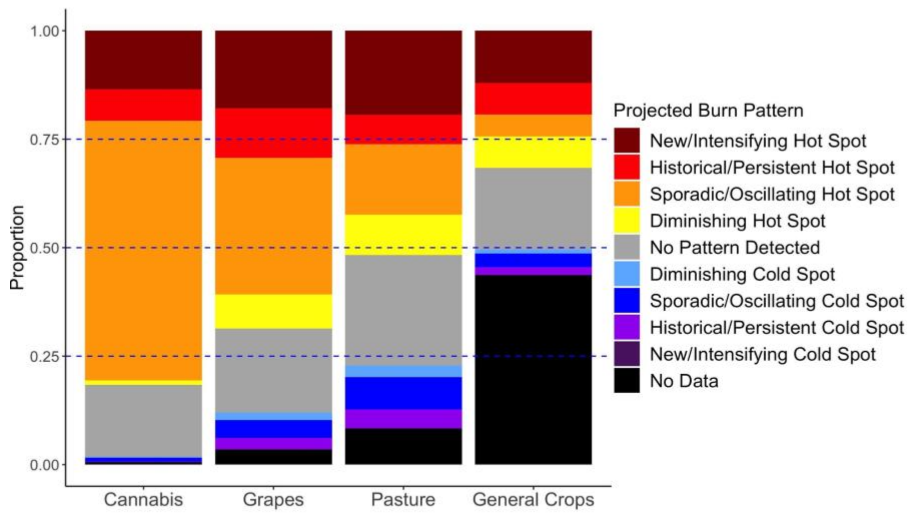

Figure 6. Projected Burn Regimes by Agricultural Type. Proportions of farms of the four agricultural types within each projected burn pattern category are summarized, within cannabis producing counties only. Categories are adapted from those used by Moanga et. al (2020). No data values result from areas for which burn probability data from Westerling (2018) were not produced due to extremely low likelihood of wildfire.

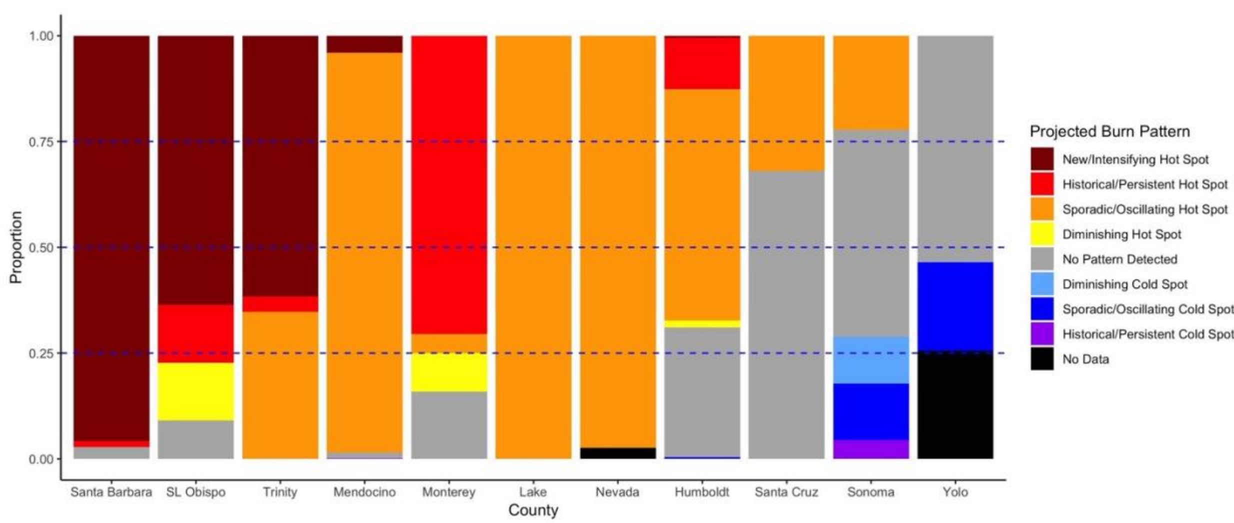

Figure 7. Projected Burn Regimes by County for Cannabis Agriculture. Proportions of cannabis farms (only) within each projected burn pattern category are summarized by county. Categories are adapted from those used by Moanga et. al (2020). No data values result from areas for which burn probability data from Westerling (2018) were not produced due to extremely low likelihood of wildfire.

4. Discussion

Global increases in the severity and occurrence of wildfires, driven by climate change and other anthropogenic factors (Liu et al. 2010), are particularly evident in drought-stressed regions such as California. Our spatial analysis of statewide wildfire risk in California suggests that cannabis agriculture is uniquely vulnerable to wildfire impacts relative to other crops. At the statewide scale, cannabis farms are on average located within 3km of a past wildfire, whereas pasture is located over twice as far, grapes three times as far, and general crops are located over four times as far from wildfires. Furthermore, although the statewide distribution of cannabis agriculture is largely confined to a handful of relatively fire-prone counties, the distribution of cannabis farms within these counties is still closer to historic wildfire perimeters, and more likely to be found in high fire hazard severity zones, than are all other agricultural types. Our results further suggest an alarming trend of increasing fire risks to cannabis in the future. The wildfire risk for cannabis increased markedly during the five year period from 2015-2020 compared to the preceding 45 years. Overall, we estimated that the distance between cannabis farms and fire perimeters has shrunk by 36% during this time period. Likewise, using data on projected burn regimes, we found that a disproportionate number of cannabis farms are located in wildfire hotspots under future climate scenarios.

4.1. Geography of Cannabis in California May Exacerbate Threat from Wildfire

The geography of cannabis farming is distinct from that of other agricultural types, as a result of both variability in county-level regulations and the illicit history of the crop (Dillis et al., 2021). Although the cannabis industry continues to expand in California, the current distribution of farms is still heavily biased toward its historical origins in the northern part of the state. Establishment of the early cannabis industry in this region was partially driven by the desire to grow undetected, leading growers to locate in remote, hilly, fire prone areas (Corva, 2014; Butsic and Brenner, 2016). As farmers have entered the legal market, many remain in these remote areas, given that their farms are already established. While these small farms vastly outnumber their counterparts elsewhere in the state, the majority of legal cannabis production has already shifted to the Central Coast, where farms are less numerous, but orders of magnitude larger (Dillis et al., 2021). Unfortunately, the future wildfire outlook for the Central Coast also poses a concern in that all three top cannabis producing counties in this region have more than half of their farms in zones projected as persistent, new, or intensifying wildfire hotspots. In fact, over 95% of its cannabis farms in Santa Barbara County, which is now the top cannabis producing county in the state, are located in new or intensifying hot spot zones.

It is worth noting the counties that produce the vast majority of the state's irrigated agricultural crops are located in the Central Valley and are generally considered to have very low wildfire risk. However, aside from Yolo County, every county in the valley has continued to prohibit cannabis agriculture through local ordinances. As a consequence, many areas suitable for cannabis cultivation that have lower fire risk are currently inaccessible. Future changes in policy that allow for cultivation within these counties may significantly lower the overall wildfire risk to cannabis in the state. Within current cannabis producing counties, many land use policies have encouraged production on lands already used for agriculture. To the extent that these lands have less exposure to wildfire, it is possible that newly establishing farms may have lower fire risk. As an example, Monterey and Trinity Counties have both experienced an exceptional amount of wildfire since 2015 (covering 16% and 33% of their land areas, respectively), yet the latter has over 90% of its cannabis farms in very high fire hazard severity zones, while the former has none. This is largely because cannabis farming in Monterey County is new and confined to agricultural zones, while production in Trinity County is still located in remote legacy areas and there is relatively little agricultural land throughout the county in general.

4.2. Cascading impacts of wildfire on the cannabis industry

Although the number of cannabis farms that were directly damaged by wildfire in 2020 (i.e., inside fire perimeters) is small (0.63%), a much larger proportion of farms were likely affected by their close proximity to fire, and experienced impacts from smoke exposure or infrastructure damage (e.g., power and water systems). It is unknown what proportion of farms experienced crop damage or losses from wildfire smoke. While the adverse effects of wildfire smoke on the chemical composition and quality of wine grapes ("smoke taint") is well documented and known to cause significant economic impacts (e.g, (e.g., Krstic et al., 2015), the effects of smoke on the quality of cannabis products is less well understood (but see Kukura, 2020; Schiller, 2020).

Wildfire smoke may also have additional implications for human health. Outdoor farm workers, including for cannabis, may be particularly vulnerable to smoke exposure and health risks from the inhalation of particulate matter from wildfire smoke (Riden et al., 2021), including severe respiratory and cardiovascular damage (Cascio et al., 2018). Farmworker health and safety may also be impacted by additional exposure to toxic particles from combusted building structures or chemicals found on site, including pesticides, as well as flame retardants used to suppress wildfires (e.g., Riden et al. 2021). There are also no publicly available data on the capacity for these chemical compounds, or the natural byproducts of wildfire smoke, to impact the safety of cannabis licensed for human consumption. Given California's stringent testing requirements for cannabis flower, the effects of wildfire smoke add further uncertainty to newly established testing protocols and there is no publicly available guidance on potential mitigation measures. Finally, the federally illegal status of cannabis has made crop insurance largely unavailable to cannabis farmers, thus increasing financial exposure should crops be either burned or rendered unmarketable as a result of smoke damage.

An economic analysis of the potential impact of wildfire on the cannabis industry would be helpful in understanding the scale of the risk and informing needed policy changes. With 2019 sales near $3 billion (McGreevy, 2019), cannabis is already one of the top five grossing agricultural sectors in California (State of California, 2020), with rapid growth expected in the coming decade (Hudock, 2019). In 2020, tax revenues from legal cannabis sales in the state amounted to over $780 million (State of

California, 2021). Considering cannabis' increasing economic importance at state- and county-levels, crop losses from wildfire are likely to have critical economic impacts, particularly in rural communities with a higher direct social and economic dependence on cannabis agriculture (Kelly & Formosa 2020). This could also disproportionately impact already marginalized small-scale cannabis farmers who may not have resources to recover from wildfire-related losses.

4.3. Conclusions

Cannabis is unique among agricultural sectors both in the threat of exposure to wildfire and the prospect of uninsurable crop losses. The geographic legacy of cannabis production in Northern California and expansion of the regulated industry in the Central Coast has rendered it more vulnerable than other types of agriculture, compounded by the regulatory exclusion of cannabis farms from traditional agricultural regions in the Central Valley with relatively lower fire risk. If production is confined to current counties, local regulations should encourage new farming in areas that are less prone to wildfire, yet remain inclusive of existing cannabis farms. For instance, fire-safety programs for farms already established in high-risk areas are needed to reduce the risks of wildfire to crops and human health. The state should also pursue options for providing crop insurance to farmers that aren't eligible for federal programs. Furthermore, given that the impacts of wildfire extend beyond fire perimeters, research on smoke exposure risks for cannabis crops and farm workers is an urgent priority. Collectively, these steps will help bolster the resilience of the developing regulated cannabis industry with respect to wildfire. The impacts of wildfire on cannabis farming may be particularly severe, but serves more generally as an example of the vulnerability of rural agriculture, and its dependent communities, in the face of climate change and the consequent increase in natural disasters such as wildfire.

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References

Bates, D., Mächler, M., Bolker, B. and Walker, S. 2014. Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.

Bauman, M.J., Yuan, J. & Williams, H.A. 2020. Developing a measure for assessing tourists' empathy towards natural disasters in the context of wine tourism and the 2017 California wildfires. *Curr. Issues Tour.*, 23, 2476–2491.

Bell R. 2015. What happens when livestock are in the path of a wildfire. National Geographic. https://www.nationalgeographic.com/culture/food/the-plate/2015/09/03/what-happens-when-livestock-are-in-the-path-of-a-wildfire/

Bodwitch, H., Carah, J., Daane, K., Getz, C., Grantham, T., Hickey, G. and Wilson, H., 2019. Growers say cannabis legalization excludes small growers, supports illicit markets, undermines local economies. *California Agriculture*, *73*(3), pp.177-184.

Boundary Solutions. 2020. National Parcelmap Data Portal. https://www.boundarysolutions.com/BSI/page1.php.

Butsic, V. and Brenner, J.C. 2016. Cannabis (Cannabis sativa or C. indica) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts. *Environmental Research Letters*, *11*(4), p.044023.

Butsic, V., Schwab, B., Baumann, M. and Brenner, J.C. 2017. Inside the Emerald Triangle: Modeling the placement and size of cannabis production in Humboldt County, CA USA. *Ecological Economics*, *142*, pp.70-80.

Butsic V, Carah JK, Baumann M, Stephens C, Brenner JC. 2018. The emergence of cannabis agriculture frontiers as environmental threats. *Environmental Research Letters,* Dec 4;13(12):124017.

CalAdapt. 2018. Wildfire: explore projected changes in average area burned by wildfires for California. Verified 22 October 2020 at https://cal-adapt.org/tools/wildfire/.

CAL FIRE. 2020a. Top 20 Largest California Wildfires. Accessed January 27, 2021 at https://www.fire.ca.gov/media/4jandlhh/top20_acres.pdf

CAL FIRE. 2020b. Fire Hazard Severity Zones. Accessed September 1, 2020 at https://gis.data.ca.gov/datasets/789d5286736248f69c4515c04f58f414

CAL FIRE. 2020c. Fire Perimeter Data (1900-2019). Accessed September 1, 2020 at https://gis.data.ca.gov/datasets/CALFIRE-Forestry::california-fire-perimeters-all?geometry=-149.872%2C31.410%2C-88.349%2C43.564

CAL FIRE. 2020d. Fire Perimeter Data (2020). Accessed December 7, 2020 at https://gis.data.ca.gov/datasets/CALFIRE-Forestry::wildfire-perimeters/data?geometry=-56.778%2C24.076%2C-170.685%2C65.012

Cascio, Wayne E. 2018. Wildland fire smoke and human health. *Science of the total environment.* 624: 586-595.

Corva, D., 2014. Requiem for a CAMP: The life and death of a domestic US drug war institution. *International Journal of Drug Policy*, *25*(1), pp.71-80.

Dillis, C., Biber, E., Bodwitch, H., Butsic, V., Carah, J., Parker-Shames, P., Polson, M., and Grantham, T. 2021. Shifting geographies of legal cannabis production in California. *Land Use Policy*. 105: 105369

Dewitz, J., 2019, National Land Cover Database (NLCD) 2016 Products: U.S. Geological Survey data release, https://doi.org/10.5066/P96HHBIE.

ESRI. 2016. Space time pattern mining concepts: how emerging hot spot analysis works. Available at https://pro.arcgis.com/en/pro-app/tool-reference/space-time-pattern-mining/learnmoreemerging.htm

Goss, M., Swain, D.L., Abatzoglou, J.T., Sarhadi, A., Kolden, C.A., Williams, A.P. and Diffenbaugh, N.S., 2020. Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*. *15*(9), p.094016.

Herskovitz, J. 2017. US Plains wildfires leave thousands of cattle dead. Reuters. https://www.reuters.com/article/us-usa-wildfires/u-s-plains-wildfires-leave-thousands-of-cattle-dead-idUSKBN16G2XG

Hudock, C. 2019. US Cannabis Cultivation in California. New Frontier Data. https://newfrontierdata.com/cannabis-insights/u-s-cannabis-cultivation-in-california/.

Jin, Y., Goulden, M.L., Faivre, N., Veraverbeke, S., Sun, F., Hall, A., Hand, M.S., Hook, S. & Randerson, J.T. 2015. Identification of two distinct fire regimes in Southern California: Implications for economic impact and future change. *Environmental Research Letters,* 10, 094005.

Keeley, J.E. and Syphard, A.D., 2018. Historical patterns of wildfire ignition sources in California ecosystems. *International journal of wildland fire*, *27*(12), pp.781-799.

Kelly, E.C. and Formosa, M.L., 2020. The economic and cultural importance of cannabis production to a rural place. *Journal of Rural Studies*, *75*, pp.1-8.

Kelly, L.T., Giljohann, K.M., Duane, A., Aquilué, N., Archibald, S., Batllori, E., Bennett, A.F., Buckland, S.T., Canelles, Q., Clarke, M.F. and Fortin, M.J., 2020. Fire and biodiversity in the Anthropocene. *Science*, *370*(6519).

Kramer, H.A., Mockrin, M.H., Alexandre, P.M. and Radeloff, V.C., 2019. High wildfire damage in interface communities in California. *International journal of wildland fire*, *28*(9), pp.641-650.

Krstic, M. P., D. L. Johnson, and M. J. Herderich. 2015. Review of smoke taint in wine: smoke-derived volatile phenols and their glycosidic metabolites in grapes and vines as biomarkers for smoke exposure and their role in the sensory perception of smoke taint. Australian journal of grape and wine research. 21:537-553.

Kukura, J. 2020. Entire West Coast marijuana crop threatened by fire, smoke, and ash. SFist.com. https://sfist.com/2020/10/06/entire-west-coast-marijuana-crop-threatened-by-fire-smoke-and-ash/

Liu, Yongqiang, John Stanturf, and Scott Goodrick. 2010. Trends in global wildfire potential in a changing climate. Forest ecology and management. 259: 685-697.

McGreevy, P. 2019. California now has the largest legal marijuana market in the world. Los Angeles Times. https://www.latimes.com/california/story/2019-08-14/californias-biggest-legal-marijuana-market

Moanga, D., Biging, G., Radke, J. and Butsic, V., 2021. The space–time cube as an approach to quantifying future wildfires in California. *International Journal of Wildland Fire*, *30*(2), pp.139-153.

Norgaard, K.M., 2014. The Politics of Fire and the Social Impacts of Fire Exclusion on the Klamath. *Humboldt Journal of Social Relations*, *36*(1).

Parks, S.A., Miller, C., Parisien, M.A., Holsinger, L.M., Dobrowski, S.Z. and Abatzoglou, J., 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere*, *6*(12), pp.1-13.

Radeloff, V.C.V.C., Helmers, D.P.D.P., Kramer, H.A., Mockrin, M.H.M.H., Alexandre, P.M.P.M., Bar-Massada, A., Butsic, V., Hawbaker, T.J.T.J., Martinuzzi, S., Syphard, A.D.A.D., Stewart, S.I.S.I., Anu Kramer, H., Mockrin, M.H.M.H., Alexandre, P.M.P.M., Bar-Massada, A., Butsic, V., Hawbaker, T.J.T.J., Martinuzzi, S., Syphard, A.D.A.D. & Stewart, S.I.S.I. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proc. Natl. Acad. Sci. U. S. A., 115, 3314–3319.

R Core Development Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria, https://www.r-project.org.

Riden, H., Felt, E., and Pinkerton, K. 2021. The Impact of Climate Change and Extreme Weather Conditions on Agricultural Health and Safety in California. *Climate Change and Global Public Health. Humana, Cham*. 353-368.

Schiller, M. 2020. Can wildfires impact cannabis quality and test results? Cannabis Business Times. https://www.cannabisbusinesstimes.com/article/can-wildfires-impact-cannabis-quality-test-results/

State of California. 2019. Department of Forestry and Fire Protection. Accessed September 1, 2020 at https://gis.data.ca.gov/datasets/CALFIRE-Forestry::california-county-boundaries

State of California. 2020. Department of Food and Agriculture. California Agricultural Production Statistics. Accessed February 10, 2021 at https://www.cdfa.ca.gov/Statistics/

State of California. 2021. California Department of Tax and Fee Administration. Accessed January 28, 2021 at https://www.cdtfa.ca.gov/dataportal/dataset.htm?url=CannabisTaxRevenues

Syphard, A.D., Radeloff, V.C., Keeley, J.E., Hawbaker, T.J., Clayton, M.K., Stewart, S.I. and Hammer, R.B., 2007. Human influence on California fire regimes. *Ecological applications*, *17*(5), pp.1388-1402.

Thach, L. and Eyler, R. 2017. Up in smoke: Will wildfires leave lasting economic scars on California's vital wine country? Australian and New Zealand Grapegrower and Winemaker https://theconversation.com/will-wildfires-leave-lasting-economic-scars-on-californias-vital-wine-country-86174.

USDA National Agricultural Statistics Service Cropland Data Layer. 2019. Published crop-specific data layer [Online]. USDA-NASS, Washington, DC. Accessed September 1, 2020 at https://nassgeodata.gmu.edu/CropScape.

U.S. Geological Survey, 2019, USGS TNM Hydrography (NHD), accessed March 1, 2020 at https://viewer.nationalmap.gov/basic/.

van Wagtendonk, J., Sugihara, N., Stephens, S., Thode, A. 2021. Fire in California's Ecosystems. University of California Press. https://www.ucpress.edu/book/9780520286832/fire-in-californias-ecosystems.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R. and Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. *science*, *313*(5789), pp.940-943.

Westerling, A.L. 2018. *Wildfire Simulations for California's Fourth Climate Change Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate: a Report for California's Fourth Climate Change Assessment*. Sacramento, CA: California Energy Commission.

Williams, A.P., Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K. and Lettenmaier, D.P., 2019. Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, *7*(8), pp.892-910.

Tables

Table 1. Descriptions of projected burn patterns adapted from ESRI (2016). Aggregates of individual burn patterns are indicated by horizontal lines. Each description of a hot spot pattern also applies to an equivalent description of a cold spot pattern.

Burn Pattern	Description
New Hot Spot	A location that is a statistically significant hot spot for the final time step and has never been a statistically significant hot spot before.
Intensifying Hot Spot	A location that has been a statistically significant hot spot for 90% of the time-step intervals, with the intensity of clustering increasing overall and that increase is statistically significant.
Historical Hot Spot	The most recent time period is not hot, but at least 90% of the time-step intervals have been statistically significant hot spots.
Persistent Hot Spot	A location that has been a statistically significant hot spot for 90% of the time-step intervals with no discernible trend indicating an increase or decrease in the intensity of clustering over time.
Sporadic Hot Spot	A location that is an on-again then off-again hot spot. Less than 90% of the time-step intervals have been statistically significant hot spots and none of the time-step intervals have been statistically significant cold spots.
Oscillating Hot Spot	A statistically significant hot spot for the final time-step interval that has a history of also being a statistically significant cold spot during a prior time step. Less than 90% of the time-step intervals have been statistically significant hot spots.
Diminishing Hot Spot	A location that has been a statistically significant hot spot for 90% of the time-step intervals, with the intensity of clustering decreasing overall and that decrease is statistically significant.
No Pattern Detected	Does not fall into any of the hot or cold spot patterns.

Table 2. Model coefficients. Results of negative binomial model predicting distance to known wildfire perimeter. Maximum Likelihood Estimates (MLE) and standard errors are provided along with the predicted estimate on the original scale (OSE).

Coefficient	MLE	Std. Error	OSE
Intercept (Cannabis)	1.46	0.11	4.30 km
Grapes	0.11	0.03	4.82 km
Pasture	0.14	0.03	4.96 km
General Crops	0.14	0.03	4.95 km