ARTICLE

Agroecosystems

The threat of wildfire is unique to cannabis among agricultural sectors 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. With the goal of determining whether cannabis is uniquely vulnerable to direct wildfire impacts (in terms of crop loss to burning), we integrated fire hazard severity zone (FHSZ) data, wildfire perimeters, and future burn regime projections in relation to the location and cultivated area of cannabis farming. We then applied descriptive statistics and generalized additive models (GAMs) to compare the location of licensed cannabis farms to other agricultural types in California, including grapes, pasture, and all other general crops combined. We found cannabis farming was located more often in high and very high FHSZs and closer to wildfire perimeters than any other agricultural type. GAM estimates of likelihood of occurrence in high and very high severity zones were highest for cannabis, even after accounting for spatial clustering of farm types, although there was no reliable difference in predicted distances to wildfire. Cannabis more often occurred in projected (from 2020 to 2100) wildfire hotspots than all other agricultural types, with GAM estimates affirming a reliably higher likelihood of cannabis in future hotspots than pasture or general crops. Our findings highlight cannabis' particular vulnerability to wildfire in California and may in fact underestimate wildfire risks given the potential indirect impacts of smoke to crops and farmworkers, which were not evaluated in this study. In light of the sector's growing economic importance in the state, these vulnerabilities should be considered in future cannabis and rural development policies.

KEYWORDS
cannabis, fire hazard severity, land use planning, marijuana, rural agriculture, wildfire

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, fire-prone vegetation, climate change, historical fire suppression, and development in the wild–urban interface (WUI) is leading to more frequent and severe wildfires statewide (Keeley & Syphard, 2018; Kramer et al., 2019; Norgaard, 2014; Parks et al., 2015; Radeloff et al., 2018; Syphard et al., 2007; van Wagtendonk et al., 2021; Williams et al., 2019). Between 2015 and 2020, California experienced its seven largest wildfires on record (CAL FIRE, 2020a) and recent studies indicate that wildfires are occurring over larger areas (Schoennagel et al., 2017), at higher elevations (Schwartz et al., 2015), and for a longer seasonal duration (State of California, 2019a). The number of acres of wildlands classified under very high or extreme fire threat is now estimated to be approximately 25 million (State of California, 2019a), approximately one quarter of the state area. Furthermore, climate change projections for the state indicate that high severity fire zones will expand (Office of Environmental Health Hazard Assessment, 2018), as warmer and drier climate conditions support more frequent and intense wildfires (Goss et al., 2020; Westerling, 2018).

Large wildfires are generating significant social, economic, and ecological impacts in the state (Jin et al., 2015; Kelly et al., 2020). Wildfire impacts, including property damage, smoke exposure, and loss of life, are disproportionately experienced by rural communities located in the WUI (McWethy et al., 2019), especially in the Sierra Nevada Mountains and California Coast Ranges. Historically, California's agricultural regions (e.g., Central Valley) have been less impacted by wildfires than forested areas due to lower fuel availability (Williams et al., 2019). However, due to climate change and WUI expansion, the threat of wildfire to agriculture appears to be increasing (Austin et al., 2021). This is especially true for the state's arid rangelands, where wildfires have increasingly disrupted ranching operations and caused livestock losses (Bell, 2015; Herskovitz, 2017). Other agricultural activities, such as wine grape cultivation, also have been affected by recent wildfires, causing property loss, reduction of wine quality from smoke damage, loss of tourism, and impacts to farmworker health and safety (Austin et al., 2021; Bauman et al., 2020; Thach & Eyler, 2017). Cannabis cultivation 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 (Butsic et al., 2018; Corva, 2014).

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). The risk of wildfire to agriculture has been shown to be elevated in landscapes where crops and woodlands are intermixed (Ortega et al., 2012), as is typical in many cannabis-producing areas in California (Dillis et al., 2021). Despite the possibility of cannabis agriculture being uniquely vulnerable to wildfire, to date, there has been no analysis of the spatial distribution of cannabis farms in relation to wildfire risk, due in part to the nascency of cannabis as a state-licensed commercial crop in California.

Although medical cannabis has been legal and regulated in California since 1996, it was not until 2016 that the state legalized adult use (via ballot proposition) and formulated a statewide regulatory framework for commercial cultivation of cannabis (State of California, 2019b). Starting in 2018, the implementation of a legal cannabis industry 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). Since that time, statewide expansion of production has led to the establishment of new, larger farms outside of this region, yet cannabis cultivation in the converted, irrigated, and otherwise less fire-prone agricultural lands of California's Central Valley with relatively no WUI remains largely prohibited under local ordinances (Dillis et al., 2021). With 2019 legal sales near $3 billion (McGreevy, 2019), cannabis is already one of the top five grossing agricultural sectors in California (State of California, 2020b), with rapid growth expected in the coming decade (Hudock, 2019). In 2020, tax revenues from legal cannabis sales amounted to over $780 million (State of California, 2021). Considering cannabis' increasing economic importance at state and county levels, crop losses from wildfire have the potential for significant impacts, particularly in rural communities with a higher direct social and economic dependence on cannabis agriculture (Kelly & Formosa, 2020).

The newly developing licensed cannabis industry has demonstrated remarkable variation in farm size and characteristics on a county-level basis (Dillis et al., 2021). The counties in which cannabis is grown also themselves vary significantly in terms of climate, vegetation, development, and other factors that may influence the occurrence, intensity, and spatial patterns of wildfire. It is therefore poorly understood how cannabis agriculture as a whole is affected by wildfire and how current and future wildfire risks compare to other agricultural crops in the state. Furthermore, it is unknown how California's cannabis policy is shaping the geography of the cannabis industry in relation to wildfire risk. To assess the

vulnerability of cannabis to wildfire relative to other agricultural types and across the counties in which it is cultivated, we addressed the following questions:

1. Are licensed cannabis farms more vulnerable to wildfire than other forms of agriculture on a statewide basis?
2. How vulnerable is licensed cannabis agriculture to wildfire under climate change, relative to other agricultural sectors?
3. How does the potential threat of wildfire vary among cannabis-producing counties now and in the future?

In this study, we restricted our analysis to licensed cannabis farms, where statewide data on farm location and size are available. The analysis did not consider the indirect impacts of wildfire, such as smoke exposure, operational disruptions due to evacuations, or damage to essential regional infrastructure, as such data are currently not available. Our assessment of threat and vulnerability is therefore focused on the potential loss of crops to burning. We expected that given the high density of cannabis farms in the WUI, cannabis would be more vulnerable to wildfire than other agricultural crops in terms of fire hazard severity, proximity to wildfire, and the proportion of cannabis cultivation area occurring within burn perimeters in a single year. We also expected that the projected frequency and severity of wildfires under climate change would disproportionately affect cannabis farms. Finally, we expected that there would be meaningful variation between cannabis counties in terms of current and future wildfire vulnerability, with farms in legacy production centers (characterized by rural, forested landscapes) particularly at risk now and in the future.

METHODS

Data

License data for outdoor cannabis farms were obtained from the California Department of Food and Agriculture (now licensed by the since formed Department of Cannabis Control [DCC]; State of California, 2020b) via a listserv distribution on 27 May 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 the number of licenses (which specify size in terms of square feet of cultivation) was used to calculate farm cultivation area. Farm sizes and locations of three other classes of agriculture were collected from the California Department of Water Resources 2018 i15 Crop Mapping Layer (CDWR, 2018): *pasture* (excluding cultivated hay

crops), *grapes*, and an aggregate of remaining crop types (referred to hereafter as *general crops*). We distinguished pasture and grapes from other crops because these have been shown to be impacted by wildfire in previous studies (Bauman et al., 2020; Bell, 2015; Herskovitz, 2017; Thach & Eyler, 2017). We assessed fire risk on the landscape by Fire Hazard Severity Zones (FHSZs; Figure 1b), as well as historical fire perimeters (Figure 1c), obtained from the California State Geoportal (State of California, 2020c). FHSZs established by CAL FIRE classify terrain as moderate, high, or very high hazard severity based on factors including vegetation, topography, climate, crown fire potential, ember production and movement, and fire history (CAL FIRE, 2020b). FHSZ is therefore a landscape level metric which is likely not sufficiently granular to reflect hazard severity as a result of the farm characteristics of the agricultural types considered in the current study. That is, FHSZ determinations are reflective of the burn probability of the landscapes in which farms are located, rather than the farms themselves. 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 generally correspond to areas devoid of vegetation (e.g., desert) or where urban development or intensive irrigated agriculture, such as the Central Valley (Appendix S1: Figure S1), render wildfire historically unlikely. Fire perimeter data for the years 1970–2020 (State of California, 2020d) were used as an additional vulnerability metric. The dataset included small brushfires, which are qualitatively different in that they are often extinguished within hours, cause little damage, and can occur almost anywhere, including highly converted and developed areas. We therefore used a minimum threshold of fire size (400 ha) for our fire perimeter dataset, following Westerling (2018).

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 spot and cold spot categories based on the spatial and temporal progression of modeled wildfire activity (Table 1; Figure 1d). The Space–Time Cube and Emerging Hot Spot Analysis functions were used to analyze the data in three dimensions across both space and time by aggregating the predicted number of hectares burned into
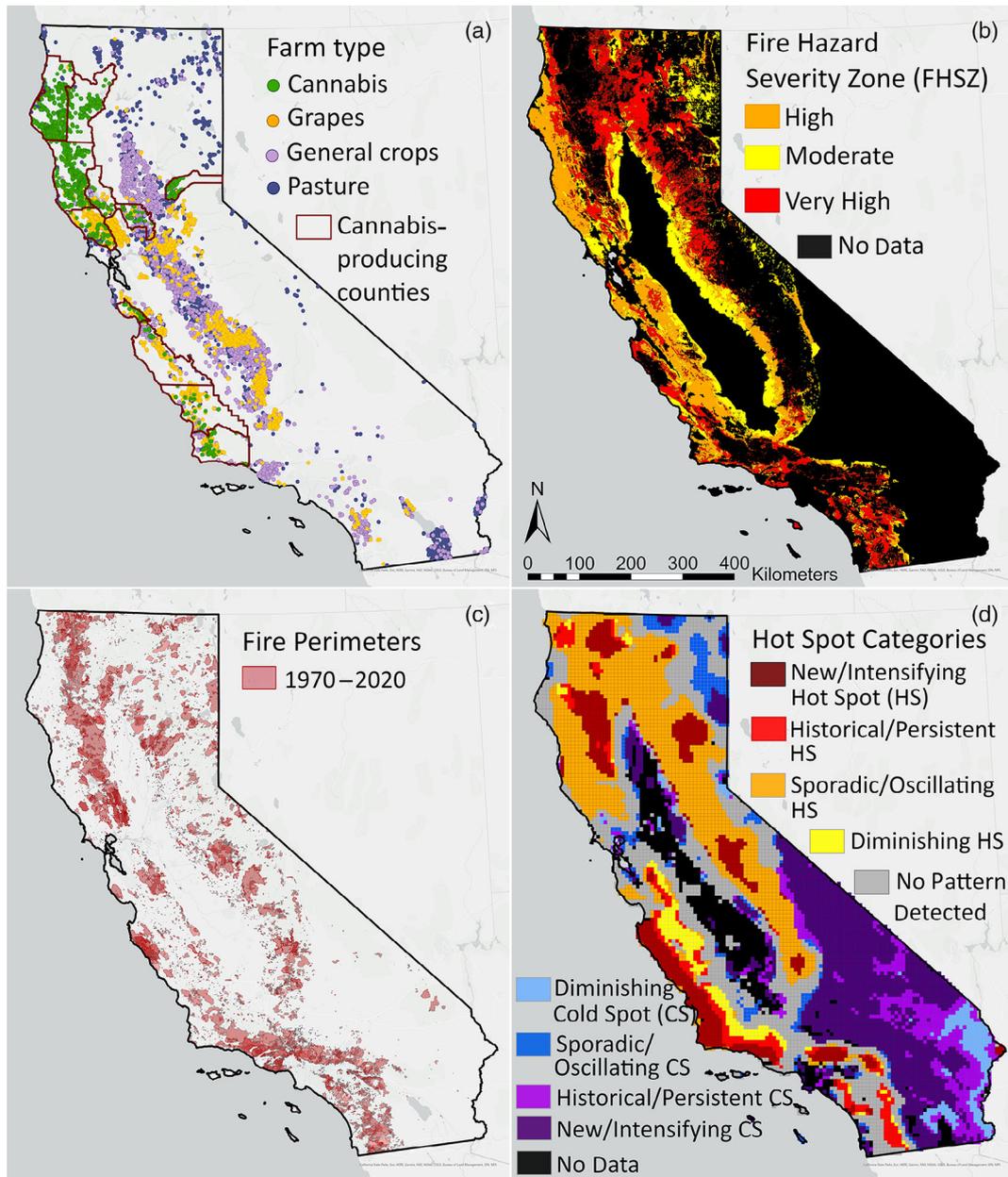
FIGURE 1 Study area map. (a) Farm types (cannabis, grapes, pasture, and general crops) and cannabis-producing counties (restricted to those comprising at least 1% of Department of Cannabis Control outdoor cannabis licenses). (b) Fire hazard severity zones, as established by the State of California (CAL FIRE). (c) Wildfire perimeters dating back 5 and 50 years. (d) Burn pattern projections from 2020 to 2100 as established by Moanga et al. (2020).

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 10,688 grid cells—one grid cell extending approximately 6 km²). The initial wildfire projection data were 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 ha of hot spots (76.90% of the study area) and 149,981 ha of cold spots (2.32% of the

study area), which represent predicted fire dynamics for the period analyzed (2020–2100).

Question 1: Are licensed cannabis farms more vulnerable to wildfire than other forms of agriculture on a statewide basis?

We compared the threat of wildfire to cannabis against the other agricultural types (pasture, grapes, and general crops) using both FHSZ data and wildfire perimeter data.

TABLE 1 Descriptions of projected burn patterns adapted from ESRI (2016).

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.

Note: Aggregates of individual burn patterns are provided in rows. Each description of a hot spot pattern also applies to an equivalent description of a cold spot pattern.

We calculated the proportion of cultivated area of each agricultural type within the four classes of FHSZ (i.e., very high, high, moderate, and no data). To further analyze the differences between agricultural classes in light of spatial clustering of farm types, we employed a generalized additive model (GAM) incorporating a spatial term along with the predictor of farm type on expected FHSZ. A multinomial GAM was fit using the mgcv package in R Statistical Computing Software (Wood et al., 2016; R Core Team, 2018; respectively), in which the predictor variable farm type (F_i) was accompanied by an interaction between latitude (T_i) and longitude (G_i) to predict FHSZ (H_i) of a given farm location. The model used a logit-link function to estimate a multinomial distribution, with the following equation structure:

$$\mathrm{mlogit}(H_i) = \alpha + \beta_f F_i + T_i \; * \; G_i \beta_r + \sum \beta_{b29} + \varepsilon. \quad (1)$$

The slope coefficients for farm type (β_f) and the spatial interaction (β_r) are added to coefficients of 29 basis functions ($\sum \beta_{b29}$) and the intercept (α) to produce a log-odds estimate of FHSZ category for each farm location. Huber–White robust SEs were calculated using the sandwich and lmtest packages in R (Zeileis, 2006; Zeileis & Hothorn, 2002; respectively). Coefficient estimates were considered reliable in cases in which 95% CIs constructed from the SEs did not overlap zero. For the purposes of multinomial comparisons among categories of FHSZ, no data was used as the reference level, with coefficient estimates calculated for each of the remaining levels (moderate, high, and very high).

To determine whether cannabis farms were on average located closer to wildfires than other agricultural types across California, we compared distance to wildfires for each agricultural class. We calculated wildfire proximity as the distance between historical wildfire perimeters (dating back to 1970) and the farm polygon locations of each agricultural class. Farm polygons for grapes, pasture, and general crops were randomly subsampled to provide a balanced sample of $n = 2228$ for each type, matching the number of licensed cannabis farms in our dataset (Figure 1a). We note that although agricultural crop locations may not have been present when historical fires occurred, we consider past fire perimeters to be a relevant proxy for the probability of fire occurring on the landscape under contemporary conditions.

To account for the effect of spatial clustering of farm types, we again employed a GAM incorporating a spatial term along with the predictor of farm type for distance from wildfire perimeter. The GAM was fit using the mgcv package in R, in which the predictor variable farm type (F_i) was accompanied by an interaction between latitude (T_i) and longitude (G_i) to predict distance between farm perimeter and wildfire perimeter (D_i). The model used an inverse link function to estimate a gamma distribution, with the following equation structure:

$$D_i^{-1} = \alpha + \beta_f F_i + T_i \times G_i \beta_r + \sum \beta_{b29} + \varepsilon. \quad (2)$$

The slope coefficients for farm type (β_f) and the spatial interaction (β_r) are added to coefficients of 29 basis functions ($\sum \beta_{b29}$) and the intercept (α) to produce an estimate of FHSZ category for each farm location. Huber–White robust SEs were calculated using the sandwich and lmtest packages in R. Coefficient estimates

were considered reliable in cases in which 95% CIs constructed from the SEs did not overlap zero.

Finally, to determine the actual extent of crop loss for each agricultural type as a direct result of fire in a single year, we calculated the proportion of cultivated area that was within a mapped fire perimeter in 2020. The year 2020 was chosen for this comparison as it provided the most robust dataset for licensed cannabis farms, compared to the first 2 years (2018–2019) of the state's cannabis program.

Question 2: How vulnerable is licensed cannabis agriculture to wildfire under climate change and how does it compare to other agricultural sectors?

To assess the future potential threat of wildfire to licensed cannabis farms, we recorded the spatiotemporal burn pattern projections from 2020 to 2100 (Figure 1d), summarized by Moanga et al. (2020), for the total cultivated area of cannabis and the other agricultural classes. We calculated the relative proportion of cultivated area within each of the following projected burn pattern types: 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). The relative proportion of cultivation area occurring within each burn pattern was summarized for each agricultural class statewide. Using a space–time approach in analyzing modeled wildfire activity throughout the 21st century allowed us to take into account not only the spatial but also the temporal dynamics 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 vulnerability of cannabis farms, but also how this vulnerability is predicted to evolve in the future.

To account for spatial clustering of farm types, an additional GAM was fit using the mgcv package in R. Due to the sparsity of cannabis farms located in cold spots, a binomial comparison (hot spot/not hot spot) was required to achieve model convergence. The predictor variable farm type (F_i) was accompanied by an interaction between latitude (T_i) and longitude (G_i) to predict the likelihood of (P_i) of a given farm to be located in a projected hot spot. The model used a logit-link function to estimate a binomial distribution, with the following equation structure:

$$\text{logit}(P_i) = \alpha + \beta_f F_i + T_i \times G_i \beta_r + \sum \beta_{b29} + \varepsilon. \quad (3)$$

The slope coefficients for farm type (β_f) and the spatial interaction (β_r) are added to coefficients of 29 basis functions ($\sum \beta_{b29}$) and the intercept (α) to produce a log-odds estimate of occurrence in a projected hot spot. Huber–White robust SEs were calculated using the sandwich and lmtest packages. Coefficient estimates were considered reliable in cases in which 95% CIs constructed from the SEs did not overlap zero.

Question 3: How does the potential threat of wildfire vary among cannabis-producing counties now and in the future?

Variation in wildfire risk to cannabis across counties was considered both based on FHSZ and future burn projections. We calculated the proportion of cannabis cultivation in each of the four FHSZ types in counties comprising at least 1% of all DCC outdoor cultivation licenses statewide (hereafter, cannabis-producing counties). These included the following: Humboldt, Lake, Mendocino, Monterey, Nevada, San Luis Obispo, Santa Barbara, Santa Cruz, Sonoma, Trinity, and Yolo Counties (Appendix S1: Figure S1). Of these counties, Humboldt, Lake, Mendocino, Nevada, Sonoma, and Trinity were considered "legacy" (all others "new") in that they all had cannabis cultivation permitting programs prior to the statewide licensing program and constitute centers of historical production that preceded legalization altogether. We also calculated proportions of cultivation area in each of the projected burn pattern types described above for each of the 11 cannabis-producing counties. The same distinction between legacy cannabis counties and new cannabis counties was considered for comparative purposes in the analysis of burn pattern projections.

RESULTS

Question 1: Are licensed cannabis farms more vulnerable to wildfire than other forms of agriculture on a statewide basis?

The amount of cannabis cultivation area in high ($n = 986$ farms, 36.43% of cultivation area) or very high FHSZs ($n = 788$ farms, 24.41% of cultivation area) was larger than any other type of agriculture (Figure 2). Grapes had the next largest percentage of cultivation in high (8.79%) or very high FHSZs (2.86%), followed by pasture (4.33% and 1.72%, respectively). General crops rarely occurred in high (1.02%) or very high FHSZs (0.46%). Because cannabis agriculture as a whole is only a fraction of the total

size of the comparative land uses, the number of hectares of cannabis cultivation in high (149.76 ha) or very high (100.34 ha) FHSZs was much smaller than the total amount of grapes (31590.70 and 10287.80 ha, respectively), pasture (24390.90 and 9696.97 ha, respectively), or general crops (25710.89 and 11715.25 ha, respectively) in these zones.

Results of the multinomial model indicated that even after accounting for spatial clustering of farm types, cannabis farms were reliably more likely to be located in high FHSZs (intercept maximum likelihood estimate [MLE] = −0.64, SE = 0.12, likelihood = 0.35) than were grapes (MLE = −1.03, SE = 0.15, likelihood = 0.16), pasture (MLE = −2.58, SE = 0.19, likelihood = 0.04), or general crops (MLE = −3.57, SE = 0.24, likelihood = 0.02; Table 2). Cannabis was also reliably more likely to be located in very high FHSZs (intercept MLE = −3.23, SE = 0.39, likelihood = 0.04) than were grapes (MLE = −1.26, SE = 0.21, likelihood = 0.01), pasture (MLE = −4.18, SE = 0.31, likelihood = <0.01), or general crops (MLE = −3.74, SE = 0.27, likelihood = <0.01). By contrast, the likelihood of a farm to be located in an area with no FHSZ data was reliably higher for grapes (likelihood = 0.68), pasture (likelihood = 0.86), and general crops (likelihood = 0.86) than it was for cannabis (likelihood = 0.34).

On a statewide scale, the distance between farms and known wildfire perimeters was smaller for cannabis (2.52 km, interquartile range [IQR] = [0.82, 5.06 km]) than grapes (3.21 km, IQR = 0.66, 9.30 km), pasture (9.33 km, IQR = 3.67, 17.67 km), or general crops (10.0 km, IQR = 4.52, 19.48 km; Figure 3). However, after accounting for spatial clustering of farm types, these distances were not reliably different, in that cannabis (intercept MLE = 0.24, SE = 0.03, distance = 4.17 km) was predicted to be only slightly closer than grapes (MLE = −0.03, SE = 0.03, distance = 4.75 km), general crops (MLE = −0.04, SE = 0.03, distance = 5.05 km), and pasture (MLE = −0.05, SE = 0.03, distance = 5.11 km; Table 3).

The percentage of cultivation area of cannabis located within fire perimeters in 2020 was small (0.59%), yet larger than those of any other agricultural crop. The
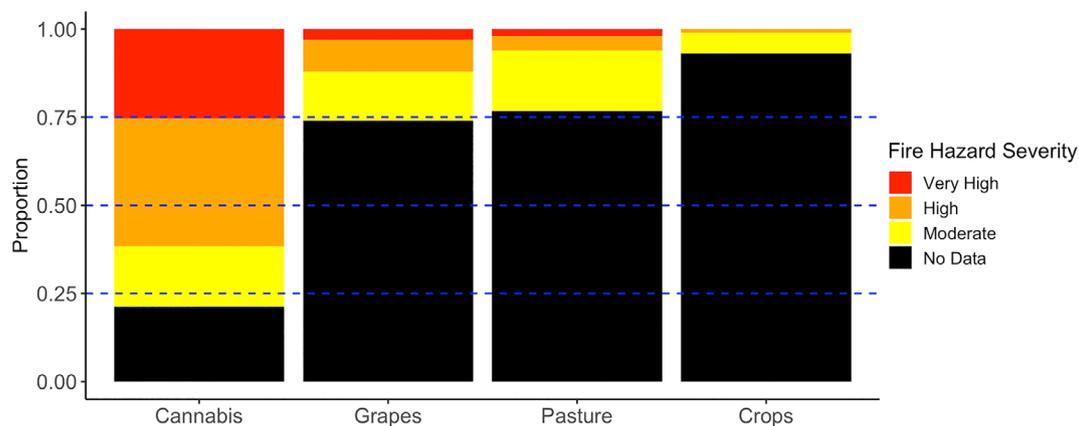
FIGURE 2 Fire hazard severity zones (FHSZs) by agricultural type. Proportions of farms of the four agricultural types within each FHSZ category are summarized, within cannabis-producing counties only. FHSZs are categorized as moderate, high, and very high, with no data values resulting from areas not categorized either due to a lack of fire danger or federal fire responsibility or local fire responsibility zones.

TABLE 2 Model coefficients. Results of multinomial model predicting likelihood of each farm type occurring in each fire hazard severity zones (FHSZs) designation.

| Farm type	Very high FHSZ		High FHSZ		Moderate FHSZ		No data FHSZ
	MLE (SE)	Lkhd	MLE (SE)	Lkhd	MLE (SE)	Lkhd	Lkhd
Cannabis (Intercept)	**−3.23 (0.39)**	**0.04**	**−0.64 (0.12)**	**0.35**	**−1.02 (0.13)**	**0.27**	**0.34**
Grapes	**−1.26 (0.21)**	**0.01**	**−1.03 (0.15)**	**0.16**	**−0.66 (0.15)**	**0.16**	**0.68**
Pasture	**−4.18 (0.31)**	**<0.01**	**−2.58 (0.19)**	**0.04**	**−1.21 (0.15)**	**0.10**	**0.86**
General crops	**−3.74 (0.27)**	**<0.01**	**−3.57 (0.24)**	**0.02**	**−1.25 (0.15)**	**0.09**	**0.89**

Note: Maximum likelihood estimates (MLE) and SE are provided along with the predicted likelihood (Lkhd). Statistically reliable estimates are indicated in boldface.

percentage of cultivation area of grapes within 2020 fire perimeters was 0.50%, while pasture was 0.10%, and general crops was less than 0.01%.

Question 2: How vulnerable is licensed cannabis agriculture to wildfire under climate change, relative to other agricultural sectors?

Nearly all of the state's cannabis cultivation area (94.40%) was located in areas identified as projected burn pattern hot spots (new/intensifying, historical/persistent, sporadic/oscillating, or diminishing hot spots) for the prediction period 2020–2100 (Figure 4). No other agricultural type exceeded 25% of cultivation area in these burn pattern categories. Rather, there were larger percentages of cultivation area in cold spots than hot spots for pasture (35.48% cold spot, 23.28% hot spot), grapes (23.90% cold spot, 18.96% hot spot), and general crops (30.80% cold spot, 5.01% hot spot).

After accounting for spatial clustering of farm types, cannabis farms were reliably more likely to occur in locations projected to be hot spots (intercept MLE = −2.01, SE = 0.63, likelihood = 0.11) than were pasture (MLE = −0.91, SE = 0.19, likelihood = 0.05) or general crops (MLE = −1.33, SE = 0.22, likelihood = 0.03; Table 4). However, grapes were more likely to occur in hot spots (MLE = 0.65, SE = 0.18, likelihood = 0.20), relative to cannabis.

(a) Cannabis **(b) Grapes**
(c) General Crops **(d) Pasture**
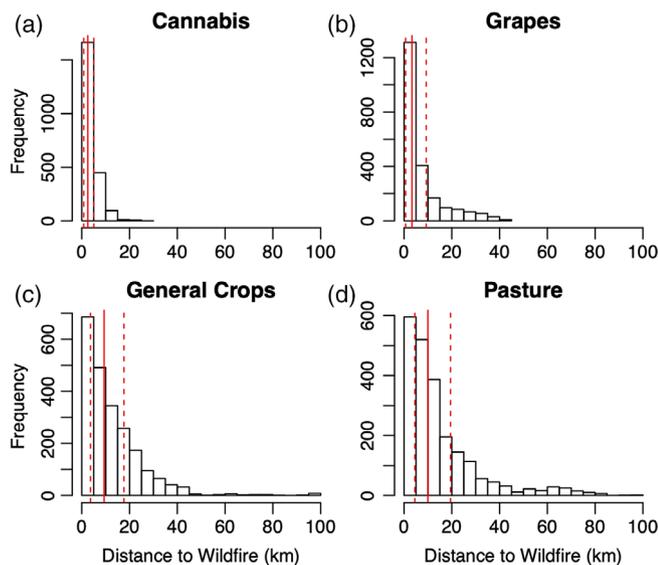
FIGURE 3 Farm proximities to known wildfires. Perimeters for fires since 1970 are compared against the geospatial locations of (a) cannabis and sampled locations for (b) grapes, (c) general crops, and (d) pasture. Median values for each agricultural type are indicated by a solid red line, with the interquartile range represented with dashed red lines.

Question 3: How does the potential threat of wildfire vary among cannabis-producing counties now and in the future?

There was notable variation in the percentage of cannabis farming within FHSZs across counties (Figure 5). For instance, Trinity (93.75%) and Nevada (53.17%) had over half of their cannabis cultivation area in very high FHSZs, while Monterey and Yolo had relatively little cannabis cultivation area in either high (4.11% and 0.00%, respectively) or very high FHSZs (0.00% and 6.41%, respectively). Among cannabis-producing counties, 9 of 11 had 75% or more of cannabis farm area located within zones projected as hot spots (Santa Barbara: 98.03%, Trinity: 100%, San Luis Obispo: 75%, Humboldt: 100%, Mendocino: 100% Nevada: 100%, Santa Cruz: 97.7%, Monterey: 83.81%, and Lake: 100%; Figure 6). There were three counties in which over half of the cannabis cultivation area was within new/intensifying hot spots (Santa Barbara: 96.62%, Trinity: 65.63%, and San Luis Obispo: 52.78%). Only two counties (Sonoma and Yolo) had less than 25% of cannabis farm area within hot spots.

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 in terms of direct loss to fire, confirming our expectations. At the statewide scale, cannabis was the only agricultural type for which the majority of cultivation area was located in high or very high FHSZs. By contrast, all other agricultural types had less than a quarter of total cultivated area in these zones. Predicted FHSZ differences between cannabis and all other crops were robust to the spatial clustering of

TABLE 3 Model coefficients. Results of gamma model predicting distance between each farm type and closest wildfire perimeter.

Farm type	MLE	SE	Distance (km)
Cannabis (Intercept)	**0.24**	**0.03**	**4.17**
Grapes	−0.03	0.03	4.75
General crops	−0.04	0.03	5.05
Pasture	−0.05	0.03	5.11

Note: Maximum likelihood estimates (MLE) and SE are provided along with the predicted distance to fire. Statistically reliable estimates are indicated in boldface.
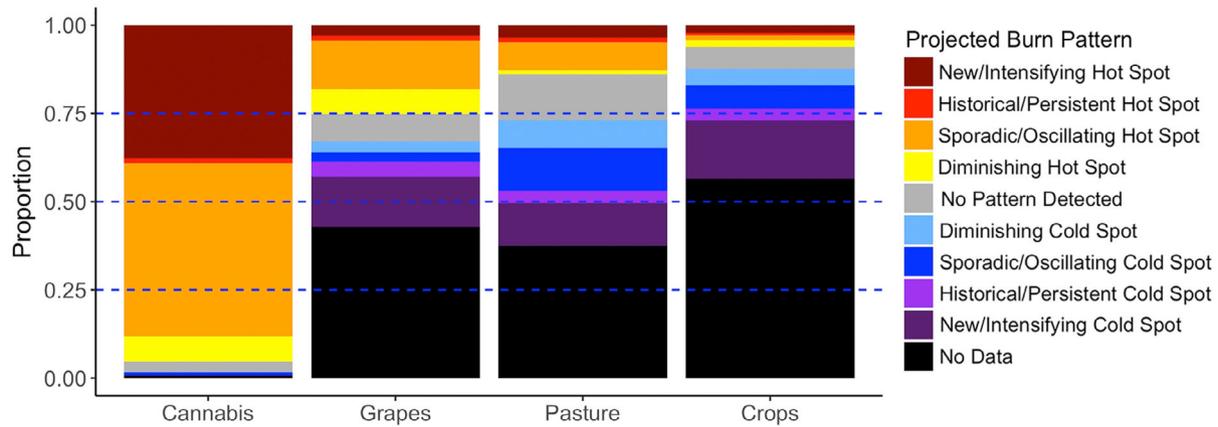
FIGURE 4 Projected burn regimes by agricultural type. Proportions of cultivation area of the four agricultural types within each projected burn pattern category are summarized. Categories are adapted from those used by Moanga et al. (2020). No data values result from areas for which burn probability data from Westerling (2018) were not produced due to extremely low likelihood of wildfire. Maps depicting projected burn patterns are available in Moanga et al. (2020).

TABLE 4 Model coefficients. Results of binomial model predicting likelihood of each farm type occurring in projected hot spot.

Farm type	MLE	SE	Likelihood
Cannabis (Intercept)	**−2.01**	**0.63**	**0.11**
Pasture	**−0.91**	**0.19**	**0.05**
Grapes	**0.65**	**0.18**	**0.20**
General crops	**−1.33**	**0.22**	**0.03**

Note: Maximum likelihood estimates (MLE) and SE are provided along with the predicted likelihood. Statistically reliable estimates are indicated in boldface.

farm types on a statewide basis. Given current geographic constraints on the distribution of cannabis (due to county and municipal cultivation bans), spatial clustering of future development into these areas is likely (Dillis et al., 2021). Our model results, which consider clustering on a statewide basis, are therefore rather conservative as they are based on FHSZ likelihoods in which the entire state is available to cannabis, instead of just particularly high-fire risk counties.

Despite the uniquely high occurrence of cannabis farms in high-risk wildfire areas, the proportion of cannabis cultivation area located within 2020 burn perimeters was very low (<1%). We nevertheless note that the proportion of cultivation area burned was greater for cannabis than for other crops. As our assessment did not account for the indirect effects of wildfire (e.g., smoke exposure), our findings likely underestimate the full impacts of wildfires on cannabis in 2020. Cannabis farms are located, on average, within 3 km of a past wildfire, whereas pasture and general agricultural crops are located over three times as far from wildfires. We found that predicted distance to wildfire was strongly influenced by spatial clustering of farm types, which is likely due in part to the spatial confinement of cannabis farms to particular counties.

Our results further suggest that cannabis farms are particularly vulnerable to future wildfire risks. Based on projected burn regimes, our results confirm that compared to other crop types, a disproportionate amount of cannabis cultivation is located in projected wildfire hot spots. After considering spatial clustering of farm types, cannabis was still more likely to occur in future hot spots than pasture or general crops. Although our models predicted grapes to be even more likely than cannabis to occur in hot spots (on account of spatial clustering), this result was likely driven by the more dispersed distribution of grapes among various hot spot areas (Figure 1a). Based on the trajectory of county bans, cannabis cultivation can be expected to remain confined and clustered in hot spot areas. Together, our findings indicate that given current farming locations, cannabis is significantly more vulnerable to direct losses (i.e., burning) from wildfire—now (based on fire hazard severity and proximity to known wildfire perimeters) and in the future (based on projected burn patterns).

On a county-level basis, proportions of cannabis cultivation within current high or very high wildfire severity zones were notably higher in legacy cannabis-producing counties than in those with more recent cannabis-producing histories. However, our future burn projection models suggest changing trajectories, as two of the three most severe hot spot projections occurred along the Central Coast rather than in legacy cannabis-producing counties. Therefore, it appears that future wildfire impacts may be more concentrated in areas where the cannabis industry is currently growing the fastest (Dillis et al., 2021).
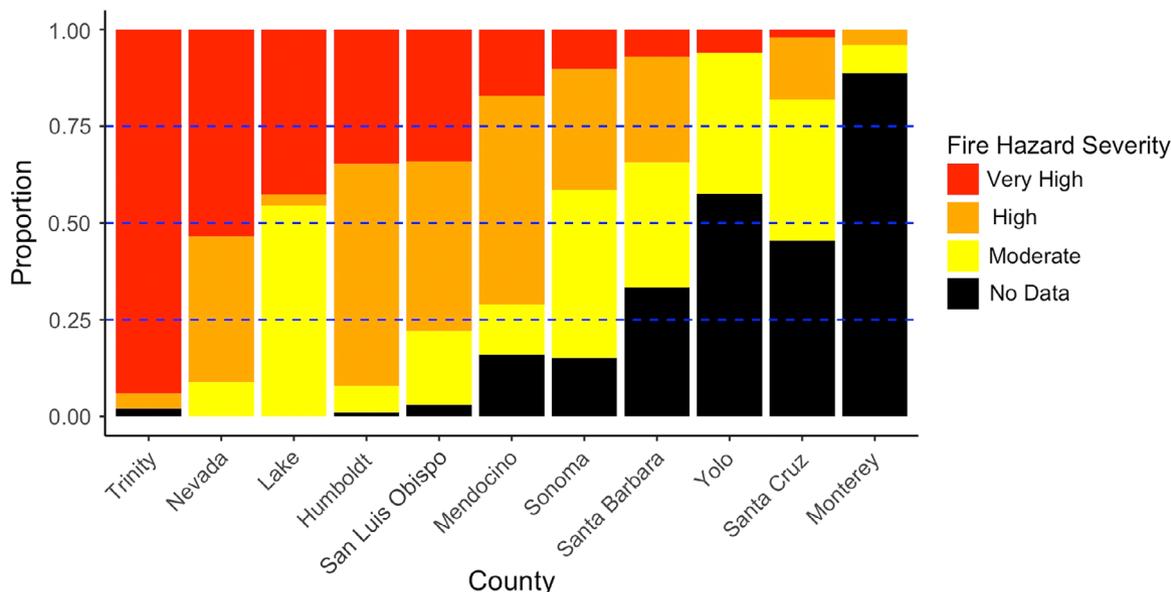
FIGURE 5 Fire hazard severity zones (FHSZs) by county. Proportions of cannabis cultivation within each FHSZ category are summarized by county. FHSZs are categorized as moderate, high, and very high, with no data values resulting from areas not categorized either due to a lack of fire danger or federal fire responsibility or local fire responsibility zones.
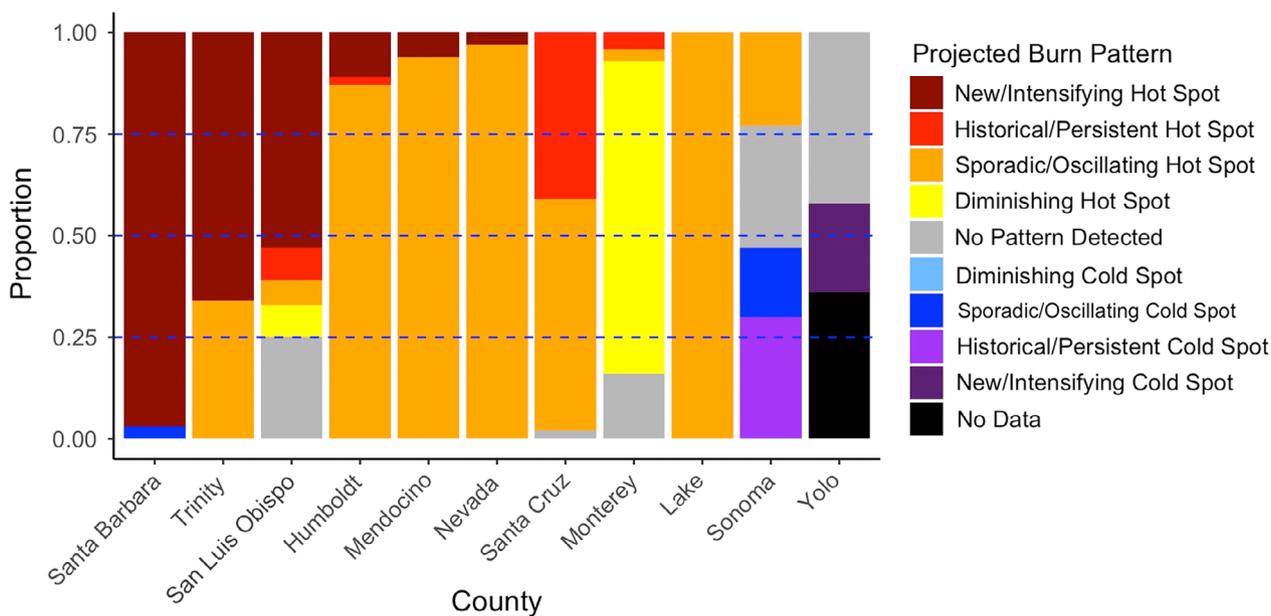
FIGURE 6 Projected burn regimes by county for cannabis agriculture. Proportions of cannabis cultivation within each projected burn pattern category are summarized by county. Categories are adapted from those used by Moanga et al. (2020). No data values result from areas for which burn probability data from Westerling (2018) were not produced due to extremely low likelihood of wildfire. Maps depicting projected burn patterns are available in Moanga et al. (2020).

Geography of cannabis in California may exacerbate potential 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, forested areas that are inherently more fire prone (Butsic & Brenner, 2016; Corva, 2014). As farmers have entered the legal market, many have remained in these remote areas, working their existing farms. While these small farms vastly outnumber those found elsewhere in the state, the majority of legal cannabis production (in terms of cultivated area) has now shifted to the Central Coast, where farms are less numerous, but orders of magnitude larger (Dillis et al., 2021). Yet, the 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 cannabis farms in zones classified as persistent, new, or intensifying wildfire hot spots. In fact, over 95% of its cannabis farms in Santa Barbara County, which is currently the top cannabis-producing county in the state, are located in new or intensifying hot spot zones. Thus, the legal cannabis industry as a whole can be expected to experience persistent vulnerability to wildfire in its current geographic configuration. Should modeled burn pattern projections prove accurate in the coming decades, it may impact where large-scale cannabis farming occurs.

It is worth noting the counties that produce the vast majority of the state's traditional irrigated agricultural crops are located in the Central Valley (Appendix S1: Figure S1) 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 at the county level, as allowed under the local control provisions of state cannabis policy. As a consequence, many areas suitable for cannabis cultivation that have lower fire risk are currently inaccessible for legal production. Future changes in policy that allow for cultivation within these counties may significantly lower the overall wildfire vulnerability of cannabis cultivation in the state. It should be noted that the presence of irrigated agriculture itself has been thought to reduce the risk of wildfire (Moriera & Peér, 2018). However, given that cannabis farms are typically orders of magnitude smaller than those of traditional agriculture (Butsic et al., 2018), it is unlikely that irrigation could mitigate wildfire impacts for cannabis farms. 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 established farms may have lower vulnerability to fire. As an example, Trinity and Monterey Counties have both experienced an exceptional amount of wildfire since 2015 (covering 33% and 16% of their land areas, respectively). While over 90% of the cannabis farms within Trinity County are located in very high FHSZs, there are none for Monterey County. This can be explained by the fact that legal cannabis farms in Monterey County were established after statewide legalization and are confined to agricultural zones, mostly in lowland valleys with low fire risk. In contrast, production in Trinity County has mostly involved the transition of (historically illicit) legacy farms, located in remote fire-prone areas, to the regulated system.

We acknowledge that the threat of wildfire to cannabis farms will also be heavily influenced by factors operating on a much finer scale than considered in this statewide study. For example, local topography, weather, fuel types, and the efficacy of fire breaks will all impact fire behavior (Finney, 2001; Price et al., 2007). We therefore underscore that our findings show the *potential* threat of wildfire to cannabis farms primarily based on the proximity to known wildfire perimeters or occurrence within high fire-risk zones. Improved, local-scale assessments of wildfire vulnerability that account for the factors listed above are needed to guide land use planning in these regions. Given the significant projected increases in wildfire intensity and severity in many parts of the state, we also recommend that the impacts of climate change be considered when assessing the vulnerability of cannabis and other agricultural crops. While there have been no peer-reviewed studies to date on the suitable range of climate conditions for cannabis cultivation based on plant physiology, there is evidence that water scarcity is a rising threat to cannabis growers in some parts of the state (Morgan et al., 2020), especially in regions lacking large groundwater basins or dam-fed irrigation networks. Thus, lack of water for irrigation might be expected to interact with growing wildfire risk to shift the geography of cannabis cultivation to other parts of the state or outside of California.

The potential for wildfire impacts on the legal cannabis industry is not limited to California, but has received attention throughout the Western United States (Hines, 2020; Simakis & Williams, 2020). Impacts to cannabis from wildfire have been reported in Colorado, Oregon, and Washington as well (Kukura, 2020), which together accounted for nearly a quarter of the US cannabis sales in 2020 (New Frontier Data [NFD], 2020). California alone represented another quarter of the market in 2020 (NFD, 2020). Thus, the current prevalence and projected increasing severity of wildfire season in the Western United States represents a significant concern for the US cannabis industry as a whole.

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 potentially affected by their close proximity to fire, experiencing impacts from smoke exposure and/or infrastructure damage (e.g., power and water systems and road

networks). While the adverse effects of wildfire smoke on the chemical composition and quality of wine grapes ("smoke taint") are well documented and have been shown to cause significant economic impacts (e.g., Krstic et al., 2015), the effects of smoke on the quality of cannabis products are less well understood (but see Kukura, 2020; Schiller, 2020). Wildfire smoke exposure also has implications for human health. Outdoor farm workers, including those on cannabis farms, are particularly vulnerable to health risks from the inhalation of particulate matter from wildfire smoke (Riden et al., 2021), which has been shown to cause severe respiratory and cardiovascular damage (Cascio, 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 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 (State of California, 2022), the effects of wildfire smoke add further uncertainty to newly established testing protocols and there is no publicly available guidance on potential mitigation measures. The potential economic impacts to farmers due to testing failures are, at present, even more difficult to estimate given the lack of available data.

An economic analysis of the potential impact of wildfire on the cannabis industry would be helpful in understanding the scale of vulnerability and informing potential policy changes. Given that cannabis is a federally illicit substance, opportunities for cannabis farms to purchase crop insurance to mitigate risk are scarce. This could disproportionately impact already marginalized small-scale cannabis farmers who may not have resources to recover from wildfire-related losses. As evidenced by insurance premiums rising exponentially (or policies being terminated altogether) for vineyards and other agriculture in fire-prone areas (Bittle, 2021), the prospect of cannabis being insured in similarly hazardous areas appears unlikely.

Despite the relatively small footprint of cannabis on the agricultural landscape, this lucrative crop plays a crucial role in local economies and constitutes a disproportionately large share of California's agricultural gross domestic product (GDP) (State of California, 2020a). For instance, Humboldt County alone contributed nearly a third (State of California, 2020b) of the estimated $2.9 billion of statewide cannabis sales in 2020 (Morrissey et al., 2020), amounting to more than double the county's GDP of all other agricultural products ($354 million; USDA, 2020). At an estimated value of $870 million, even a 10% loss of the county's cannabis crop to wildfire, whether directly or through smoke impacts, would therefore amount to a significant economic

impact. Cannabis agriculture also plays a critical role in supporting adjacent industries, including equipment suppliers, construction companies, and service providers (Kelly & Formosa, 2020). A thriving cannabis industry has been demonstrated to bolster rural communities due to increased government revenue, business expansion, job growth, and higher property values (Kavousi et al., 2022). From a statewide perspective, losses of cannabis to wildfire represent a potentially significant economic impact as well. For instance, a loss of 25% of cannabis production (~$725 million) would equate to more than the total value of the state's entire orange crop in 2019, estimated at $670 million (State of California, 2020a). While more data are needed on the extent of crop loss due to combined direct and indirect impacts of wildfire, cannabis is certainly in a precarious position considering that nearly 2000 cannabis farms ($n = 1774$) are currently in high or very high FHSZs.

CONCLUSIONS

Cannabis is unique among agricultural sectors in its vulnerability to wildfire impacts, now and likely into the future. If production is confined to current counties, local regulations should encourage new farming in areas that are less prone to wildfire. Attention should also be given to the social, political, and regulatory barriers that are excluding cannabis from more traditional and less fire-prone agricultural areas (e.g., the Central Valley). For farms already established in high-risk areas, fire-safety programs are needed to reduce the impacts of wildfire to crops and human health. These could include traditional fire-risk reduction actions, such as vegetation management and fire breaks, but should also include measures that address the risks of wildfire smoke exposure to crops and farm workers. Finally, the state should pursue options for providing crop insurance to cannabis farmers, who are currently not eligible for federal programs. Collectively, these steps will help bolster the resilience of the developing regulated cannabis industry to wildfire. If successful, efforts to address wildfire vulnerability of cannabis farms could potentially serve as a model for reducing the vulnerability of other forms of rural agriculture, and their dependent communities, especially in a changing climate.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sets utilized for this research are as follows:

Parcel Data: Boundary Solutions (2020): https://www.boundarysolutions.com/BSI/ParcelAtlas/page1.html.

Crop Data (non-cannabis): California Division of Water Resources (2018): https://gis.data.ca.gov/datasets/66744a45fa8748c7ba1c3ef0be938da5_0/explore (accessed 26 March 2022).

Burn Projection Data: Moanga et al. (2020): https://doi.org/10.1071/WF19062. Data (Dillis et al., 2021) are available from Dryad: https://doi.org/10.6078/D16H7Z.

Cannabis Farm Data: State of California (2020b): https://search.cannabis.ca.gov (accessed 5 April 2022).

Fire Hazard Severity Zone Data: State of California (2020c): https://gis.data.ca.gov/maps/31219c833eb54598ba83d09fa0adb346/explore (accessed 7 December 2020).

Wildfire Perimeter Data: State of California (2020d): https://gis.data.ca.gov/datasets/CALFIRE-Forestry::fire-perimeters/explore (accessed 1 June 2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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