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Wildfire smoke exposure has significant economic impacts on California's licensed cannabis industry

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Abstract

California (USA) supports the largest legal cannabis market in the world, yet faces increasing risk from wildfire. While anecdotal evidence of impacts to cannabis crops has been documented during recent extreme fire seasons, the economic losses resulting from smoke exposure and other indirect effects (e.g., ash fall, mandatory evacuations, power outages) are not well understood. We conducted an online survey of licensed cannabis farms across the state, reporting wildfire impacts on cannabis crops from 2018 through 2021. We summarized regional variation in reported cannabis crop losses, fit a hierarchical multinomial model to assess the effects of proximity to fire and smoke exposure on crops, and trained a random forest model to make impact predictions for all state-licensed outdoor cannabis farms. We found that cannabis farms experienced wildfire-related crop losses across all cannabis growing regions in 2020, but that northern regions experienced particularly high crop loss across all four study years. We also found that exposure to wildfire smoke was a stronger predictor of reported impacts than proximity to wildfire. The output of our random forest model suggested substantial impacts for the cannabis industry in 2020, with predicted crop losses between 4.54% and 21.61% statewide, and between 9.09% and 42.83% in the northernmost counties. Estimated potential economic losses in 2020 and 2021 were as high as $1.44 billion and $970.04 million, respectively—losses which themselves exceed annual values of many of California's other agricultural commodities. Together our results indicate substantial impacts of wildfire for the California cannabis industry as a whole. We suggest that more attention be given to strategies for mitigating cannabis crop losses from wildfires, especially in light of increasing fire occurrence and severity under climate change.

1. Introduction

Legal cannabis is rapidly becoming one of the most lucrative agricultural products worldwide. Combined medical and adult-use global cannabis sales were valued at $23.7 billion in 2020 (Morrissey *et al* 2023) and are projected to reach $46.8 billion by 2025 (Murphy 2019, Adams 2020). The United States represents the largest share of global cannabis sales at $20.3 billion in 2020, with California playing a dominant role in the industry nationwide (Huddock 2019). California represented over a quarter of the total US market in 2020 and is expected to remain more than twice the size of the other state markets in the near future (Morrissey *et al* 2023). Here the licensed cannabis industry has already become a significant economic engine, now one of the top five grossing agricultural products in the state (CDFA 2022) and generating over $780 million in tax revenue in 2021 alone (State of California 2021a).

There is evidence that California's adult-use licensed cannabis industry, established in 2018, has already begun a transformation toward industrialized agricultural production (Dillis *et al* 2021a), with large-scale tenant farming replacing small-scale farms as the dominant source of cannabis products by volume (Dillis *et al* 2021b). However, as production in terms of total *acreage* has moved into more traditional agricultural areas of the state, legacy producing counties in Northern California still retain by far the greatest *number* of cannabis farms and continue to represent a significant proportion of total production (Dillis *et al* 2021b). In this region, the licensed cannabis industry remains a particularly important driver of local economies (Kelly and Formosa 2020, Kavousi *et al* 2022). However, the licensed cultivators in the region have also faced challenges associated with farming in rural and remote areas. For instance, farmers have reported greater difficulty complying with stringent environmental regulations (Bodwich *et al* 2019), which relate to the close proximity of many farms to sensitive natural resources (Bauer *et al* 2015, Carah *et al* 2015, Butsic *et al* 2018, Wartenberg *et al* 2020, Dillis *et al* 2021b). More recently, cannabis farms have experienced impacts from wildfire, which has disproportionately affected small scale cultivators in rural areas of the state (Dillis *et al* 2022).

Wildfire has increasingly become recognized as a threat to agriculture (Herskowitz 2017). In addition to direct impacts from burning, exposure to wildfire smoke can be a significant cause of crop losses. In wine production, for example, research on smoke impacts is well-established (Favell *et al* 2019). While smoke does not appear to impair plant growth or leaf function (Bell *et al* 2013), 'smoke taint' often occurs in wine made with grapes that have been exposed to smoke prior to harvest (Kennison *et al* 2009, Kelly *et al* 2012, Noestheden *et al* 2018), with estimated losses to the wine industry in the billions of dollars (Summerson *et al* 2020). The presence of smoke taint has also been anecdotally reported in cannabis products (Hines 2020, Schiller 2020, Schroyer and Schaneman 2020). Given increasing trends in wildfire in California (Williams *et al* 2019), smoke exposure represents a potentially significant threat to the cannabis industry.

California has experienced several severe fire seasons since the inception of the licensed cannabis industry in 2018. Prior work has demonstrated cannabis farms are more likely to occur near wildfire than any other agricultural crop, now and likely into the future (Dillis *et al* 2022). To understand how cannabis crops were affected by smoke and other indirect effects of wildfire, we performed a statewide survey of licensed farmers. We combined survey responses with spatial analysis of wildfire impacts, assessing proximity to wildfire perimeters and exposure to smoke plumes, to ask the following questions:

(1) How are impacts from wildfire smoke on outdoor cannabis farms distributed across the state?
(2) Do distance from wildfire and presence of wildfire smoke plumes accurately predict reported crop impacts?
(3) What are the potential production losses and economic impacts of wildfire smoke to the licensed California cannabis industry?

2. Methods

2.1. Survey and spatial data

We developed an on-line survey for outdoor cannabis farmers in California using the Qualtrics survey platform (Qualtrics, Provo, UT). The survey was designed to document the impacts that wildfire has had on cannabis cultivators and the ways in which wildfire affects crop production, quality, and values. Survey respondents were recruited via email, using addresses obtained from license data for cannabis farms for the years 2018–2021 from the California Department of Cannabis Control (DCC; State of California 2021b). Additional promotion was conducted via industry associations, social media, and the University of California (Liaw and Wiener 2002) Berkeley Cannabis Research Center website. To ensure anonymity of respondents, spatially-referenced data were collected and analyzed at the zip code scale. Respondents reported data from the 2018–2021 growing seasons, although not all participants cultivated cannabis in each year. Only outdoor and mixed-light licenses were considered for estimating impacts, as indoor farms typically have heating, ventilation, and air conditioning systems that are able to filter smoke. The number of licensed cannabis cultivation businesses in operation prior to the commencement of 2021 growing season, fitting the above qualifications, was $n = 1533$. Based on the number of survey respondents ($n = 199$), our response rate was calculated as 13%.

Smoke plume data (Hazard Mapping System (HMS)-Smoke) for the years 2018–2021 were downloaded from the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS) HMS Fire and Smoke Product portal (NOAA 2022). To produce the daily HMS-Smoke product, smoke plumes were delineated and their density (thin, medium, heavy) classified by NOAA using visual analysis of sequential geostationary satellite observations at 2 km resolution. For each farm, we calculated the proportion of days during the flowering period (July–October) in which a 'heavy' smoke plume overlapped the corresponding zip code. It is during this period that cannabis plants are developing the consumable portion of the crop (i.e., flower) and are thus most susceptible to smoke taint.

Fire perimeter data for the years 2018–2021 were downloaded from the California State Geoportal (State of California 2021c). Following Westerling (2018), a minimum fire size (400 ha) was established to filter smaller brush fires from the dataset (such smaller wildland fires are often extinguished within hours, cause little damage, and produce only

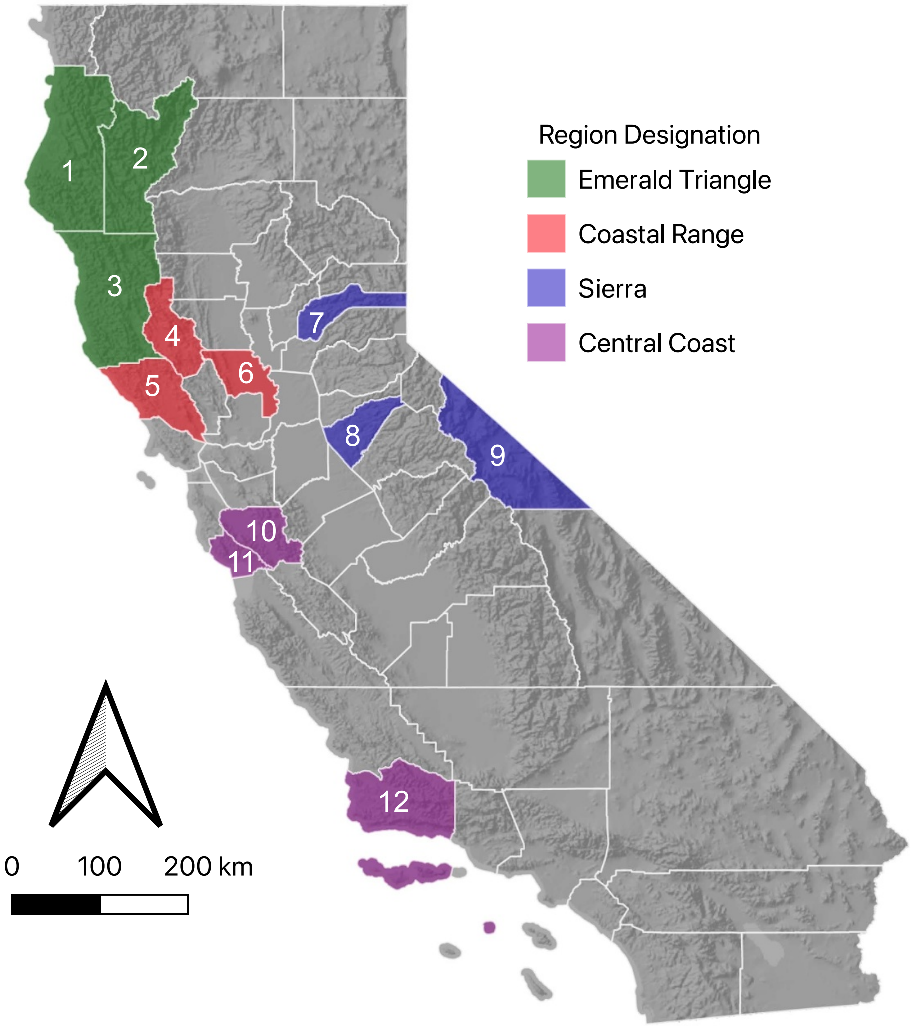

Figure 1. Study area map. Regional designations are depicted for cannabis-producing counties with survey responses, including Humboldt (1), Trinity (2), Mendocino (3), Lake (4), Sonoma (5), Yolo (6), Nevada (7), Calaveras (8), Mono (9), Santa Clara (10), Santa Cruz (11), Santa Barbara (12) counties.

ephemeral smoke plumes). For each farm, the proximity to wildfire in a given year was calculated as the minimum distance between the farm zip code centroid and the closest fire perimeter.

We chose to independently evaluate the effects of smoke exposure and proximity to wildfire perimeters because they represent distinct threats to cannabis crops. In addition to potential direct impacts from wildfire (e.g., burning of crops and farm infrastructure), we expected proximity to wildfire to correspond to impacts from road closures and mandatory evacuations, which could lead to crop losses by disrupting farm operations. In contrast, exposure to smoke was expected to affect crop production, quality, and value. We also determined that the two variables were weakly negatively correlated ($R = -0.38$), indicating that the distribution of smoke is not primarily driven by the location of wildfires, likely due to the effects wind and long-distance plume transport (Goodrick *et al* 2012, Garcia-Menendez *et al* 2013, Sokolik *et al* 2019). Therefore, we considered the effects of both factors in our analysis.

2.2. How are impacts from wildfire smoke on cannabis farms distributed across the state?

Survey respondents were asked to report crop damages associated with wildfire for each year they cultivated cannabis between 2018 and 2021. We aggregated responses for crop yield impacts as 'no impact' (0% crop loss), 'partial loss' (10%–75% crop loss), and 'total loss' (100%). Reported impacts were then aggregated by county and further categorized by region (figure 1). The *Emerald Triangle* region was composed of Humboldt, Mendocino, and Trinity counties. The *Coastal Range* region was composed of Lake, Sonoma, and Yolo counties. The *Sierra* region contained Calaveras, Nevada, and Mono counties, and the *Central Coast* region consisted of Santa Barbara, Santa Clara, and Santa Cruz counties.

Reported impacts for each county were summarized on a yearly basis between 2018 and 2021.

2.3. Do distance from wildfire and presence of wildfire smoke plumes accurately predict reported crop impacts?

We employed a hierarchical multinomial model, fit using the lme4 package in R Statistical Software (Bates *et al* 2015, R Core Team 2018; respectively) to predict the likelihood of one of three impacts to cannabis crops (I; no impact, partial crop loss, or total crop loss). Fixed effects predictors included distance to wildfire (*wf_dist*; d) and percent of flowering period (July through October) underneath a heavy smoke plume (*under_plume*; p). Random intercepts were included for *county* (c), *zip code* (z), and *year* (r). This generalized linear model used a logit link function and fit the following equation:

$$m\text{logit}\,(I_i) = \alpha + \alpha_\text{c} + \alpha_\text{z} + \alpha_\text{r} + \beta_\text{d} D_i + \beta_\text{p} P_i + \varepsilon \tag{1}$$

Random intercepts for *county* (α_c), *zip code* (α_z), and *year* (α_r) are added to the overall intercept (α) and slope coefficients for *wf_dist* (β_d) and *under_plume* (β_p) to produce log-odds estimates for partial crop loss and total crop loss relative to no impact (reference level). The log-odds estimates were subsequently converted to likelihood estimates for reporting. Coefficient estimates were considered reliable in cases in which 95% confidence intervals constructed from the standard errors (SEs) did not overlap zero.

2.4. What are the potential production losses and economic impacts of wildfire smoke to the licensed California cannabis industry?

We developed a random forest model (Liaw and Wiener 2002) to generate categorical predictions of impact (no impact, partial crop loss, total crop loss) based on *wf_dist* and *under_plume.* The trained random forest model was then applied to DCC cannabis license data to produce impact predictions for 2018–2021 based on the zip codes of all licensed cannabis farms. Model outputs were reported as the proportion of farms in a county reporting no impact, partial crop loss, or total crop loss, as well as the amount of cultivated acreage belonging to each impact category. High rates of partial or total crop loss within a given county and year were identified as *crop loss events* if the proportion of farms predicted to have at least partial loss exceeded one third of the county total within a single year. Identification of crop loss events was intended to explore the potential for severe localized impacts relative to broader yet less extreme production losses.

We next estimated the total cultivated area affected by farm-level crop losses. Using predictions from our model, we assumed all farms with 'total crop loss' had a 100% reduction in cultivation area. Farms predicted to experience 'partial crop loss' were assumed to have lost 25% of cultivated area. We also evaluated cultivation area impacts at 10% and 50% for farms with partial crop loss to represent lower and upper bounds that correspond to our reporting data. Predicted cultivation area impacts of both partial and total crop loss at the individual farm scale were aggregated at county, region, and statewide scales and compared to the total cultivation area, calculated from licensing data.

To estimate the economic value of production losses, we first estimated the total amount of marketable cannabis flower lost to wildfire-related impacts. We calculated grams of flower per square foot of cultivation area using data collected from a follow up survey of cannabis farmers ($n = 24$). The median value of flower per area was 292 g of cannabis flower per square meter of cultivated for mixed-light farms and 195 g m^{-2} for outdoor farms. Using the predicted crops loss areas, estimated above, we then calculated corresponding amount of cannabis flower (in grams) lost at each farm. We next estimated the economic value of these losses by evaluating statewide point-of-sale data for mixed-light and full sun outdoor cannabis flower products. Average and median gross sales were calculated from more than 44 million transactions in California from 2021 and 2022 (Treez 2023). The dataset did not distinguish sales of outdoor cannabis flower products from those produced indoor, which are typically priced higher. We therefore used the 25th percentile to estimate the average value of outdoor cannabis at \$6.07 g^{-1} (USD) in 2021 and \$4.99 g^{-1} in 2022. These values were reduced by 25% to account for required excise, sales, and local taxes. Finally, total production losses in USD were estimated as the cannabis lost (in grams) at prices reported for the following year (e.g., crops losses for 2020 were evaluated at 2021 prices), aggregated at county, regional, and statewide scales.

3. Results

3.1. How are impacts from wildfire smoke on cannabis farms distributed across the state?

On a statewide basis, reported crop losses associated with wildfire were greater in 2020 and 2021 than in 2018 or 2019 (figure 2), though there was variation among counties. Reported partial crop loss was common among farms in all three counties in the Emerald Triangle region in 2020 (Humboldt: 32.3%; Mendocino: 51.9%; Trinity: 33.3%), while somewhat less so in 2021 (Humboldt: 16.1%; Mendocino: 18.5%; Trinity: 26.7%). Trinity county reported a large percentage of total loss among cannabis crops in 2021 (20.0%). No county in the Emerald Triangle region reported percentages of partial or total crop losses in 2018 or 2019 in excess of 16.7%.

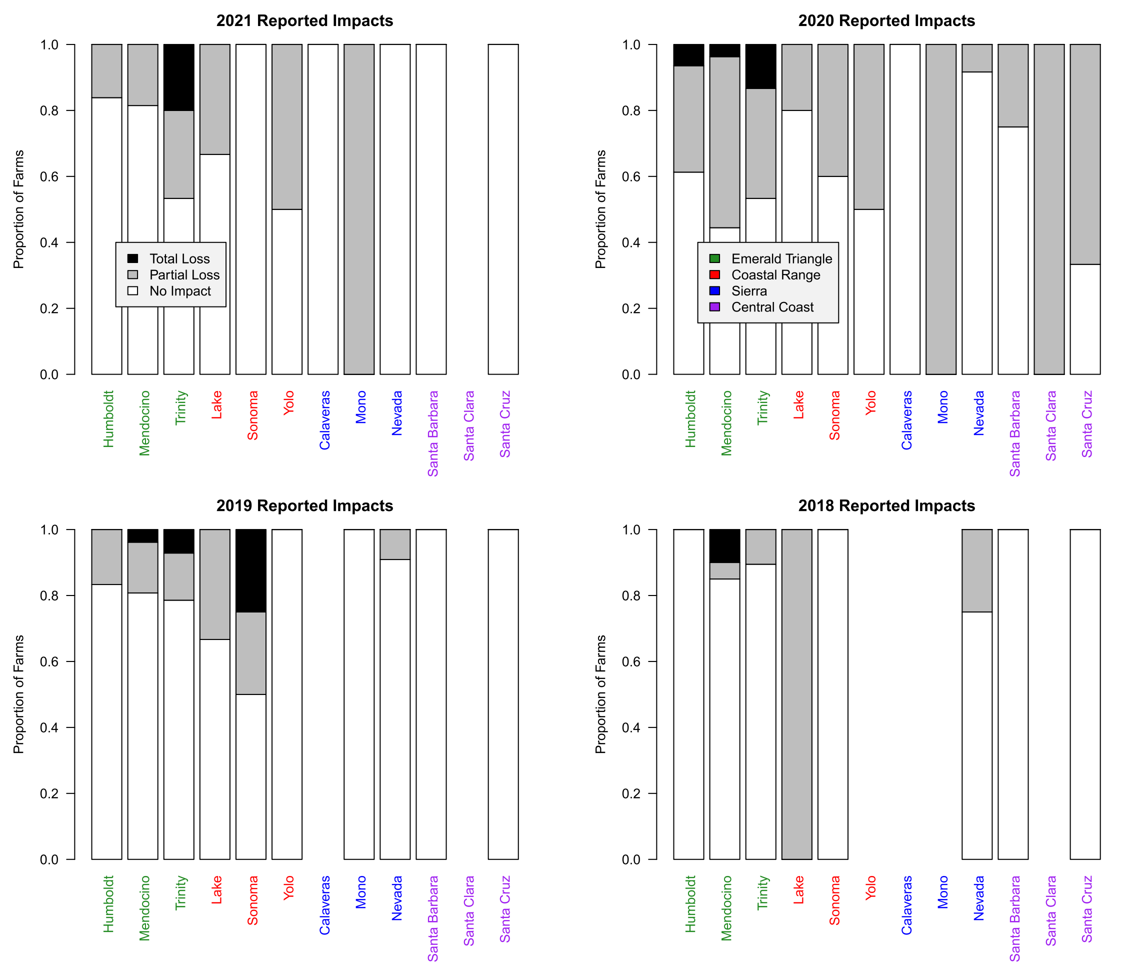

Figure 2. County impacts summary. Proportion of farms reporting impacts from wildfire from 2018 to 2022 in each county. Color coding of county names corresponds to the Emerald Triangle (green), Coastal Range (red), Sierra (blue), Central Coast (purple) regions.

The Coastal Range region (Lake, Sonoma, and Yolo counties) was the only region besides the Emerald Triangle to report substantial levels of partial crop loss in 2021 (23.1%). However, partial crop losses were widespread in 2020, with rates of 50.00% in the Central Coast (Santa Barbara, Santa Clara, and Santa Cruz counties), 33.3% in the Coastal Range, 38.6% in the Emerald Triangle, and 14.3% in the Sierra (Calaveras, Mono, and Nevada counties). The Coastal Range also reported high rates of partial loss in 2019 (22.2%) and 2018 (50.0%), although sample sizes were particularly limited in these years ($n = 9$ and $n = 2$, respectively). Neither the Central Coast nor the Sierra reported high rates of partial loss outside of 2020, other than in the Sierra (25.0%) in 2018, although this represented only a single farm from a small sample size ($n = 4$).

3.2. Do distance from wildfire and presence of wildfire smoke plumes accurately predict reported crop impacts?

Inspecting the distributions of distance to wildfire and percent of flowering days under heavy smoke plumes among the three impact categories suggested that both factors were associated with likelihood of crop impacts (figure 3). The median distance to wildfire among farms reporting partial crop loss (median = 23.68 km; interquartile rang (IQR) = [0.00 km, 55.16 km]) and total crop loss (median = 22.29 km; IQR = [1.58 km, 29.63 km]) was smaller than farms reporting no impacts (median = 38.51 km; IQR = [19.19 km, 70.27 km]), as might be expected. A trend also existed for impacts from smoke plumes, as farms reporting partial losses experienced a greater percentage of flowering period under smoke plumes (median = 27.50%; IQR = [18.75%, 39.17%]) than those reporting no impact (median = 18.33%; IQR = [2.50%, 30.00%]), while farms reporting total crop loss experienced an even greater percentage of smoke days (median = 36.67%; IQR = [20.83%, 43.33%]).

The hierarchical multinomial model indicated that, when simultaneously considering both distance to wildfire and the percentage of flowering period under heavy smoke plumes, the latter was a more important predictor of crop loss (figure 4; table 1). Of the two fixed-effect variables, *under_plume* had

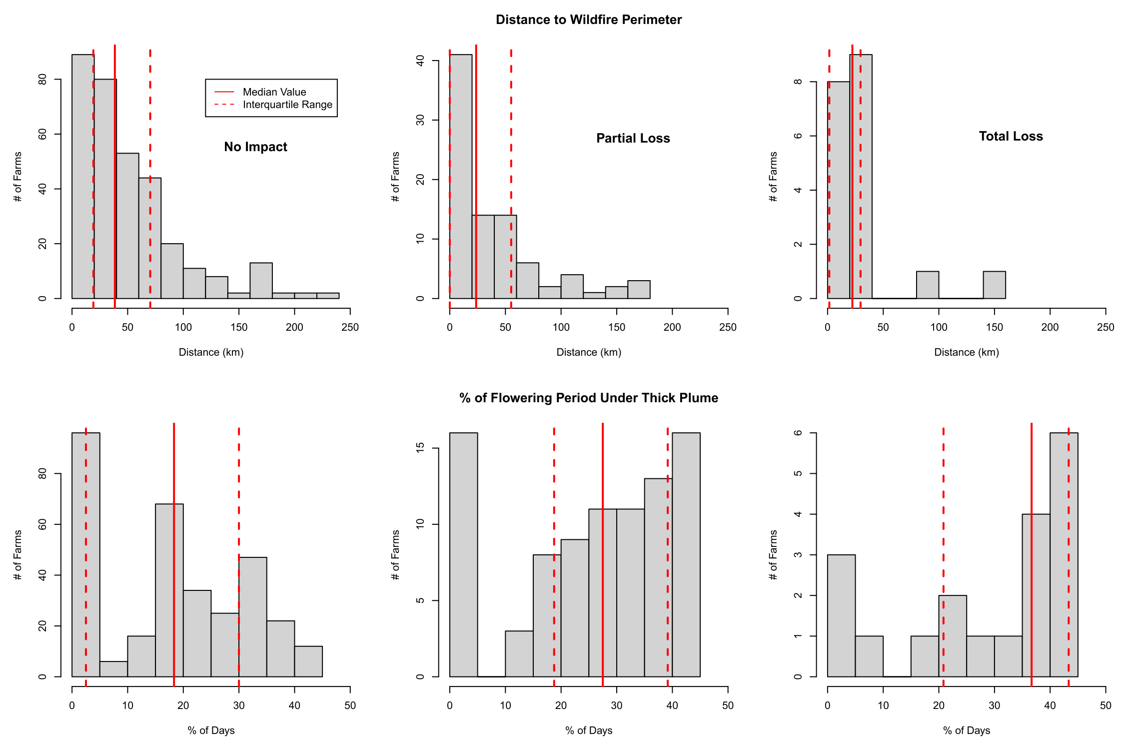

Figure 3. Wildfire exposure summary. Raw data are provided as histograms for farms reporting no impact, partial crop loss, and total crop loss as a result of wildfire. Median (solid line) and interquartile range (dashed lines) of the distribution for each impact category are provided for both distance between zip code centroid and wildfire perimeter and the percent of flowering period underneath a heavy smoke plume.

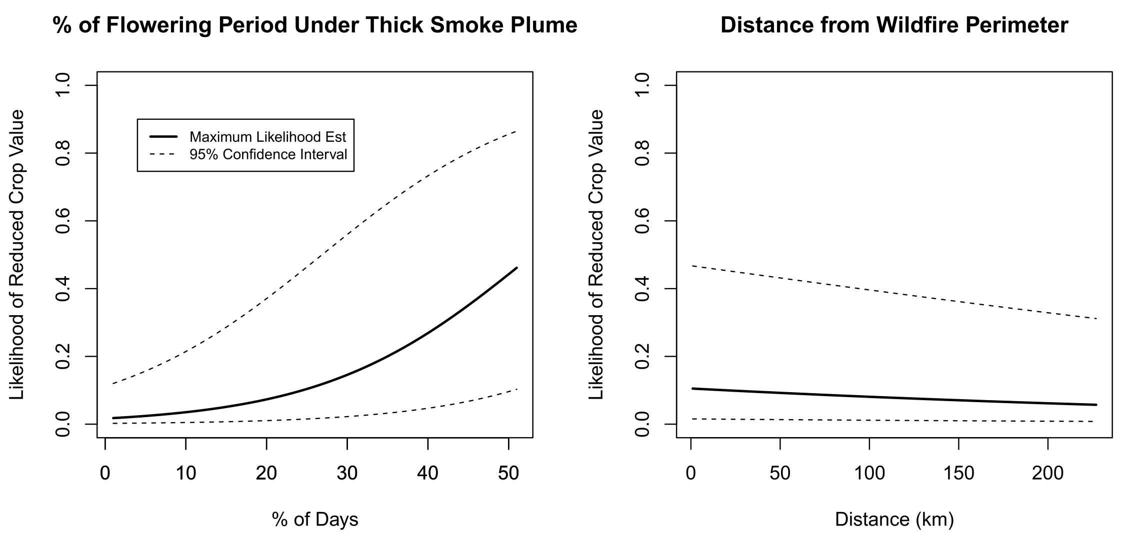

Figure 4. Multinomial model predictions. Maximum likelihood estimates (solid lines) are depicted over the range of values for distance to wildfire and percent of days under a heavy smoke plume. 95% confidence intervals of mean estimates are depicted as dashed lines.

a reliable (positive) effect on the likelihood of both partial crop loss (maximum likelihood estimate (MLE) $= 0.08$; SE $= 0.03$) and total crop loss (MLE $= 0.11$; SE < 0.01). By contrast, *wf_dist* did not have a reliable effect on the likelihood of partial crop loss (MLE $= -0.01$; SE $= 0.01$), but did have a reliable but small negative effect on total crop loss (MLE $= -0.02$; SE < 0.01). Finally, because the majority of total crop losses were geographically confined, the incorporation of random effects for *county* and *zip code* resulted in a low overall likelihood that a general location (i.e., overall estimate) would experience total crop losses. For instance, even when 50% of the flowering period occurred under heavy smoke plumes, the model indicated the likelihood of total crop loss was less than 1%.

Table 1. Multinomial model estimates. Coefficient estimates for both partial loss and total loss of cannabis crops, relative to no impact for distance of wildfire burn perimeters (wf_distance) and exposure to heavy smoke plumes during the flowering period (under_plume).

	Partial loss		Total loss	
	MLE	Std Err	MLE	Std Err
Intercept	−3.94	0.99	−9.14	1.88
wf_distance	−0.01	0.01	−0.02	0.01
under_plume	0.08	0.03	0.07	0.03

3.3. What are the potential production losses and economic impacts of wildfire smoke to the licensed California cannabis industry?

Performance of the random forest model demonstrated an acceptable level of predictive accuracy (median = 70.04%; IQR = [66.21%, 72.49%) across the 100 validation sets (figure S1). Bias values were negligible in all three impact categories: no impact (median = −0.46%, IQR = [−5.73%, 5.47%]), partial loss (median = 0.45%, IQR = [−6.34%, 9.19%]), and total loss (median = −0.47%, IQR = [−4.00%, 2.34%]). Error balance was a performance priority, given the goal of making population-level estimates, and we confirmed that prediction error occurred in similar proportions of false positives and false negatives for each prediction class (table S1).

The model predicted 13 crop loss events during the study period. Of the 13 county-level crop loss events predicted during the four years of the study (2018–2021), six occurred in the Emerald Triangle region (figure 5). Trinity county in particular was predicted to have had moderate or severe crop loss events in three of the four years. Every other region in the study was also predicted to have had at least one crop loss event during the study period: Coastal Range (Sonoma and Lake in 2020; Lake in 2018), Central Coast (Santa Barbara in 2021), and Sierra (Calaveras in 2021; Inyo 2021; Nevada in 2020).

The random forest model predicted that statewide production impacts amounted to a 10.9% reduction in cultivated area in 2020, assuming 25% of crop lost for all farms predicted to experience partial crop losses (figure 6; table 2). Statewide cultivation area losses for 2020 ranged from 4.5% to 21.6%, corresponding to lower (10%) and higher (50%) assumptions of 'partial crop loss' at the farm scale. Predicted cultivation area losses were slightly lower in 2021 at 6.9% (3.5%–12.0%). There was very little production loss predicted in 2019 (0.4% [0.1%–0.8%]) but production loss in 2018 was estimated to be 5.4% of total cultivated area (2.3%–10.6%). The Emerald Triangle region, specifically, was estimated to have experienced higher levels of crop loss than other regions of the state in all four study years (figure 7; table 2). Cultivation area loss estimates in the Emerald Triangle were particularly high (21.7% [9.1%–42.8%]) in 2020 compared to the rest of the state (3.5% [1.4%, 7.1%]).

Within the Emerald Triangle, Trinity county was predicted to have lost over a third (39.3% [30.0%, 54.8%]) of its cannabis cultivation area in 2021, while Humboldt (4.6% [1.8%, 9.1%]) and Mendocino (0.0% [0.0%, 0.0%]) were expected to have had small or no losses. However, in 2020, all three counties were estimated to have had substantial production losses (Humboldt: 22.2% [9.5%, 43.3%]; Mendocino: 19.5% [7.8%, 39.0%], Trinity: 23.6% [9.6%, 47.0%). Trinity county was the only of the three Emerald Triangle counties to have predicted impacts in 2019 (5.9% [2.4%, 11.8%]). Both Mendocino (16.6% [6.7%, 33.3%]) and Trinity (19.3% [8.7%, 37.1%) were estimated to have had larger losses in cultivated area in 2018 than Humboldt county (5.7% [2.5%, 10.9%]).

The total area of statewide outdoor (and mixed-light) cannabis cultivation in 2020 and 2021 was 599.56 ha and 626.83 ha, respectively. Based on our estimates of crop pricing, the total corresponding value is $6.7 billion in 2020 and $5.7 billion in 2021. These values rank cannabis as California's second most valuable agricultural commodity (behind dairy production) in both years (CDFA 2022). Using our estimates of cultivation area losses, the economic impacts from wildfire for 2020 and 2021 were $719 million ($288 million, $1.4 billion) and $485 million ($194 million, $970 million), respectively. In 2020, a loss of $1.4 billion would be larger than the total annual commodity values of all but eight other agricultural sectors in California (CDFA 2022).

4. Discussion

Our results indicate that licensed cannabis producers in California experienced substantial crop losses during the first four years of the state's legal cannabis industry. Impacts were heaviest in the Emerald Triangle, the epicenter of legacy small-scale cannabis production, although all cannabis-producing regions of the state experienced some degree of wildfire-related losses in most years. Proximity to wildfire and exposure to heavy smoke plumes both appeared to be associated with crop losses, but with smoke exposure being a better predictor of impacts. The output of our machine learning model demonstrates that not only can particularly severe fire seasons lead to meaningful statewide cannabis crop losses, but that a real threat

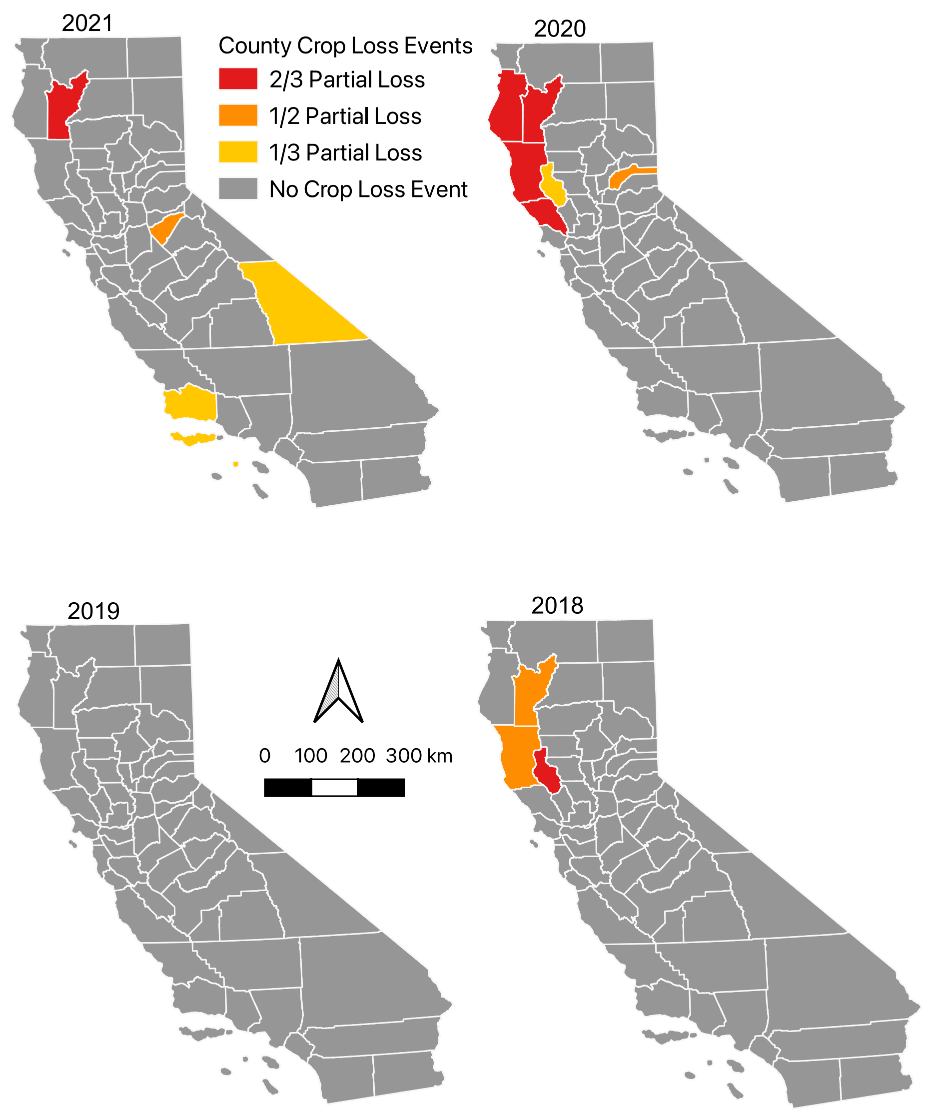

Figure 5. County level crop loss events. Yearly crop loss events, defined as at least one third of DCC licensed farms in a county predicted to have at least partial crop loss (indicated in yellow). Moderate crop loss events constitute at least half of farms predicted to have at least partial loss (orange), while severe crop loss events constitute at least two thirds of farms predicted to have at least partial crop loss (red).

exists in the form of intensive, localized losses at the county level.

4.1. Crop loss events

Given the severity of recent fire seasons in California, we estimate that statewide cannabis production losses could potentially exceed 25% in a single year. Partial losses in the Emerald Triangle were estimated to be as much as a third of total regional production in a single year (2020). As wildfire occurs more frequently and extensively as a result of climate change (McKenzie *et al* 2014), the potential for extreme losses on a regional or statewide basis becomes is likely increasing. Our models suggest that every region experienced crop loss related to wildfire since 2018. However, regions with higher densities of small-scale farms in rural landscapes, including the Emerald Triangle region, appear particularly at risk of wildfire impacts. Because these farms operate on tight profit margins, they may also be the least able to recovery from farm losses. Furthermore, crop insurance programs that currently cover losses for most other agricultural crops are largely unavailable to cannabis cultivators in California because of the plant's continued federally illicit status (Dillis *et al* 2022).

4.2. Smoke plume transport and impacts

We found that both proximity to wildfire and the likelihood of thick smoke were significant predictors of crop loss, but that they appear to affect cannabis farms in distinct ways. For example, farms in the Emerald Triangle and Coastal Range regions experienced nearly the same average percent of flower period under heavy smoke plumes (20.8% and 20.0%, respectively) despite the former being located much closer to wildfire on average (31.5 km) than the latter (109.1 km). Furthermore, farms in the Central Coast averaged only 7.5% of the flowering period

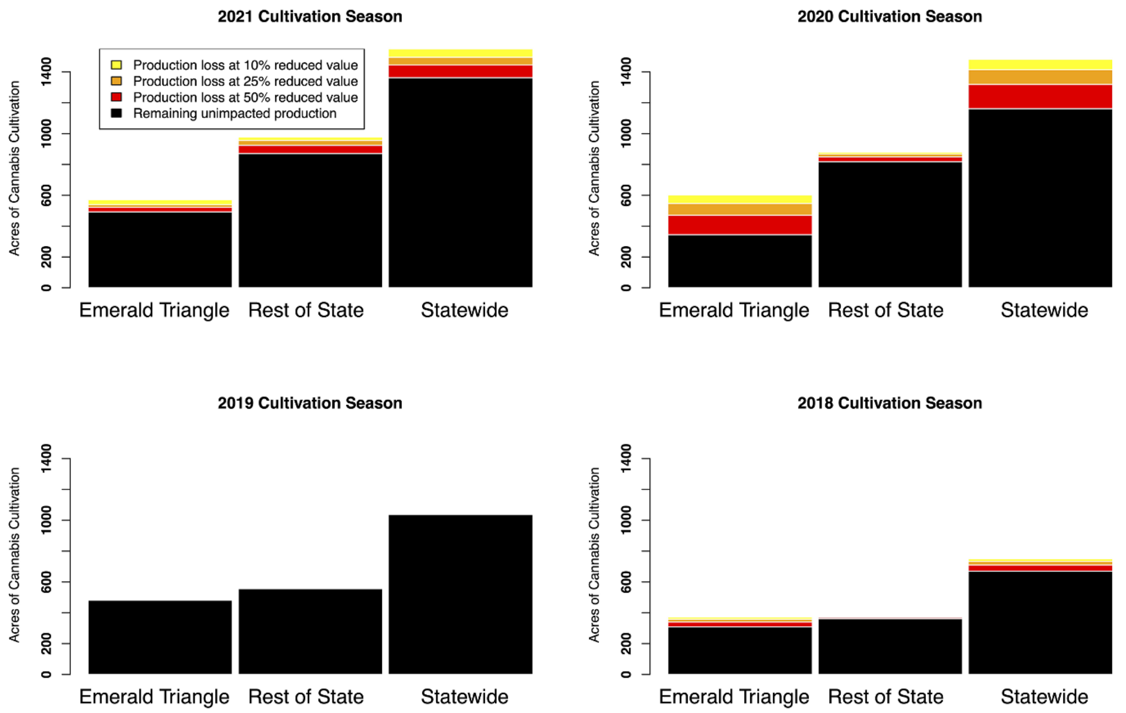

Figure 6. Estimated production impacts—region. Results of the random forest model trained on survey data to estimate impact level (no impact, partial crop loss, or total crop loss), as applied to all DCC licensed cannabis acreage in 2021 and 2020. Bar heights represent the total acreage of cannabis cultivation by area, with yellow, orange, and red portions indicating the predicted total reductions that would result from considering partial crop loss as 10%, 25%, and 50% of cultivated area loss in affected farms, respectively.

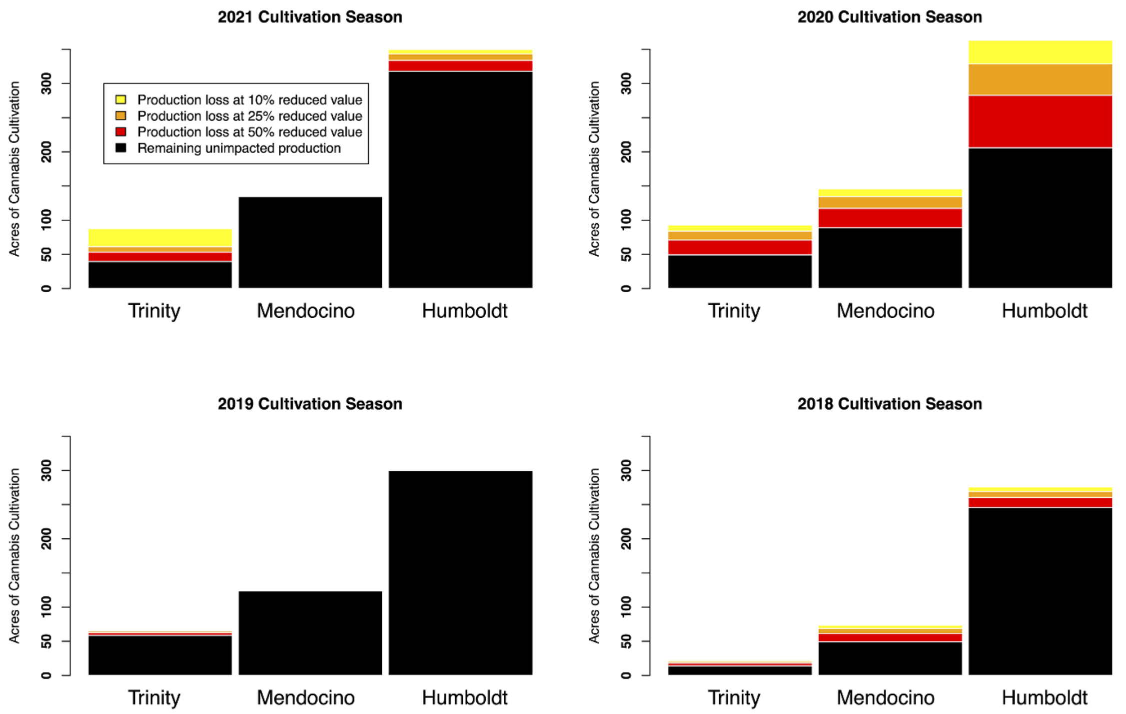

Figure 7. Estimated production impacts—county. Results of the random forest model trained on survey data to estimate impact level (no impact, partial crop loss, or total crop loss), as applied to all DCC licensed cannabis acreage in 2021 and 2020. Bar heights represent the total acreage of cannabis cultivation by area, with yellow, orange, and red portions indicating the predicted reductions that would result from considering partial crop loss as 10%, 25%, and 50% of cultivated area loss in affected farms, respectively.

Table 2. Yearly crop loss estimates, expressed as percent reduction of licensed cultivation area, predicted from random forest model, and reported for the three counties in the Emerald Triangle region (Humboldt, Mendocino, and Trinity), regionwide, statewide excluding the Emerald Triangle, and statewide across all regions. Percent reduction in cultivation area is estimated for three scenarios in which predicted 'partial loss' of cannabis crops corresponds to a 10%, 25%, and 50% crop loss for affected cannabis farms.

Year	Area	% Reduction: partial loss 10% scenario	% Reduction: partial loss 25% scenario	% Reduction: partial loss 50% scenario
2021	Emerald Triangle region	5.71%	8.80%	13.59%
	Humboldt county	1.82%	4.55%	9.09%
	Mendocino county	0.00%	0.00%	0.00%
	Trinity county	30.03%	39.31%	54.78%
	Rest of state	2.18%	4.46%	10.91%
	Statewide total (all regions)	3.49%	6.69%	12.03%
2020	Emerald Triangle region	9.09%	21.74%	42.83%
	Humboldt county	9.48%	22.16%	43.29%
	Mendocino county	7.81%	19.52%	39.03%
	Trinity county	9.59%	23.61%	46.97%
	Rest of state	1.42%	3.54%	7.09%
	Statewide total (all regions)	4.54%	10.94%	21.61%
2019	Emerald Triangle region	0.32%	0.80%	1.60%
	Humboldt county	0.00%	0.00%	0.00%
	Mendocino county	0.00%	0.00%	0.00%
	Trinity county	2.37%	5.92%	11.84%
	Rest of state	0.03%	0.08%	0.16%
	Statewide total (all regions)	0.12%	0.42%	0.84%
2018	Emerald Triangle region	3.68%	8.64%	16.93%
	Humboldt county	2.48%	5.65%	10.94%
	Mendocino county	6.65%	16.62%	33.25%
	Trinity county	8.66%	19.34%	37.14%
	Rest of state	0.89%	2.22%	4.44%
	Statewide total (all regions)	2.27%	5.41%	10.63%

underneath heavy smoke plumes, despite a median proximity of only 44.4 km from wildfire perimeters. These observations follow work demonstrating that localities at great distances from wildfire may still experience heavy smoke, as plume transport can lead to severe inundation far from the source (Langmann 2009, Lareau and Clements 2015). By contrast, some locations may experience only mild or brief smoke inundation despite being in relatively close proximity to wildfire due to prevailing wind conditions (Sokolik *et al* 2019). Although smoke transport models are still unable to fully explain and predict impacts of wildfire smoke (Goodrick *et al* 2012, Garcia-Menendez *et al* 2013, Sokolik *et al* 2019), understanding of atmospheric conditions that affect plume behavior is rapidly advancing (Reisen *et al* 2015). For example, there is evidence that more intensely burning fires produce plumes that rapidly rise to upper levels of the atmosphere and be transported much further (Paugam *et al* 2016). Given the recent frequent occurrence of high-severity wildfires in California, it therefore not surprising that the likelihood of heavy smoke exposure is decoupled from proximity to the location of wildfires themselves.

4.3. Study limitations and further research

Further research on this topic would benefit from data representing a broader geographic range. In particular, additional data from farms and wildfire impacts in the newer cannabis producing regions in the Central and Southern Coast—where growing systems and wildfire impact risks may differ from those in the Emerald Triangle (Dillis *et al* 2021a)—would improve the accuracy of our model and estimates of the impacts. Standardized methods for recording farm losses from wildfire would also be beneficial. For example, we suggest that state could expand upon the reporting and tracking systems already in place to include capacity for documenting crop losses from smoke and other wildfire-related impacts. Finally, experimental studies to understand the ways in which smoke exposure affects cannabis crop yields and quality, as well as the efficacy of mitigation techniques, would be beneficial for cannabis farmers who face threats of wildfire.

5. Conclusions

The current study quantified indirect impacts of wildfire on cannabis production and provided a novel use of spatial smoke data to estimate impacts to agricultural crops. Considering the high value of cannabis crops in California, even small production losses from wildfire can equal millions of dollars in lost revenue. Although cannabis can be grown indoors to be protected from wildfire smoke, there are complications of licensing, infrastructure, and operational costs that make the transition from outdoor to indoor production difficult. Indoor production facilities require significant capital investments and are subject to distinct permitting requirements and regulations that are unfamiliar to many outdoor cannabis farmers. Furthermore, there are significant concerns about the growing energy demands of indoor production, including the load on regional power grids and contributions to greenhouse gas emissions (Mills *et al* 2021). Therefore, a broadscale transition from outdoor to indoor cannabis production is unlikely. This suggests that mitigation strategies will be increasingly important for reducing the impacts of wildfire smoke on outdoor cannabis crops, particularly for rural communities reliant on the industry for local livelihood and well-being. Although the cannabis industry in California stands to remain as the world's largest cannabis market for the time being, its continued status and long-term viability will likely depend in part on addressing the reality of production losses as a result of wildfire.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. Data will be available from 1 October 2023.

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