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Shifting geographies of legal cannabis production in California

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ABSTRACT

The cannabis industry in California is attempting to transition from an international epicenter of unpermitted production to one of the world's largest legal markets. This formalization process will likely establish new centers of production outside the state's historical cannabis-producing regions, with implications for local communities and the environment. In this paper we analyzed how cultivation regulations and land characteristics correlate with the geographical development of permitted cannabis production centers in California. We used permit data from the first two years of California's statewide cannabis regulatory program to document geographic variation in cannabis production and farm characteristics (prevalence of onsite residence, non-landowner farming, county zoning classifications, size of cultivation area). We also used multilevel regression models to analyze whether geospatial characteristics likely to be relevant to environmental regulations (size of parcel, average slope of parcel, density of stream network, land cover type) were associated with farm size (cultivation area) or the likelihood of a parcel being enrolled in the state program. We found that a small number of large farms represented the majority of the permitted cultivation area, with the top 10% of largest farms comprising 60% of total cultivated area statewide. The counties with the most growth in permitted cannabis cultivation area also had the highest rates of tenant (non-landowner) farming and lowest proportions of farms with permanent onsite residency. Farms in these counties were almost exclusively sited on parcels zoned for agriculture. On a statewide scale, parcel size was a reliably positive predictor of enrollment, while average slope and stream network density had reliably negative effects. The same relationships held in predicting cultivation area, together suggesting that the development of the newly-formalized cannabis industry in California may be responsive to environmental regulation. Our results suggest two divergent paths of industry development: one in which smaller farms, which often pre-date legalization, navigate regulations in more remote and rugged regions and a second comprising large farms, which are often newer and operate in areas more favorable to meeting environmental requirements of state and county policies.

1. Introduction

Liberalization of medical and recreational cannabis policies over the last twenty years have led to an expansion of the legal cannabis market. Uruguay, Canada, and 16 states in the United States (including California) have now legalized recreational cannabis, while 36 countries have legalized medical cannabis use (Bahji and Stephenson, 2019; Chouvy, 2019; National Conference of State Legislatures (NCSL), 2020). While much of the global market remains supported by unpermitted production (Wartenberg et al. 2021), legal markets are projected to continue to expand globally by 2025 (Beadle, 2019). California has been an international epicenter of unpermitted cannabis production for many years (United Nations Office on Drugs and Crime (UNODC), 2017; Butsic et al., 2018), but is now transitioning into one of the largest regulated markets worldwide (Hudock, 2019). While medical use was decriminalized in 1996 in California, production remained largely unregulated until 2016 (Stoa, 2015; Butsic et al., 2018). Adult recreational cannabis use was legalized in California in 2016, with specific provisions to grant local authority over production and distribution. A statewide regulatory framework for cultivation was implemented at the beginning of 2018,

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and many counties and municipalities have followed with their own regulations. As a result, the number of farms participating in the new formal, or legal, cannabis market in California continues to increase (Hudock, 2019).

Formalization may involve the establishment of new permitted farms, but also existing farms transitioning from the unpermitted to the regulated economy. As such, California state and county officials must navigate challenges other governments have encountered when regulating informal agricultural systems, as well as other previously informal industries involving timber and non-timber forest products, small-scale mining, and fisheries (see Putzel et al., 2015 for a review). In particular, conditions that favor establishment of new farms over unpermitted farms attempting to transition to the legal industry may result in the persistence of illicit markets, thus undermining the success of nascent legal markets (Sepulveda and Syrett, 2007; Caulkins and Bond, 2012). The possibility of this dynamic exists in California's cannabis industry, as new participants may have an economic advantage, if they can choose farm sites better suited to meeting regulatory requirements, and thereby encounter lower compliance costs (Uthes et al., 2010; Kuhn et al., 2019). In this way, environmental regulations may play a significant role in shaping the geography of legal cannabis production. Especially in contexts where landscape characteristics vary regionally, variation in compliance challenges based on terrain may serve as a powerful filter influencing the geography of legal cannabis production.

The spatial distribution of cannabis farming in California agriculture substantially diverges from that of traditional agriculture. While traditional agriculture is concentrated on large industrial farms in the Central Valley and Central Coast areas (U.S. Department of Agriculture (USDA), 2017) where lands with natural cover were converted to agricultural lands decades ago, cannabis agriculture has historically been absent from these areas, largely due to a legacy of cannabis prohibition (Carah et al., 2015; Gianotti et al., 2017). In an effort to avoid detection and enforcement, unpermitted cannabis farms generally remained much smaller than those of traditional agriculture and unpermitted farmers sought out rugged terrain in remote watersheds in Northern California (Corva, 2014). These historical centers of cannabis production are primarily undeveloped, forested watersheds, harboring multiple U.S. Endangered Species Act-listed species, such as Coho salmon (*Oncorhynchus kisutch*), steelhead trout (*Oncorhynchus mykiss*), and Northern spotted owl (*Strix occidentalis caurina*) (Katz et al., 2013; Gabriel et al., 2018).

Owing to the potential for cannabis agriculture to threaten these sensitive species and other natural resources (Carah et al., 2015), the development of cannabis cultivation policy has included much stronger environmental protections than those enacted for other, traditional agricultural crops (State of California, 2019a, 2019b). As a consequence, farmers in historical cannabis-producing regions have reported difficulty complying with state and county environmental regulations, especially among small farms (Bodwitch et al., 2019). Reported costs of site remediation and upgrades to roads and stream crossings can significantly outpace costs of permits themselves (Bodwitch et al., in Review). The relatively rugged terrain of historical cannabis producing regions (Corva, 2014; Butsic and Brenner, 2016) may therefore influence the feasibility of permitted cannabis farming, in addition to restricting farm size, based on site development and permit costs. However, to date, little attention has been given to the way terrain characteristics are influencing the geographic distribution of the legal cannabis industry in California. Indeed, there has been no formal study of where expansion of the regulated industry is occurring as it develops within and beyond the historical epicenter of production in Northern California.

It remains unclear whether the emerging regulated industry will be characterized by the transition of unpermitted operations in historic centers of production or by development of new farms (or by some combination of the two). It is also unknown how farm characteristics may change in association with shifting geographies. For instance, cannabis farming in California has historically occurred predominantly on parcels not zoned for agriculture, often with landowners living onsite (Corva, 2014). It is unclear if formalization will drive a transition in farm characteristics toward those more typical of large-scale traditional agriculture, such as tenant-operators, living off site, and farming parcels in agricultural zones (Varble et al., 2016).

The goal of this paper is to understand how the geography of cannabis production and cannabis farm characteristics have shifted in the first two years following California's establishment of a statewide cultivation regulatory framework. To characterize the geographic dimensions of the formalization process of this newly regulated industry, we used state enrollment data to address the following questions:

1) Where has expansion in permitted cultivation occurred, and to what extent is there regional variation in cultivation area, ownership, and zoning?
2) Do geospatial characteristics related to regulatory requirements influence whether parcels are used for permitted cannabis farms?
3) Do geospatial characteristics related to regulatory requirements influence the size of cultivation area on permitted cannabis farms?

2. Material and methods

2.1. Data

This study focused exclusively on permitted outdoor cannabis farms in California. Permit data, received via a Public Records Act request, include farms that enrolled in the California Water Board's (CWB) statewide cannabis program between January 2018 (when the permit became available) and December 2019. Enrollment in this regulatory program is one of several conditions required for a cultivation license, issued by the California Department of Food and Agriculture (CDFA). Although other analyses have used CDFA enrollment data (Dillis et al., in press), we opted to use CWB enrollment data to distinguish existing farms that had participated in historic CWB cannabis regulatory programs prior to 2018 from those that enrolled following the adoption of a statewide regulatory program. These early CWB regulatory programs existed in several counties (Humboldt, Lake, Mendocino, Nevada, Trinity, and Yolo), dating back to as early as 2015. However, all farms enrolled in regional CWB regulatory programs were required to transfer to the statewide permitting program following its adoption in 2018. We refer to farms that transferred to the new program as *existing* farms, which may or may not have originally been unpermitted farms.

Although the geographic extent of this analysis covered the State of California, as of December 2019 only a subset of counties had enacted local ordinances to permit outdoor cannabis cultivation (Fig. 1), and many had banned commercial cultivation. Counties included for analysis were restricted to those that contained at least 2% of the total number of CWB permits issued between 2018 and 2019.

Each enrollment supplied a single point location for their farm, which were joined to parcel layers of each county to identify enrolled parcels. GIS data from multiple sources were then used to generate several geospatial variables for all parcels included in the study. Average slope was calculated from Digital Elevation Models (10-meter resolution) downloaded from the USGS National Elevation Dataset (U.S. Geological Survey, 2020a). The summed length of perennial, ephemeral, and intermittent watercourses on each parcel were calculated using data from the USGS National Hydrography Dataset (U.S. Geological Survey, 2020b). Land cover characterizations of each parcel were generated using a classified raster image with 30 m cell resolution, downloaded from the National Land Cover Database (Dewitz, 2019). The zoning of each parcel was determined using spatial data obtained from county websites or by request. Parcel boundary data was obtained from the National Parcelmap Data Portal (Boundary Solutions, 2020). Finally, county ordinance data were obtained from county websites and summarized for six prominent cannabis producing counties to provide a brief vignette of inter-county variation and local control in cannabis

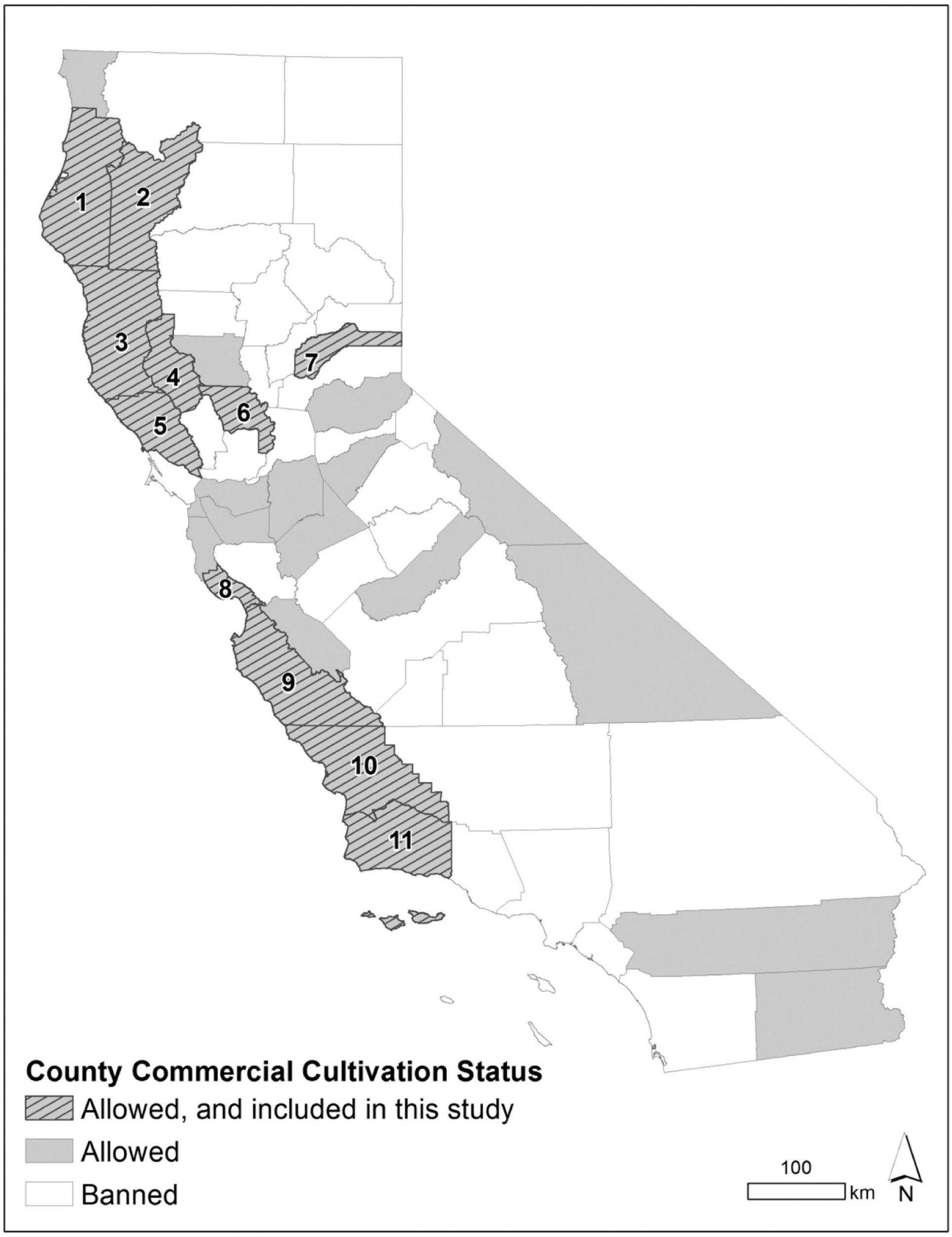

Fig. 1. County Cannabis Map. Counties in California, depicting whether outdoor commercial cannabis cultivation is allowed (shaded) or banned (white). Counties indicated with hashing are included in this study: Humboldt (1), Trinity (2), Mendocino (3), Lake (4), Sonoma (5), Yolo (6), Nevada (7), Santa Cruz (8), Monterey (9), San Luis Obispo (10), and Santa Barbara (11).

Table 1
Descriptions of all variables included in analyses for research questions 1–3.

Variable	Definition	Data Source	Research Question
Onsite residency	Permanent residency on enrolled parcel	California Water Boards	1
Tennant operator	Farming by party other than the landowner	California Water Boards	1
Zoning classification	County zoning label	Individual Counties	1
Parcel size	Area of parcel (mˆ2)	California Water Boards	2, 3
Average slope	Average slope value of parcel	USGS National Elevation Dataset (https://viewer.nationalmap.gov/basic/)	2, 3
Density of streams	Streams (m) per area of parcel (mˆ2)	USGS National Hydrography Dataset (https://viewer.nationalmap.gov/basic/)	2, 3
Land cover	Dominant (>50%) land cover classification	National Land Cover Database (https://www.mrlc.gov/data)	2, 3
Presence of stream	Binary presence/absence of stream on farm	USGS National Hydrography Dataset (https://viewer.nationalmap.gov/basic/)	2, 3
County	Grouping variable for random effects	Individual Counties	2, 3
Trinity grouping	Nesting variable specific to Trinity County	California Water Boards	2, 3

regulations.

2.2. Geography of licensed cannabis production and farm characteristics

In order to assess where permitted cultivation is occurring in the state, enrolled cannabis farms were summarized at the county level using three metrics: number of enrollments per county, median operation size per county, and sum of cultivation area by county. For counties in which regional CWB cannabis regulatory programs existed prior to 2018, *existing* farms were separated from *new* enrollments (originating after January 1, 2018) to identify new industry growth occurring exclusively after adoption of a statewide regulatory program. All permitted farms were further classified by their ownership characteristics (Table 1). Parcels were designated as *tenant operator* when the zip code of the listed landowner differed from the zip code of the listed operator. The spatial resolution of zip code was used to protect personal identifying information and may have resulted in false negatives, in which a tenant operator happened to live in the same zip code as the landowner. Therefore, the actual proportion of tenant operators may be higher, although there is no reason to suspect systematic differences between counties. We also reviewed the enrollment forms to determine if the applicant lived on site (*onsite residency*). *Onsite residency* does not necessarily imply permanent residency by the landowner, as a tenant applicant could also live on site. Finally, *zoning classification* was determined by the county zone designation at the point location of the enrollment. The zoning classifications of each county were aggregated to one of four categories: Residential, Agricultural, Timber, and Other.

2.3. Predicting enrollment from geospatial variables

We fit a multilevel logistic regression model, using the lme4 package in R Statistical Computing Software (Bates et al., 2014; R Core Development Team, 2018), to examine relationships between cultivation regulations and the geospatial characteristics of parcels used for permitted cannabis farms. Zoning classifications were used to designate which parcels were eligible for cannabis cultivation, with any zoning classification in which cannabis farms were located being considered as eligible zones. Selection of unenrolled parcels (i.e. the outgroup) were restricted to eligible zones and compared with enrolled parcels, using logistic regression to predict the likelihood of enrollment in the CWB permitting program. Because this analysis focused exclusively on permitted cannabis farms, there was no distinction made between outgroup parcels that had no cannabis farms and those that had unpermitted cannabis farms. That is, outgroup parcels may have contained unpermitted cannabis farms, however, we were only concerned with determining differences between parcels that grew permitted cannabis and those that did not.

For each parcel we calculated the *parcel size*, *average slope*, and *density of streams,* to include as continuous predictor variables for the model (Table 1). *Parcel size* was chosen as a predictor given that large parcels would potentially increase the amount of land subject to regulation. *Average slope* was expected to influence site suitability for cultivation. *Density of streams*, calculated as the total length of stream divided by the area of the parcel, was similarly expected to influence site suitability. We incorporated all watercourses classified as perennial, ephemeral, or intermittent, as these would be subject to environmental regulations wherever they intersected roads or occurred in proximity to cannabis cultivation.

Two categorical predictors were also included in the model: *Presence of stream* and *Land cover*. *Presence of stream* on each parcel (gleaned from *Density of streams*) was included as a binary predictor, given that many parcels contained no watercourses. *Land cover* was assigned to one of seven classes (Forest, Shrub, Forest-Shrub codominant, Herbaceous, Planted, Developed, None) based on the original dominant (>50% of area) land cover type within a parcel. Given the small size of cannabis cultivation operations relative to the parcels on which they occur, there was no alteration made to *land cover* based on operation size. For modeling purposes, Herbaceous cover type was chosen as the reference level for the variable *land cover*, because it was the only class represented in every county (Table 1).

We used a mixed-effects logistic regression model to produce a binomial prediction (P) of whether a parcel had a permitted cannabis farm or not. The fixed-effects included *parcel size* (scaled to standard Z-score; z), *average slope* (v), *density of streams* (d), *presence of stream* (s) and *land cover* (l). Random intercepts for *county* (c) were specified for *presence of stream* and *land cover*. Random slopes for *county* and *land cover* (nested within *county*) were specified for the three continuous predictors (z, v, and d). In Trinity County, a large set of enrollments (n = 341) came from a single subdivision of approximately 15 km^2, with potentially similar geospatial characteristics, and we therefore included an additional random effect variable (t; nested within *county*) to account for the *Trinity grouping*.

The generalized linear model (GLM) used a logit link function, fitting the following equation:

$$\begin{aligned} logit(P) = {} & \alpha + \alpha_c + \alpha_{cl} + \alpha_{ct} + \beta_s S + \beta_l l \\ & + (\beta_z + \beta_{zc} + \beta_{zcl} + \beta_{zct})z \\ & + (\beta_v + \beta_{vc} + \beta_{vcl} + \beta_{vct})v \\ & + (\beta_d + \beta_{dc} + \beta_{dcl} + \beta_{dct})d + \varepsilon \end{aligned} \tag{1}$$

The overall intercept (α) was added to random intercepts for *county* (α_c), *land cover* nested within *county* (α_{cl}), and *Trinity grouping* nested within *county* (α_{ct}). Because of the nesting structure, the model did not estimate *Trinity grouping* outside of Trinity County, nor types of *land cover* that were not present in a particular county. Fixed-effects terms for *parcel size* (β_z), *average slope* (β_v), and *density of streams* (β_d) were accompanied by random slope coefficients for *county* (β_{zc}, β_{zc}, β_{dc}), *land cover* nested within *county* (β_{zcl}, β_{vcl}, β_{dcl}), and where appropriate, *Trinity grouping* nested within *county* (β_{dct}, β_{vct}, β_{dct}). All slope and intercept terms were summed to produce an estimate of log-odds, which was then converted to likelihood values (L) for purposes of plotting model predictions:

$$L = \frac{1}{1 + e^{\widehat{p}}} \tag{2}$$

Model predictors were considered reliable if 95% confidence intervals, constructed from the standard errors, did not overlap zero.

2.4. Predicting cultivation area size from geospatial variables

The model parameters generated for the binomial enrollment model were used for an additional model predicting operation size (S; ha of cultivation area), using only enrolled parcels. We fit another GLM, using a negative binomial distribution and a log link function. The model structure was identical to Eq. (1), aside from the link function:

$$\begin{aligned} log(S) = {} & \alpha + \alpha_c + \alpha_{cl} \boxed{f()} + \alpha_{ct} + \beta_s s + \beta_l l \\ & + (\beta_z + \beta_{zc} + \beta_{zcl} + \beta_{zct})z \\ & + (\beta_v + \beta_{vc} + \beta_{vcl} + \beta_{vct})v \\ & + (\beta_d + \beta_{dc} + \beta_{dcl} + \beta_{dct})d + \varepsilon \end{aligned} \tag{3}$$

Descriptions of model coefficients are therefore as outlined for Eq. (1). Model estimates (log scale) were used for plotting without transformation back to the original linear scale of the response variable. Model results were overlaid on log-transformed values of cultivation area for the purposes of model interpretation relative to the raw data. Model predictors were considered reliable if 95% confidence intervals, constructed from the standard errors, did not overlap zero.

3. Results

3.1. Geography of licensed cannabis production and farm characteristics

The greatest number of *new* permitted farms were located in

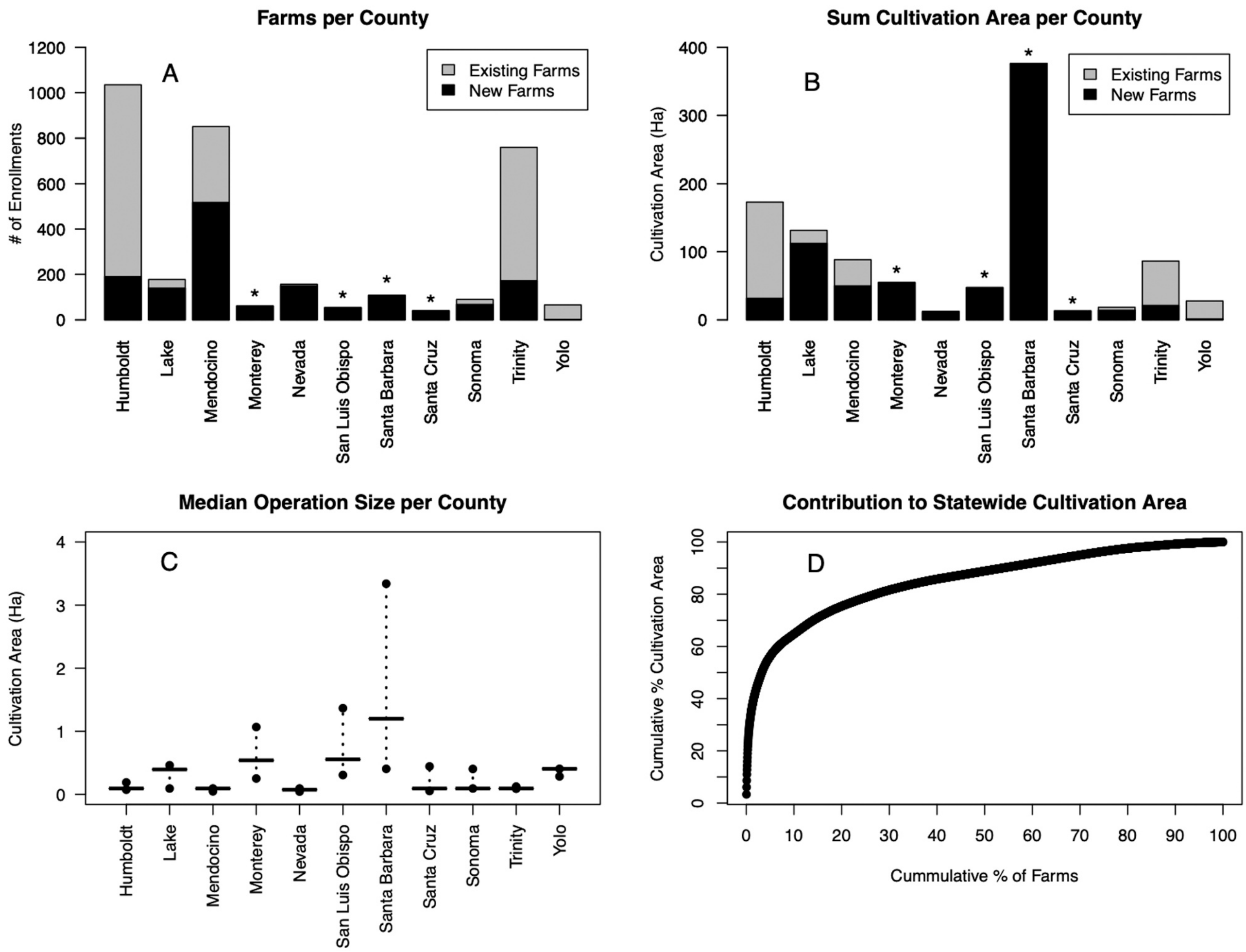

Fig. 2. County growth and operation size. (A) Enrollment data, displayed as the number of existing and newly enrolled farms by county. Asterisks indicate that a county did not have a CWB cannabis program prior to 2018. Accounting for differences in county sizes, the number of farms per km^2 largely followed the general pattern: Humboldt: 0.10; Lake: 0.05; Mendocino: 0.09; Monterey: 0.01; Nevada: 0.06; San Luis Obispo: 0.01; Santa Barbara: 0.01; Santa Cruz: 0.03; Sonoma: 0.02; Trinity: 0.09, Yolo: 0.03. (B) The sum of cultivation area of existing and newly enrolled farms by county. (C) The median size of cultivation area per farm by county, displayed as a bar with dashed lines and circles representing the interquartile range. (D) The relative contribution of individual farms to the total statewide cultivation area. The number of individual farms as a percent of total cultivated area, plotted against the total cultivation area statewide represented as a percent, with farms in descending order (largest farms beginning on the left).

Mendocino (n = 517), Humboldt (n = 191), and Trinity (n = 173; Fig. 2A) counties. However, counties with the greatest sum of *new* cultivation area were Santa Barbara (376 ha), Lake (112 ha), and Monterey (55 ha; Fig. 2B), which were ranked 5th, 6th, and 8th in terms of number of new farms, respectively. This mismatch was the result of smaller individual operation sizes within Humboldt (median= 0.09 ha; IQR= (0.07, 0.19)), Mendocino (median = 0.09 ha; IQR = (0.05, 0.09)), and Trinity (median = 0.09 ha; IQR = (0.09, 0.12)) (Fig. 2C). Operations were substantially larger in Santa Barbara (median = 1.20 ha; IQR = (0.41, 3.34)), Lake (median = 0.39 ha; IQR = (0.09, 0.46)), and Monterey (median = 0.54 ha, IQR = (0.25, 1.07)) counties. On a statewide basis, relatively few large farms represented the majority of total cultivation area, with the top 10% of largest farms accounting for 60% of total cultivated acreage (Fig. 2D).

There were also notable geographic differences in farm characteristics. Santa Barbara and Monterey were the only two counties to have less than 25% of their enrollments report permanent *onsite residency* (Fig. 3A). Santa Barbara was the only county to report *tenant operators* on more than 50% of its farms, whereas Humboldt, Mendocino, and Trinity counties all reported *tenant operators* on less than 25% of farms (Fig. 3B). Farms in Santa Barbara and Monterey were almost exclusively in areas zoned for agriculture, while the percentage of farms in agricultural zones was no greater than 50% in Humboldt, Mendocino, or Trinity counties; the majority of enrolled farms in these counties were located on parcels zoned as timberland and residential (Fig. 3C).

There was substantial variation in the dominant *land cover* of enrolled cannabis parcels across counties (Table 2). In Monterey, San Luis Obispo, and Santa Barbara, the dominant *land cover* was Developed, Planted or Herbaceous for the majority of farms, whereas Forest and Shrub were the dominant *land cover* classes for the majority of farms in Humboldt, Mendocino, and Trinity counties. There was notable grouping of *average slope* values, with Humboldt, Mendocino, Lake, and Trinity counties having significantly higher values than Monterey, Santa Barbara, San Luis Obispo, and Yolo counties (Table 2).

3.2. Geospatial predictors of enrollment

There was no reliable effect of *land cover* on the probability of enrollment (Table 3). The other categorical predictor, *presence of stream*, did however have a reliably positive effect (MLE = 0.52, SE = 0.06). Among the continuous predictors, *parcel size* had a reliably positive fixed-effect on enrollment probability statewide (MLE= 0.97, SE= 0.39, Fig. 4). Monterey, Trinity, and Yolo were the only counties without predicted positive random slope for *parcel size*. The fixed-effect of

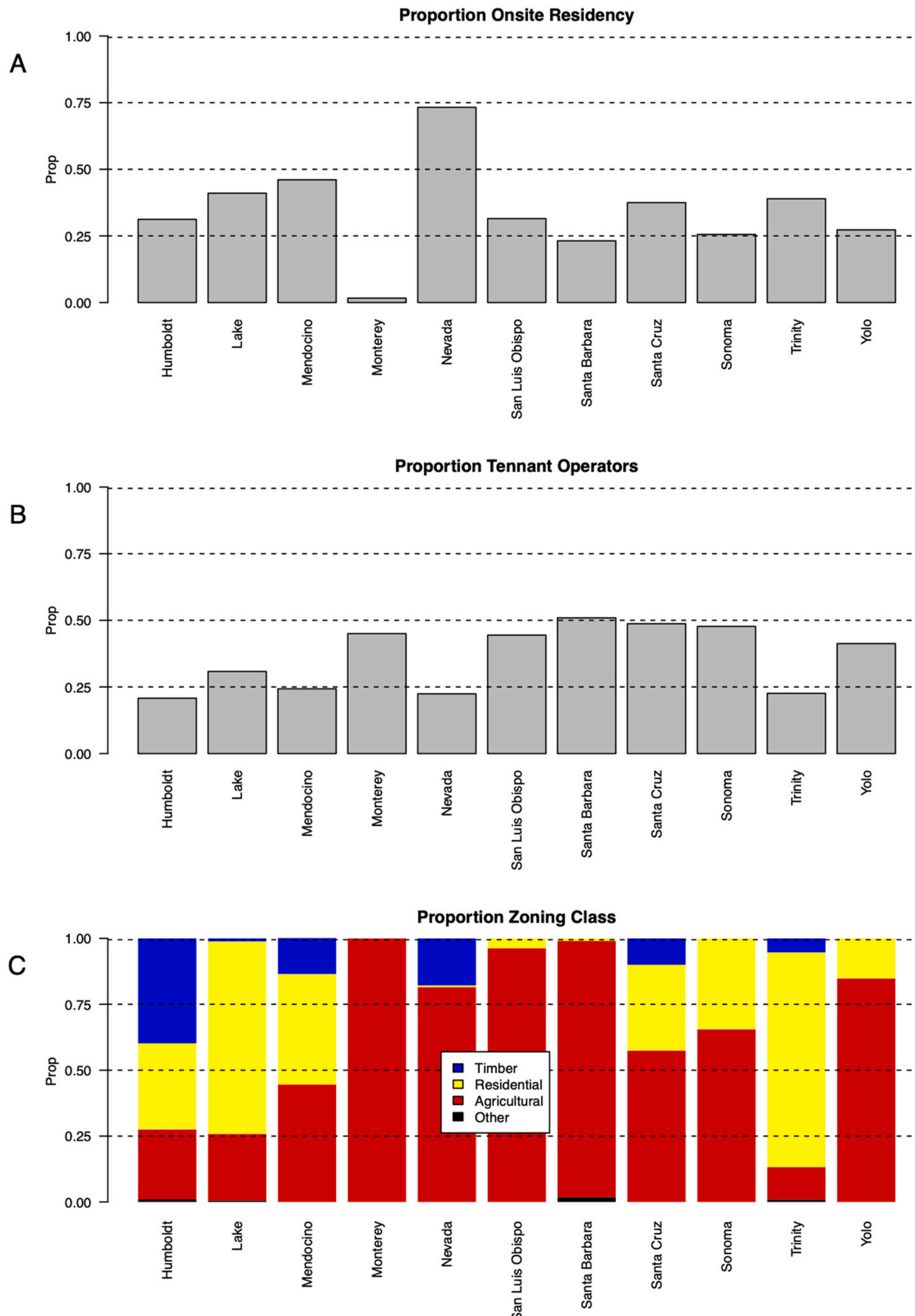

Fig. 3. Farm Characteristics by county. Proportion of farms in each county: (A) with permanent onsite residency, (B) with a non-landowner operator, and (C) within four different zoning classes.

average slope was by contrast, reliably negative (MLE = −1.28, SE = 0.58), decreasing the probability of enrollment overall. The only exceptions were in Humboldt and Mendocino counties, for which increasing *average slope* increased the probability of enrollment, likely due to a high prevalence of previously unpermitted farms among *existing* farms. To explore this further, the model was run again with *existing* farms excluded in Humboldt and Mendocino and the random slope estimates were reduced for both counties. *Stream density* had a reliably negative effect (MLE = −24.46, SE = 12.36) on the probability of enrollment, statewide. The random slope estimates for each county were also negative.

3.3. Geospatial predictors of cultivation area size

There was a reliably negative effect of Forest *land cover* on the predicted size of cultivation area (Table 3): relative to parcels with the dominant class of Herbaceous, predicted cultivation area was less for parcels with the classification of Forest (MLE = −0.42, SE= 0.14). There was a reliably positive effect of *presence of stream* (MLE= 0.09, SE= 0.03).

Among the continuous predictors, *parcel size* had a reliably positive overall (fixed) effect on the predicted size of cultivation (MLE= 0.67, SE= 0.10) on a statewide basis (Fig. 5). The random slope estimates for each county all predicted a positive relationship between *parcel size* and

Table 2
Summary statistics of enrolled parcels

County	Mean parcel size (Ha)	Mean avg. slope (%)	Mean dens. of streams (m per m^2)	% Forest	% Shrub	% Forest/ Shrub	% Herb	% Developed	% Planted
Humboldt	20.42 (B)	0.29 (E)	0.0023 (BC)	0.68 (E)	0.06 (A)	0.12 (A)	0.07 (A)	0.01 (A)	0.02 (A)
Lake	20.01 (B)	0.23 (CD)	0.0022 (BC)	0.22 (BC)	0.38 (C)	0.04 (A)	0.29 (BC)	0.01 (A)	0.01 (A)
Mendocino	16.28 (B)	0.25 (D)	0.0018 (B)	0.44 (D)	0.25 (B)	0.10 (A)	0.08 (A)	0.01 (A)	0.08 (BC)
Monterey	8.56 (A)	0.02 (A)	0.0014 (AB)	0.00 (AB)	0.00 (A)	0.00 (A)	0.05 (A)	0.66 (D)	0.23 (D)
Nevada	8.79 (A)	0.19 (BC)	0.0031 (CD)	0.79 (E)	0.07 (A)	0.07 (A)	0.05 (A)	0.01 (A)	0.00 (A)
San Luis Obispo	22.32 (B)	0.14 (B)	0.0025 (BCD)	0.10 (ABC)	0.10 (AB)	0.08 (A)	0.44 (CD)	0.00 (A)	0.24 (D)
Santa Barbara	21.59 (B)	0.16 (B)	0.0022 (BC)	0.03 (A)	0.19 (AB)	0.08 (A)	0.23 (A)	0.20 (C)	0.16 (D)
Santa Cruz	12.71 (AB)	0.21 (BCD)	0.0018 (ABCD)	0.40 (CD)	0.11 (AB)	0.00 (A)	0.14 (AB)	0.11 (BC)	0.20(CD)
Sonoma	21.76 (B)	0.21 (BCD)	0.0015 (AB)	0.30 (CD)	0.11 (A)	0.13 (A)	0.39 (CD)	0.01 (A)	0.03 (AB)
Trinity	9.87 (A)	0.21 (CD)	0.0032 (D)	0.37 (D)	0.39 (C)	0.11 (A)	0.05 (A)	0.02 (A)	0.00 (A)
Yolo	14.03 (AB)	0.05 (A)	0.0005 (A)	0.00 (A)	0.05 (A)	0.02 (A)	0.44 (D)	0.05 (AB)	0.39 (E)

Note: Summary statistics for continuous model parameters in both the binomial and negative binomial models. Land cover class values represent the percentage of parcels with dominant land cover (>50%) in each respective class. Letters depict statistically significant groupings within each parameter, based on Tukey HSD post-hoc analysis.

Table 3
Model outputs.

Coefficient	Probability of enrollment		Cultivation area	
	Estimate	Std. error	Estimate	Std. error
Intercept	**−3.06**	**0.89**	**10.79**	**0.27**
Stream Present	**0.52**	**0.06**	**0.08**	**0.03**
Land Cover: Forest	−0.24	0.38	**−0.42**	**0.14**
Land Cover: Forest/Shrub	0.10	0.39	−0.20	0.14
Land Cover: Shrub	0.03	0.37	−0.22	0.12
Land Cover: Planted	−0.31	0.38	0.12	0.13
Land Cover: Developed	−0.40	0.39	−0.12	0.16
Land Cover: None	−0.52	0.37	−0.17	0.14
Parcel Size	**0.97**	**0.39**	**0.67**	**0.10**
Average Slope	**−1.28**	**0.58**	**−1.64**	**0.36**
Stream Density	**−24.46**	**12.36**	**−22.76**	**0.57**

Note: Coefficient estimates for fixed-effects of the binomial and negative binomial models predicting probability of enrollment and size of cultivation area, respectively. Coefficients in bold are considered reliable (i.e. 95% confidence interval does not overlap zero).

cultivation area also. In contrast, the overall fixed-effect estimate for *average slope* was reliably negative (MLE= −1.64, SE= 0.36). Individual county-level estimates revealed a significant negative correlation between the intercepts and slopes ($r^2 = 0.81$), indicating that the negative effect of *average slope* on cultivation area was more pronounced at larger values of cultivation area. Finally, *density of streams* had a reliably negative effect (MLE= −22.76, SE= 0.57) on the predicted size of cultivation on a statewide basis and in all counties individually (Fig. 5).

4. Discussion

This study provides the first statewide analysis of the geography of legal cannabis cultivation in California, the ownership characteristics of permitted farms, and the potential factors influencing geographic variation in counties with legal production. We found that, since 2018, California's formalization of the cannabis industry has corresponded to rapid transformations in where and how cannabis is produced. Our results suggest a bifurcated development of legal cannabis production geographies. On the one hand, the most growth in the *number of permitted farms* has occurred in historical centers of production—Humboldt, Mendocino and Trinity counties. On the other hand, the greatest increase in *permitted production area* has occurred elsewhere, especially the Central Coast region (i.e. Monterey and Santa Barbara counties) where cannabis agriculture is relatively new. This growth in permitted area has been driven by the development of large farms, which now represent the majority of total cultivation area statewide. Most of these new, large farms are distinct from the smaller, owner-operated and owner-occupied model characteristic of historical cannabis producing regions, suggesting an alternative mode of farming that follows industrial agriculture models, in which operators do not live on the farm and tend to lease instead of own the farmed land (Varble et al., 2016).

Geospatial characteristics had statistically meaningful effects on the likelihood of a permitted cannabis farm occurring on a given parcel. Parcel size was a reliable positive predictor of enrollment. Selection of bigger parcels may be an approach to avoid resistance from neighboring parcel owners (Polson and Petersen-Rockney, 2019), a reflection of historical siting on large rural parcels to avoid detection by law enforcement (Corva, 2014), or may relate to the availability of terrain suitable for cultivation. Parcel terrain was also a reliable predictor of enrollment, with the likelihood of enrollment decreasing with greater average slope. The exceptions to this relationship were Humboldt and Mendocino counties, in which historical siting of farms made enrolled parcels more likely to occur on steep terrain (Butsic and Brenner, 2016). On a statewide basis, permitted farms appear to be preferentially operating on parcels that are both flatter and with fewer streams. These characteristics make the parcels more suitable to agriculture, but also less constrained by regulations (e.g., stringent environmental requirements for roads, stream crossings, and site development)—suggesting that both factors may be shaping where and how cultivation is occurring in the state.

Geospatial characteristics of parcels also predicted the scale of operations. There was a reliable effect of land cover type statewide, with forested parcels likely to have smaller cultivation area than those with mostly herbaceous land cover. This may be explained by the difficulty of clearing forest land for cultivation, which may be restricted by both regulations and cost. There was also a unanimous (among all counties) and reliable positive effect of parcel size on cultivation area, with larger operations tending to occur on larger parcels. With increasing parcel size comes more suitable terrain for potential cultivation. Similarly, parcel slope had a negative effect on size of cultivation area. The observation that this effect was stronger with increasingly larger farms indicates that siting particularly large operations likely requires flatter parcels, perhaps due to the site grading and permitting that would otherwise be required. Finally, the density of stream networks on a parcel had a negative effect on the size of cultivation area. This is likely explained by state regulations that require cultivation areas be sited as much as 46 m from watercourses in some cases (State of California, 2019b), which may

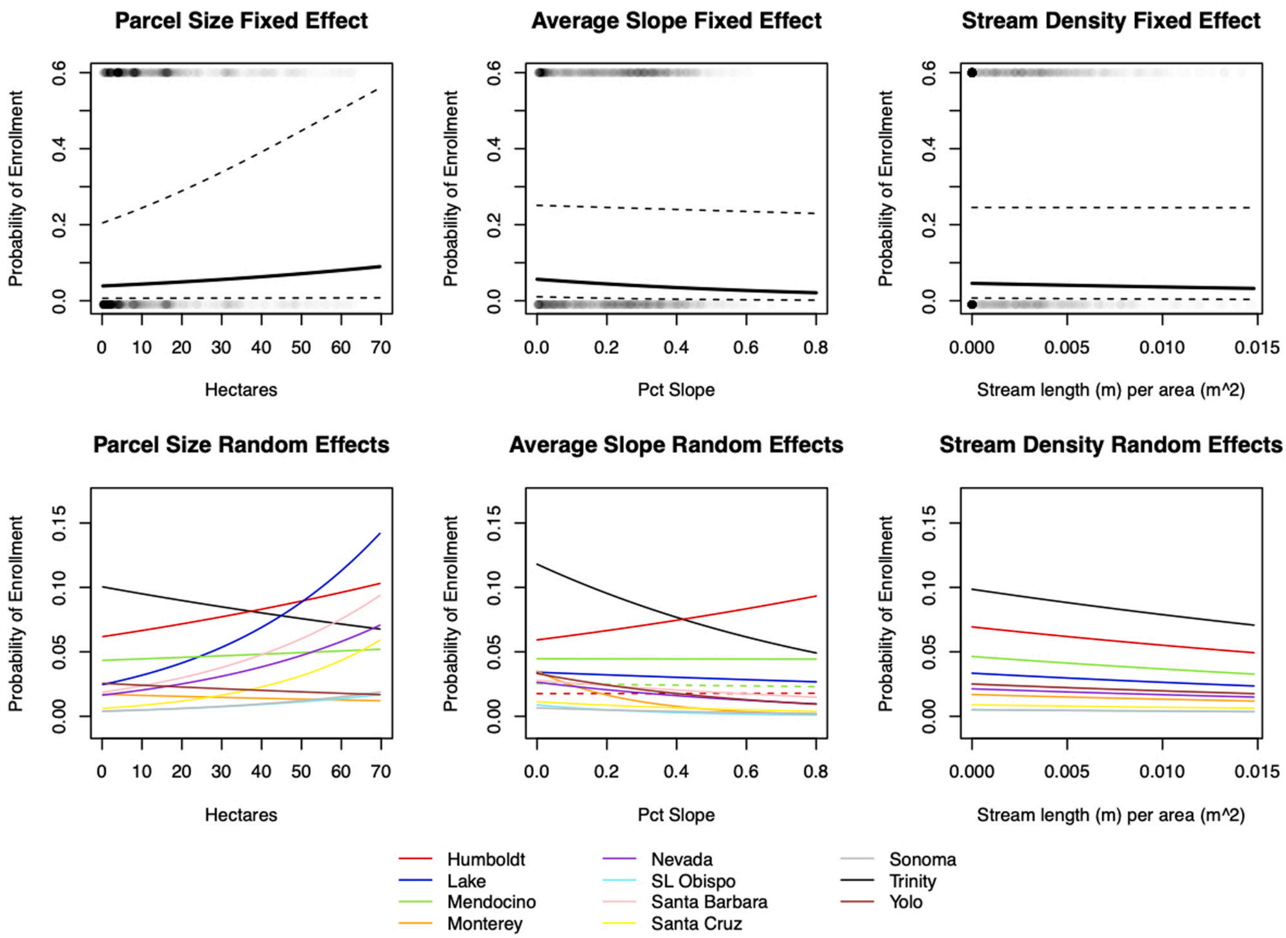

Fig. 4. Predictors of Enrollment. Both fixed effects and random effects are plotted for the continuous variables: *parcel size*, *average slope*, and *stream density*. Dashed lines depict the 95% confidence interval for the fixed-effects. Individual random effects (intercepts and slopes) for each county are depicted below the fixed-effects. The average slope estimates for Humboldt and Mendocino counties are depicted twice, with the dashed lines representing a second run of the model in which existing enrollments for these counties were excluded. The y-axes of random effects plots are reduced to increase resolution of inter-county differences.

reduce the area of land available for cultivation (and thus cultivation area size) on a given parcel.

4.1. Dual paths of development and the implications for production geography

Our study suggests that there are two emerging paths of development for the formalized cannabis industry, both of which were anticipated in pre-legalization discussions of "boutique" and "mass" cultivation subsectors (Polson, 2017). One is characterized by the presence of numerous, smaller, owner-occupied farms commonly in rugged, forested landscapes in the regions of historical cannabis production. The other is characterized by the emergence of fewer, larger farms on parcels in other regions in traditional agricultural zones, but with less history of cannabis cultivation, such as the Central Coast, and with fewer permanent onsite-resident and landowner-farmers. The geographic dimensions of these two paths are influenced by available land and local tenure patterns, but also appear to be affected by a host of other factors, particularly local permitting and land use requirements. This divergence in production models may be the result of specific objectives within the regulatory system that disincentivize large-scale farming on parcels located in environmentally sensitive areas.

It remains to be seen if either cultivation mode (small- or large-scale) will become dominant or if this bifurcated development pattern will continue. Costs and permitting requirements pose significant barriers to smaller, unpermitted farmers' abilities to enter the legal market (Bodwitch et al., In Review). The bulk of these costs are related to managing and addressing the potential environmental effects of farms in non-agricultural landscapes, such as, building culverts and engineering roads to protect nearby watercourses, holding inspections for protected species, establishing water storage systems to meet forbearance requirements, and remediating past unlicensed land uses (Bodwitch et al., In Review). Our results suggest that small farms entering the formalized industry will likely remain relatively small due to the terrain limitations and associated regulatory restrictions. That said, new competitive pressures may spur market and policy innovations to keep small farms feasible in the new formalized cannabis industry in California. State, third-party, and farmer-organized efforts to support small-scale farmers' access to markets, technologies and financial support, may increase the likelihood that historical cannabis regions will continue to produce cannabis under a formalized framework. Support for producer cooperatives, brand development, and other creative policy mechanisms to ensure farms of varied size can meet costs of production and avoid systematic indebtedness, have been shown to counter market-based pressures for industry consolidation in other sectors (Fischer and Qaim, 2012; Reed and Hickey, 2016; Wossen et al., 2017; Scaramuzzi et al., 2020; Stull, 2009). State efforts to support small farms, such as an appellations certification program (State of California, 2017; Stoa, 2018) are currently being developed. There are a host of other complications faced by small farms (e.g. lack of access to banking or credit, lack of savings, lack of administrative capacities), which will require innovative solutions if this mode of cannabis farming is to remain viable.

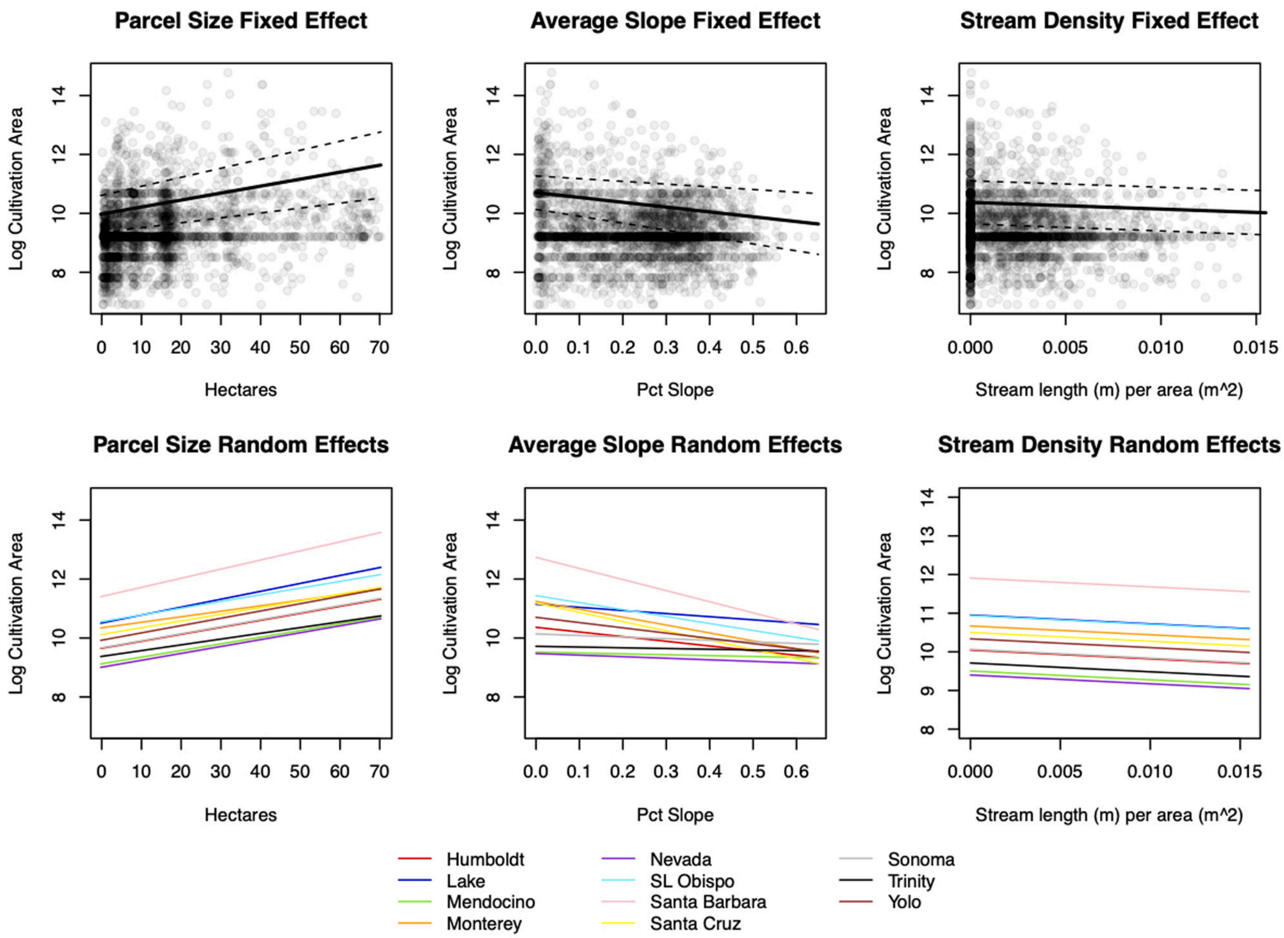

Fig. 5. Predictors of Cultivation Area. Both fixed effects and random effects are plotted for the continuous variables: *parcel size*, *average slope*, and *stream density*. Dashed lines depict the 95% confidence interval for the fixed-effects. Individual random effects (intercepts and slopes) for each county are depicted below the fixed-effects.

Costs and permitting requirements pose significant barriers to larger farms in new production regions as well (Bodwitch et al., In Review; Schwab et al., 2019). Farmers are likely to encounter unique political and regulatory challenges at the local level, especially in areas unaccustomed or opposed to cannabis cultivation. Particularly in counties closer to consumer centers, where relative population density may be higher, issues like odor from cannabis plants can cause significant tension (County of Santa Barbara, 2018). In flatter, agriculturally-dense regions, pesticide drift from other crops is already threatening to make cannabis crops ineligible to pass stringent quality and safety testing requirements (Valdes-Donoso et al., 2019). Access to credit and financing is a perennial issue for farms of all sizes, due to federal restrictions on cannabis and banking. As mentioned above, however, there are many factors that augment the trend toward larger farms: economies of scale, technological innovations, increasing organization and power to influence policy, as well as state policies like high taxes that pressure actors down the supply chain to seek lowest cost products (Henderson, 1998; Cochrane, 2003; Hauter, 2012). Though cannabis farms are currently small, relative to other agricultural crops statewide, trends toward larger farms in agricultural zones and without onsite residency, suggest the potential industrialization of cannabis production in California (Dillis et al., In Press).

4.2. Local control and inter-county variation in regulations

In addition to state-level cultivation policy, county-level regulation of cannabis farming has potential to shape the geography of the formalized cannabis industry in California and may at least partially explain the patterns observed here. State law gives counties broad powers to regulate or even prohibit most forms of cultivation and counties vary in how they have used that authority. A brief survey of county-level regulations (obtained from official county websites) for a subset of counties included in the current study reveals substantial inter-county variation (Table 4). Humboldt, one of the counties with the longest history of cannabis cultivation and a high proportion of small, previously unpermitted farms, has the most restrictive regulations in that it has a total cap on the county-wide sum of cultivated cannabis acreage, as well as caps on the size of individual farms, restrictions on the slopes that are permissible for cannabis farming, strict requirements for the standards and maintenance of the roads to access a farm, and a requirement of on-site residence for pre-existing farms. At the other extreme, Santa Barbara has among the least stringent requirements, with only a cap on total acreage and relatively general road and slope standards. Santa Barbara is also the county with the greatest growth of large, new farms. Thus, at least at the extremes, county regulations appear to play a role in influencing industry trends in California.

However, there are also some commonalities among county regulations that introduce uncertainties in interpreting the role of regulation in driving farm siting and size. All counties require some sort of discretionary review for the permitting process, where the local government can reject a project for a large number of reasons, as well as impose a wide range of conditions on a permitted project. Discretionary review means that permitting can be more or less stringent, more uncertain and time-consuming, and also trigger environmental review requirements. It

Table 4
County-specific regulations.

County	Cap on total acreage or permits	Cap on individual farm size	Permit required	Slope restrictions	Dwelling requirement	Road requirement
Humboldt	Acreage and permits	Yes	Use Permit	15% or less, up to 30% for preexisting	For small preexisting farms	Yes
Mendocino	No	Yes	Cannabis- specific	No	For some farms	No
Trinity	Permits	No	Cannabis-specific	Yes	Yes	No
Lake	No	Yes	Use Permit	No	No	Yes
Monterey	No	No	Administrative Permit	No	No	Limited
Santa Barbara	Acreage	No	Conditional Use Permit	Limited (through CUP)	No	Yes (through CUP)

Note: The top three rows represent counties with the largest number of new farms, also comprising the historical production center in Northern California. The bottom three rows represent counties that comprise the largest sum of new cultivation area. Six key characteristics of county-level cannabis regulation are provided: whether the county has a cap on the total amount of acreage or number of permits; whether the county has restrictions (either absolute or varying by zone) on size of individual farms; type of permit required for farms; categorical restrictions for cultivation on steep slopes; presence of an on-site dwelling required; and whether the county regulates the condition or maintenance of road access to a farm.

is hard to know how discretionary review actually shapes cannabis cultivation without cataloguing how it plays out in practice for specific projects, which has yet to be done. The universality of discretionary review makes clear that local governments see cannabis cultivation as a significant enough land-use activity to require careful scrutiny, likely in response to pressure from neighbors and communities and historic stigmas inherited from prohibition (Polson, 2015; Polson and Petersen-Rockney, 2019).

Still, variation in county-specific regulations does give some insights as to the types of regulations that are most impactful for shaping cannabis cultivation. Counties with caps on the total size of individual farms (Humboldt, Mendocino) have smaller farms than counties without those caps (Santa Barbara, Monterey). Likewise, counties requiring an on-site residence for permitting have higher rates of permanent on-site residency for cultivation. On the other hand, county road requirements and slope requirements do not appear to correspond with our findings. It is possible that the existence of overarching state requirements, which can be quite strict, overwhelm any impact from these county-level regulations.

While environmental characteristics are a key factor in siting decisions, those decisions (for the legal market) can only be made within the confines of county and state regulations. Given the variation in county and local regulation, it is difficult to confidently establish connections between specific regulations and land use and operational patterns of cannabis farms. In particular, discretionary review, which is widespread in California land-use regulation more generally (O'Neill et al., 2019), likely plays a large role that requires further investigation. Further research into siting decisions could survey the uneven regulatory landscape across localities and other factors, including proximity to consumer centers, land markets, local agricultural-economic dynamics (e.g. economic health of other agricultural sectors; county need for economic growth), and, given the still-controversial status of cannabis, political outlook.

4.3. Unpermitted cannabis production

While the focus of this study is the formalization of the cannabis industry, it is important to point out the large role unpermitted cannabis farms still play in California. Estimates of unpermitted production are more than 1.5 times the total amount of permitted cannabis produced in the state (Hudock, 2019). This unpermitted production comes from trespass grow sites on public lands, as well as unpermitted producers on private lands. While the total number of grow sites in each category is difficult to estimate, some experts report nearly 2000 trespass sites in California (McDaniel, 2019, Weber, 2019). Unpermitted sites on private lands are likely even more numerous. For instance, re-analysis of data used by Butsic et al. (2018) documents nearly 5000 unpermitted farms in just half of the sampled watersheds in Humboldt and Mendocino counties alone. There is some evidence that trespass grows have declined after legalization (Klassen and Anthony, 2019). Changes in the number of unpermitted grows on private lands is currently unknown, although research indicates that larger farms are generally much more likely to apply for permits than smaller farms (Schwab et al., 2019). Understanding how the development of the legal cannabis industry is influencing the number of sites, size, and distribution of illicit cultivation remains a critical research priority for California.

5. Conclusions

The formalization of the California cannabis industry holds broad relevance for several reasons. California is one of the world's largest agricultural producers generally, with substantial potential to be the leading producer of permitted cannabis as the worldwide industry continues to develop. Furthermore, the current and future exports of unpermitted and/or permitted cannabis from California will likely continue to impact nascent legal markets nation- and worldwide (Caulkins and Bond, 2012; Hudock, 2019). Finally, California's experience models how the transition from unpermitted to regulated cannabis production may occur elsewhere, especially where there is a similar history of illicit production. Strong environmental protections have been embedded in cannabis regulations (State of California, 2019a; 2019b), and our results indicate that the development of the legal cannabis industry in California has been responsive to state environmental and other local regulations during the first two years of formalization. Within California, where and how the formalized industry develops now will likely inform where expansion of the industry occurs in the future. The implications for the environment, farmers, and cannabis-growing communities are inextricably linked to this development.

Understanding geographical and operational trends is particularly important in light of the potential for federal legalization permitting interstate commerce. With the influx of capital investment that is likely to bring, we can expect the current trend toward large industrial-scale cannabis in California to continue. If small farms are to persist, farmer innovation and continued development of initiatives to support small farms will likely be needed to maintain parallel development trajectories during the formalization of the cannabis industry in California.

CRediT authorship contribution statement

Christopher Dillis: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project Administration. **Eric Biber**: Conceptualization, Investigation, Writing - original draft, Visualization, Funding acquisition. **Hekia Bodwitch**: Conceptualization, Investigation, Writing - original draft. **Van Butsic**: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Funding acquisition.

Jennifer Carah: Conceptualization, Writing - original draft, Visualization. **Phoebe Parker-Shames**: Writing - original draft. **Michael Polson**: Conceptualization, Investigation, Writing - original draft. **Theodore Grantham**: Conceptualization, Methodology, Formal analysis, Writing - original draft, Funding acquisition.

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