

PAPER • OPEN ACCESS

Cannabis farms in California rely on wells outside of regulated groundwater basins

To cite this article: Christopher Dillis *et al* 2021 *Environ. Res. Commun.* **3** 075005

View the [article online](#) for updates and enhancements.

You may also like

- [Cannabinoids detected in exhaled breath condensate after cannabis use](#)
Jennifer L. Berry, Ashley Brooks-Russell, Cheryle N. Beuning et al.
- [Cannabis \(*Cannabis sativa* or *C. indica*\) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts](#)
Van Butsic and Jacob C. Brenner
- [Water demands of permitted and unpermitted cannabis cultivation in Northern California](#)
Christopher Dillis, Van Butsic, Phillip Georgakakos et al.



PAPER

OPEN ACCESS

RECEIVED
25 February 2021

REVISED
21 June 2021

ACCEPTED FOR PUBLICATION
5 July 2021

PUBLISHED
21 July 2021

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Cannabis farms in California rely on wells outside of regulated groundwater basins

Christopher Dillis¹ , Van Butsic¹ , Jennifer Carah² , Samuel C Zipper³ and Theodore Grantham¹

¹ University of California Berkeley, Berkeley, CA, United States of America

² The Nature Conservancy, 830 S Street, Sacramento, CA, United States of America

³ Kansas Geological Survey, University of Kansas, Lawrence, KS, United States of America

E-mail: cdillis@berkeley.edu

Keywords: marijuana, agriculture, irrigation, groundwater, streamflow depletion

Supplementary material for this article is available [online](#)

Abstract

As permitted cannabis farming in California continues to expand statewide, including in ecologically sensitive watersheds, an improved understanding of water-use practices is needed. Existing evidence suggests widespread reliance on groundwater wells for cannabis irrigation may result in streamflow depletion, yet our understanding of where and why well use for cannabis is most prevalent is currently limited. Here, we use California state cannabis permitting data to address four important information gaps regarding well use by cannabis farming: (1) the prevalence of groundwater wells as an irrigation source for regulated cannabis farms statewide, (2) the extent to which groundwater use occurs outside of regulated groundwater basins, (3) the most useful predictors of whether a farm will rely on groundwater for irrigation, and (4) the potential well use from cannabis farms that are currently unpermitted. Well use by cannabis farms is common statewide, with percentages in excess of 75% among permitted farms in nine of the 11 top cannabis producing counties. In eight of these 11 counties, more than one quarter of farms using wells are located outside of groundwater basins subject to state groundwater use regulations. We found that cultivation area size was a positive predictor of well use, while annual precipitation and on-farm stream network density were negative predictors, highlighting the influences of water demand and surface water availability. The output of a machine learning model trained with data from permitted farms in Northern California suggests that the majority (60%) of unpermitted farms are likely to use groundwater wells if they follow the same patterns as the regulated industry. Our results suggest that proactive steps be taken to address groundwater use in cannabis regulations in California and call for further research into the effects of groundwater use on streamflow, especially outside of large groundwater basins.

Introduction

Irrigated agriculture is the largest consumer of freshwater globally, using up to 70% of all water withdrawals worldwide (Gruère *et al* 2020). Reliance on irrigation has allowed agriculture and food production to develop in regions that would otherwise be challenging for farming, such as arid regions of the Western United States. However, water withdrawals to satisfy irrigation demands can have negative environmental impacts by depleting groundwater (Konikow 2015, Ojha *et al* 2018), altering streamflow (Foglia *et al* 2013, de Graaf *et al* 2019), and harming fish and wildlife (Perkin *et al* 2017, Gleeson and Richter 2017). Limiting environmental impacts from irrigated agriculture while providing food, fiber, and other crop commodities for 8 billion people remains one of the greatest challenges for the 21st century.

This challenge is exemplified in California, which supports a \$50 billion (USD) agricultural economy that heavily relies on irrigation water supplied by federal and state surface water storage and conveyance projects and by extraction from large groundwater aquifers (Johnson and Cody 2015). Cannabis, however, is unique in

California because it generally occurs outside of valley and low-land areas typical of other agricultural crops and often does not have access to centralized water conveyance systems or regulated groundwater basins upon which the state's traditional agricultural sector relies (Butsic and Brenner 2016, Dillis *et al* in press). This pattern is a result of a history of enforcement-avoidance leading to the development of cannabis farms in remote areas, especially in Northern California (Corva 2014, Butsic and Brenner 2016). Although this industry is currently transitioning from an unpermitted to formalized statewide economy following implementation of a statewide regulatory framework in 2018, the geographic distribution of cannabis farms in California remains linked to a legacy of prohibition and exclusion from traditional agricultural lands (Dillis *et al* 2021).

The high density of farms in remote Northern California watersheds has raised concerns over the environmental impacts of cannabis cultivation (Carah *et al* 2015). In particular, previous work has demonstrated the potential for cannabis surface water diversions to reduce flows or dewater streams that support salmon and other threatened and endangered species (Bauer *et al* 2015). However, there is also growing evidence that cannabis farms in the regulated industry may rely predominantly on groundwater wells, rather than direct surface water diversions, to meet their irrigation needs (Dillis *et al* 2019). Compared to impacts of direct surface water diversions, the impacts from groundwater wells in the remote locations typical of many California cannabis farms are understudied and largely unregulated (Zipper *et al* 2019b). In these locations, well extraction by cannabis farms in upland areas may stress surface water resources and associated aquatic ecosystems by capturing groundwater that otherwise would have flowed into streams (Zipper *et al* 2019b), via a process known as streamflow depletion (Barlow and Leake 2012, Barlow *et al* 2018). Although the environmental impacts of groundwater use within large groundwater basins in California are addressed in the Sustainable Groundwater Management Act (SGMA, State of California 2014), these regulations do not extend to groundwater wells outside of these basins.

State cannabis cultivation policy and water use regulations, in particular, have been responsive to potential environmental threats (State of California 2019a, Bodwitch *et al* 2019), yet so far they have been focused largely on the diversion of surface water. For example, permitted cannabis farms are prohibited from extracting water from springs or streams for the duration of the outdoor growing season (April–October), necessitating that farms relying on these water sources have the storage capacity to collect and store all irrigation water in offseason months to sufficiently meet crop demands during California's dry season (State of California 2019a). Initial data from permitted farms in Northern California suggest there are challenges associated with developing the capacity to store this amount of water (often in excess of 400,000 liters for the typical farm size) in irrigation ponds or above ground storage tanks (Dillis *et al* 2020). While irrigation ponds typically provide sufficient storage, roughly only 10% of farms use ponds, as they are subject to many restrictions on siting and use (State of California 2019a, Dillis *et al* 2020). Thus, many growers may seek to access groundwater, which is not subject to the same seasonal use restrictions as surface water sources. There is also evidence that well use among cannabis farms is more common in drier regions, suggesting that farmers may be more likely to dig wells where the availability of surface water is less reliable (Dillis *et al* 2019). As a consequence, the geographic expansion of cannabis production to drier parts of the state (Dillis *et al* 2021), coupled with transition of cannabis farms to the regulated market, suggest that groundwater may be the primary source of water for cannabis irrigation throughout California, although no formal analysis of these trends have been conducted to date.

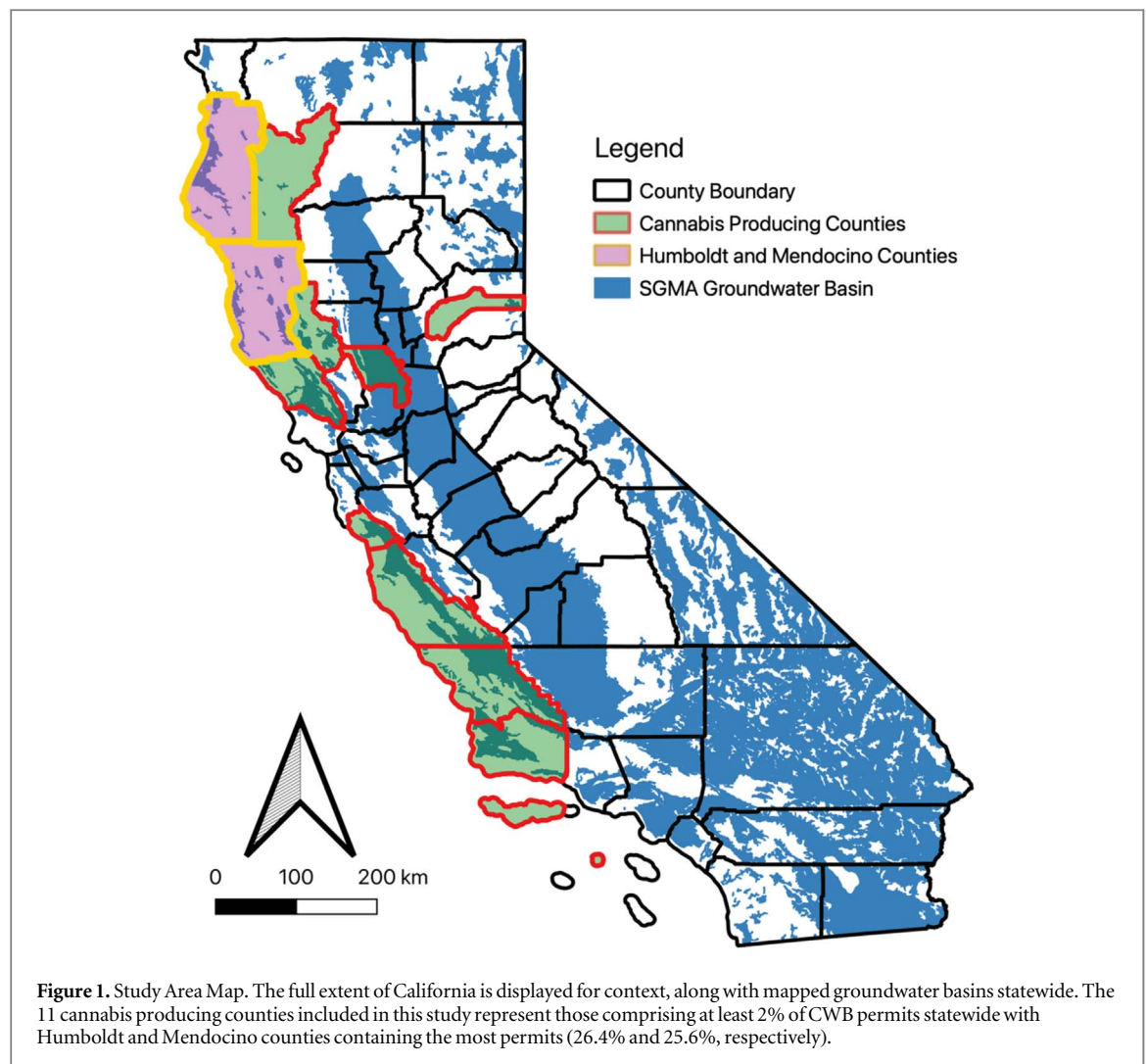
In Northern California, up to 80% of cannabis farms in the region have not received permits and remain in the illicit market (Butsic *et al* 2018). These unpermitted farms represent a large pool of prospective entrants to the regulated industry and regulatory agencies are actively engaging unpermitted farmers to incentivize their participation through enforcement actions, civil penalties, and targeted outreach (Bodwitch *et al* 2021). While data on farming practices of unpermitted farms in California remains limited (but see Wilson *et al* 2019), farms that have already become permitted may serve as a model for prospective new entrants to the regulated cannabis industry and provide insights into operations on currently unpermitted farms and how the growth of the regulated industry may influence water use practices and the environment.

In this study, we analyze cannabis cultivation permit data from 2018 and 2019 to understand well use among permitted cannabis farms in California. We explore drivers of well use and apply our findings to both the development of new permitted cannabis farms statewide, as well as the potential transition of a multitude of farms currently operating without permits. The overall goal of the study was to document the statewide prevalence of well use by cannabis farms and assess trends in well use by the regulated industry that warrant attention by local and state policymakers. Specifically, we addressed the following questions:

How prevalent is well use among permitted cannabis farms statewide?

How commonly does well use occur outside of regulated groundwater basins?

What are the most important predictors of well use among permitted cannabis farms?



What proportion of farms that are currently operating outside of the regulatory framework are expected to use wells if they follow the same patterns as farms in the regulated industry?

Methods

Data

Cannabis cultivation permit data were obtained via a Public Records Act request to the California Water Boards (CWB). We focused on enrollments from 11 counties, referred to hereafter as *cannabis producing counties* (figure 1), which collectively account for 98% of all CWB permits in California. Permit data included both enrollment forms and annual monitoring reports for the 2018 and 2019 cultivation seasons, each of which indicated the water sources used for irrigation. Enrollment data included geospatial coordinates of farms, which were overlaid on parcel data obtained from the National Parcelmap Data Portal (Boundary Solutions 2020). Data for location and size of unpermitted cannabis farms was collected through digitization of 2018 imagery from the National Agricultural Imagery Program (NAIP; Butsic and Brenner 2016). The data for unpermitted cannabis farms was collected for a representative sample (50%) of the watersheds (HUC12) in Humboldt and Mendocino Counties (Butsic *et al* 2018). Spatial data for statewide SGMA groundwater basins were downloaded from the California State Geoportal (State of California 2019b). GIS data used to quantify farm characteristics for model parameterization included Digital Elevation Models (DEMs) from the National Elevation Dataset (USGS 2018), vector watershed boundary and stream network data from the National Hydrography Dataset (USGS 2019), and land cover raster layers from the National Land Cover Dataset (Dewitz 2019). Finally, precipitation data (30-year annual averages) were downloaded from the PRISM Climate Group (PRISM Climate Group 2018).

Predictors of well use in Humboldt and Mendocino Counties

Our analysis of factors predicting the likelihood of wells as an irrigation water source employed a multilevel logistic regression model, fit using the lme4 package in R Statistical Computing Software (Bates *et al* 2014, R Core Development Team 2018). This analysis was restricted to two of the 11 cannabis producing counties, Humboldt and Mendocino (figure 1), which comprised the majority of permitted cannabis farms statewide (55%) and are the only counties where accessible, reliable maps of non-permitted cannabis farms exist (Butsic *et al* 2018). We calculated several continuous and categorical predictor variables for each permitted farm in these counties (Table S1 (available online at stacks.iop.org/ERC/3/075005/mmedia)) using the spatialEco package within R Statistical Computing Software (Evans 2020, R Core Development Team (2018)). Continuous predictors included: the density of stream networks on the farmed parcel (*Stream Density*; d), the average annual precipitation (*Watershed Precipitation*; t), catchment size of streams on parcel (*Watershed Size*; z) in which they were located, and the square footage of cultivation area (*Cultivation Area*; c) obtained from annual reports. Because cannabis is grown almost exclusively via irrigation from natural sources, *Stream Density* and *Watershed Precipitation* were intended to capture the amount of available surface water on a given parcel. *Cultivation Area* was used as a measure of water demand. All continuous variables were scaled (to Z-score) to improve model fit. Categorical predictors included: whether a USGS-mapped spring was located on the parcel (*Onsite Spring*; o), whether there were any streams on the parcel (*Stream Present*; s), whether there was a mapped groundwater basin underlying the parcel (*Groundwater Basin*; g), and whether the farm used an irrigation pond for water storage (*Pond*; p). As alternative water sources, *Onsite Spring* and *Stream Present* were hypothesized to decrease the likelihood a farm would need to use a well, while the presence of an underlying *Groundwater Basin* was expected to increase this likelihood, given that groundwater should be reliably accessible on these parcels. Previous work has found that the presence of an irrigation *Pond* significantly increased the likelihood a cannabis farm would have sufficient storage capacity to meet regulatory requirements (Dillis *et al* 2020), and thus herein, would reduce the likelihood a farm would use a well.

The generalized linear model (GLM) used a logit link function, predicting the likelihood of well as an irrigation source (P_i) using the following equation:

$$\text{logit}(P_i) = \alpha + \alpha_y + \alpha_w + \beta_d d + \beta_t t + \beta_z z + \beta_c c + \beta_p p + \beta_o o + \beta_s s + \beta_g g + \varepsilon \quad (1)$$

Fixed-effects terms for Stream Density (β_d), Watershed Precipitation (β_t), Watershed Size (β_z), Cultivation Area (β_c), Onsite Spring (β_o), Stream Present (β_s), Groundwater Basin (β_g), and Pond (β_p) were accompanied by random intercepts for County (α_y) and Watershed (HUC12; α_w) and added to the overall intercept (α). 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:

$$L = \frac{1}{1 + e^{\hat{p}}} \quad (2)$$

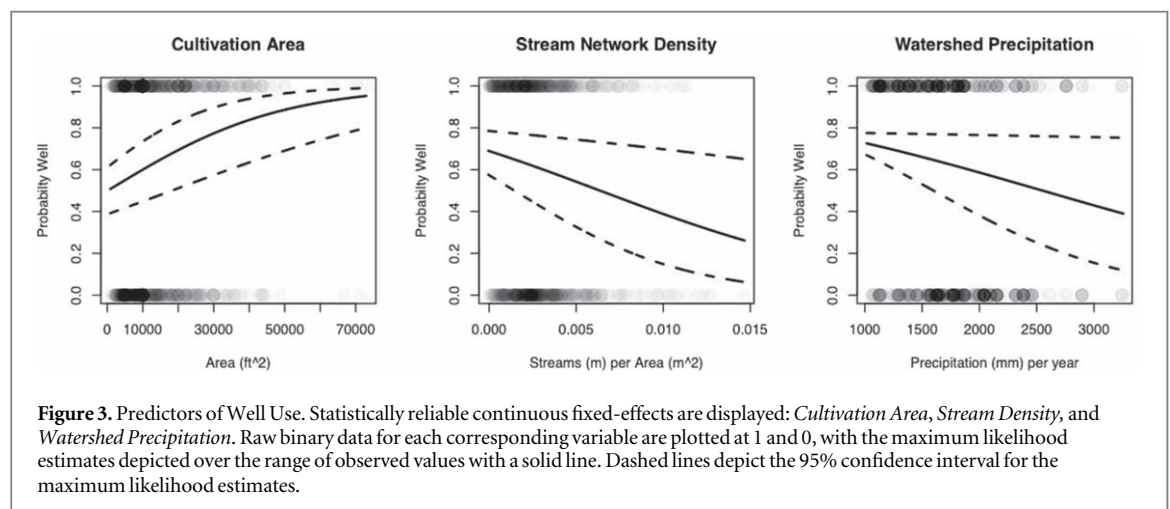
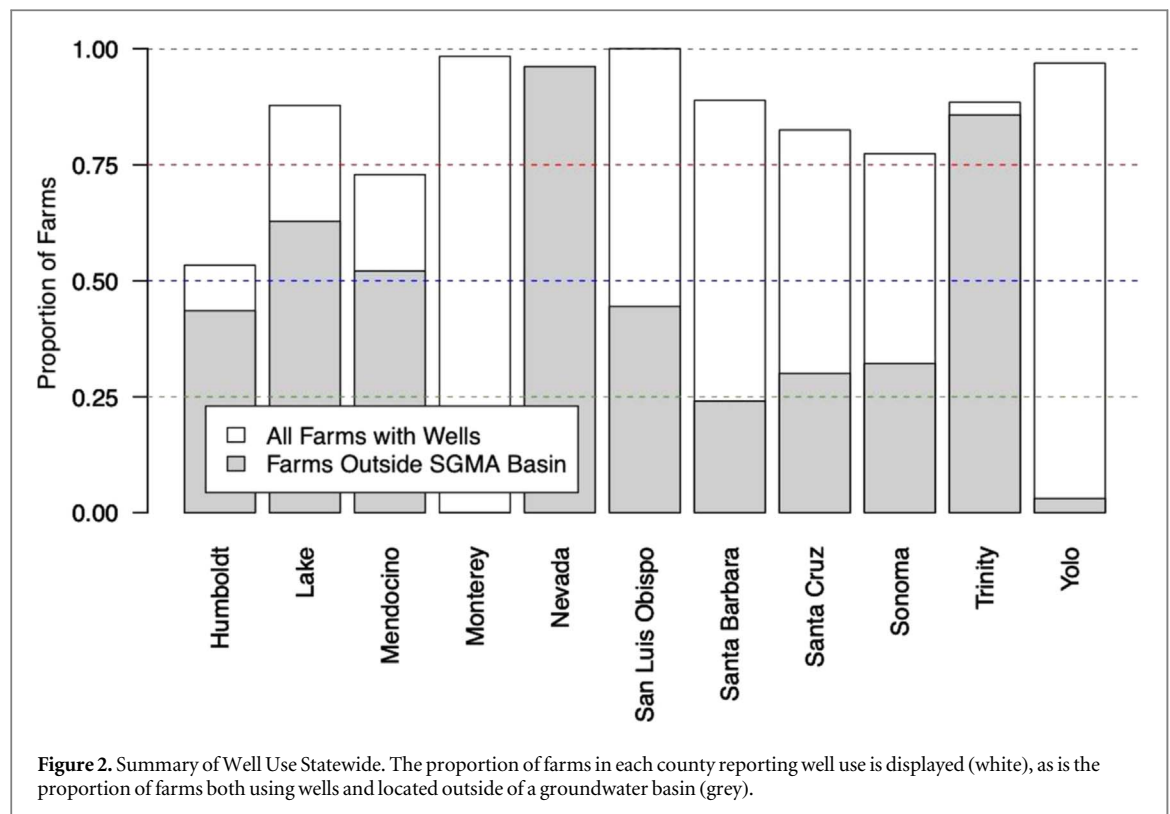
Model predictors were considered reliable if 95% confidence intervals, constructed from the standard errors, did not overlap zero.

Prospective well use and scenario modeling

Enrollment data was used to distinguish permitted cannabis farms ($n = 1,237$) from those operating without permits ($n = 6,010$), as of December 2019, for all mapped farms in Humboldt and Mendocino County (Butsic *et al* 2018). Predictions (well/no well) for unpermitted farms were generated using training data from current CWB permit holders and the same set of spatial variables (Table S1). Initial performance evaluation of the logistic regression model (based on k-fold cross validation) demonstrated an unacceptable level of bias (+8.74% toward predicting wells), thus motivating the use of machine learning models with more flexibility in structure and optimization.

The classification algorithm used for prediction (well/no well) employed an ensemble of random forest and gradient boosting models (Table S2), using the randomForest and xgboost packages (respectively) within R Statistical Computing Software (Liaw and Wiener 2002, Chen and Guestrin 2016, R Core Development Team (2018)). This ensemble model was evaluated using 1,000 iterations of k-fold cross validation sets (Figure S1) and the top performing model yielded a mean predictive accuracy of 72.13% (std dev = 1.73) and mean bias of -0.01% (std dev = 3.70).

The trained classifier was applied to mapped unpermitted farms and summarized at the HUC12 subwatershed scale to depict the potential extent and location of well use among unpermitted farms. Additionally, we made adjustments to farm characteristics to simulate three industry growth and regulatory scenarios. The first (*Minimum Farm Size Scenario*) is a scenario in which all unpermitted farms in the region increase their cultivation area to match the median size (929 m²) of those farms currently operating in the



regulated cannabis industry. The second scenario (*Restricted Pond Use Scenario*) considers how the use of irrigation ponds may be restricted as unpermitted farms enter the regulated industry. We identified all unpermitted farms with ponds located on steep terrain and/or near streams that would be prohibited under current regulations and assigned them to the ‘no pond’ class for model simulations. The suitability threshold was determined using values of average slope and stream network density from data on permitted farms with ponds. The third scenario (*Combination Scenario*) combined the first two scenarios, including an increase in minimum farm size and restrictions on pond use. Outputs of the three scenario simulations were summarized at the HUC12 watershed scale.

Results

Statewide patterns of well use

Well use was common, with an overall reported percentage of 76% among all permitted cannabis farms and percentages universally above 50% (figure 2) in all cannabis producing counties. Only two counties had reported percentages below 75% (Humboldt: 53%; Mendocino: 73%), while four counties were above 95% (Monterey: 98%; Nevada: 96%; San Luis Obispo: 100%; Yolo: 97%). There was more variation between counties in the

Table 1. Model coefficients. Results of logistic regression model predicting well presence. Rows in bold indicate coefficients for which 95% CIs did not overlap zero.

Coefficient	Estimate	Std. error
Intercept	0.54	0.34
Pond	−2.75	0.29
Onsite Spring	0.40	0.36
Stream Present	0.10	0.20
Groundwater Basin	0.48	0.25
Cultivation Area	0.40	0.08
Watershed Precipitation	−0.27	0.12
Watershed Size	−0.05	0.07
Stream Density	−0.28	0.09

percentage of farms using wells that were outside of SGMA groundwater basins. In three counties, fewer than 25% of the farms using wells were located outside of groundwater basins (Monterey: 0%; Santa Barbara: 24%; Yolo: 3%), whereas four counties recorded more than half of all farms using wells outside of groundwater basins (Lake: 63%; Mendocino: 52%; Nevada: 96%; Trinity: 86%; figure 2).

Predictors of well use in Humboldt and Mendocino County

The logistic regression model indicated that the most influential predictor of well use was the presence of an irrigation *Pond*, which had a reliable negative effect on the likelihood of well use ($MLE = -2.75$, $SE = 0.29$). This Maximum Likelihood Estimate translates to a reduction from a 63.18% baseline likelihood of well use to just 9.85% for farms with irrigation ponds (table 1). Three of the four continuous predictors had reliable effects on the likelihood of well use (figure 3). The effect of *Cultivation Area* was reliably positive ($MLE = 0.40$, $SE = 0.08$), whereas *Watershed Precipitation* ($MLE = -0.27$, $SE = 0.12$) and *Stream Density* ($MLE = -0.28$, $SE = 0.09$) had reliably negative effects on the likelihood of well use. The random intercept estimates for Humboldt ($MLE = -0.39$) and Mendocino ($MLE = 0.32$) counties diverged in opposite directions from the overall intercept, following the pattern of observed well use (figure 2), indicating a higher likelihood of well use in Mendocino compared to Humboldt County, all else equal.

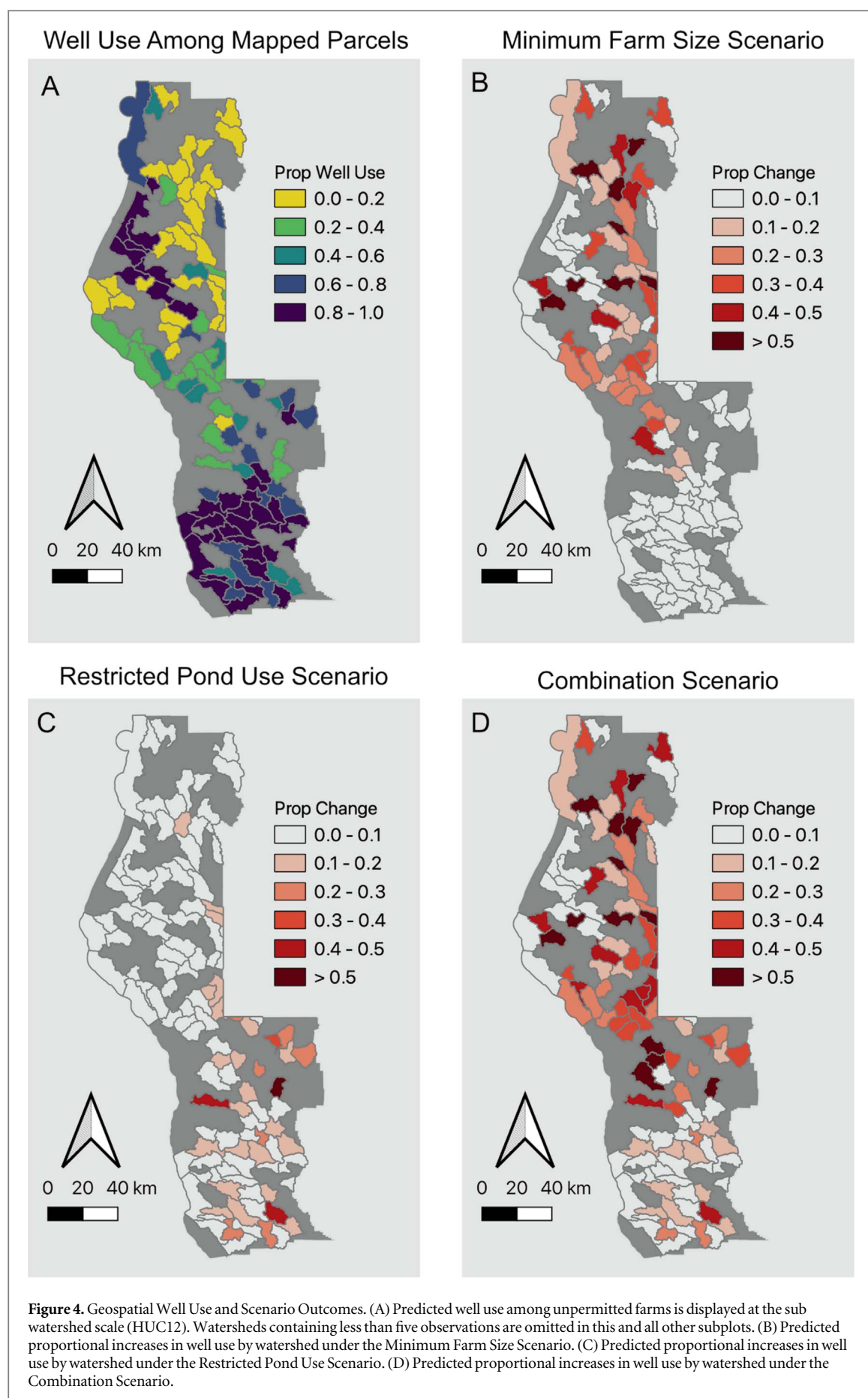
Prospective well use and scenario modeling

Based on the characteristics of permitted farms that influenced well use in our model, we estimated that over half of unpermitted farms (60%) in Humboldt and Mendocino counties are likely to use wells if they follow patterns of farms in the regulated industry. The majority of farms predicted to use wells in these counties (73% in Mendocino County; 77% in Humboldt County) were located outside of a SGMA groundwater basin, and thus not subject to SGMA regulations. The results of the scenario modeling showed dramatic increases in well use overall relative to the baseline predictions, but there appear to be divergent causes of predicted increases in either county (figure 4, table 2). In Humboldt County there was a proportional increase in predicted well use of 23% for the *Minimum Farm Size Scenario* relative to the baseline prediction, while in Mendocino this increase was 6%. In contrast, the increase for *Pond Restriction Scenario* relative to baseline was only 3% for Humboldt, but 11% for Mendocino.

The distribution of potential baseline well use among unpermitted farms, summarized at the subwatershed level demonstrated a slight tendency for clustering at high and low values (figure 5(A)). Median values of well use in each watershed increased relative to the baseline (56%) under the *Minimum Farm Size Scenario* (69%) and *Pond Restriction Scenario* (70%) and were highest in the *Combination Scenario* (86%; figure 5(B)–(D)).

Discussion

We found that groundwater wells appear to be the primary water source for cannabis irrigation across the state, but that many wells occur outside of SGMA-regulated groundwater basins. This suggests that many cannabis farms rely on wells that are subject to limited regulatory oversight and highlights a potentially significant gap in cannabis cultivation policy. In particular, current water-use regulations are designed to avoid impacts to sensitive stream habitats from surface water diversions via a summer forbearance period prohibiting surface diversions for the length of the dry season (contemporary with the growing season) (State of California 2019a). However, the use of wells, especially outside of SGMA basins, is not subject to the same restrictions, despite the potential for groundwater withdrawals to deplete streamflow.



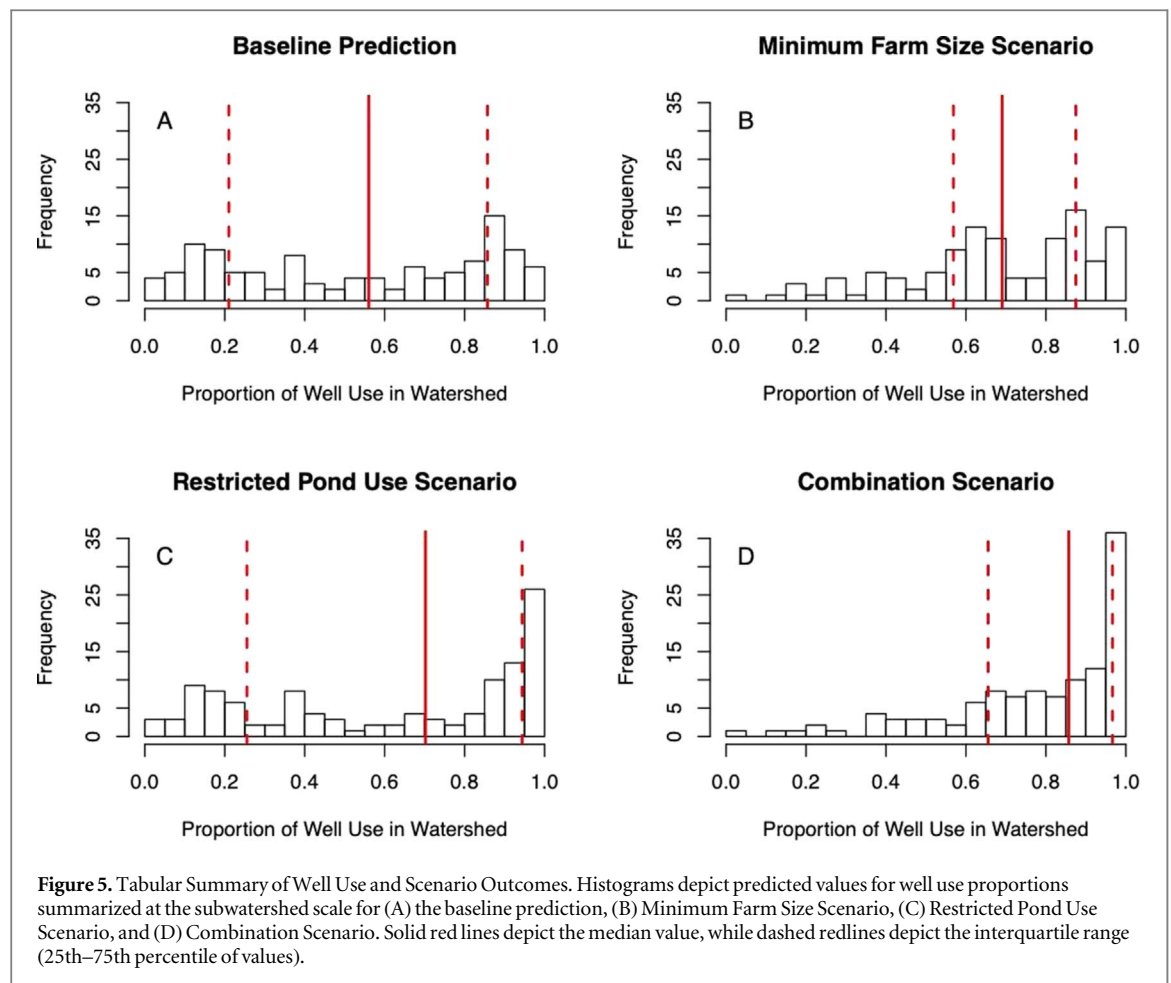


Table 2. Ensemble model predictions. Predicted proportions of well use, overall, and summarized by county.

	Baseline well use prediction	Minimum farm size scenario prediction	Pond restriction scenario prediction	Combination scenario prediction
Overall	0.60	0.72	0.67	0.82
Humboldt County	0.38	0.61	0.41	0.66
Mendocino County	0.71	0.77	0.82	0.90

We also found that well use was not uniform across the landscape and that environmental factors can play an important role in influencing farmer decisions to use groundwater wells. Based on our analysis of well use in Humboldt and Mendocino Counties, we found that farms with less access to streams and lower annual precipitation increased the likelihood of groundwater wells. Model results also indicated that farm size had a positive effect on well use. These findings are consistent with patterns observed in the rest of the state, where high rates of well use correspond to regions of lower annual precipitation and larger farm sizes (Dillis *et al* 2021). In Humboldt and Mendocino Counties, farms with ponds had a significantly lower likelihood of well use, consistent with findings reported by Dillis *et al* (2020), who found that irrigation ponds in the region were consistently large enough to meet dry season irrigation demands, thereby precluding the need for using groundwater. However, similar to those findings, only a small fraction (14%) of farms in the current dataset actually had irrigation ponds, while the majority of farms used wells.

As the cannabis industry in California continues to transition from unpermitted production to a regulated agricultural sector, groundwater is likely to remain the primary water source for cannabis irrigation. Although the current use of wells by unpermitted farms is unknown, the proportion of farms is likely similar to permitted farms if it is assumed that the environmental factors that lead permitted farms to use wells - such as the lack of surface water and low rainfall - have the same effect on unpermitted farms. The well use models for Humboldt and Mendocino Counties further suggest that the transition of unpermitted farms to the regulated market will increase the prevalence of well use, especially if unpermitted farms increase in size and change water use practices to avoid surface water diversion and storage requirements. In particular, unpermitted farms currently

using wells may face fewer obstacles in obtaining permits than those currently relying on surface sources that are either unable or unwilling to build water storage infrastructure.

A central question and major source of uncertainty related to reliance on groundwater by cannabis farms in California is the extent to which well use threatens streamflow and sensitive species. While most studies of streamflow depletion have focused on heavily-extracted aquifers with substantial row-crop agriculture (i.e., Foglia *et al* 2013, Tolley *et al* 2019, Zipper *et al* 2021), pumping in upland settings more characteristic of cannabis cultivation has also been shown to cause potentially significant streamflow depletion (Zipper *et al* 2019a, 2019b). In areas such as California with a seasonally dry climate, groundwater sustains summer baseflow in streams and provides crucial cold water habitat for aquatic species, including salmon and steelhead protected under the federal Endangered Species Act (Burns *et al* 2017, Larsen and Woelfle-Erskine 2018, Lovill *et al* 2018). Naturally low dry-season flows are highly vulnerable to surface water diversions, when even small water withdrawals can cause stream drying (Gasith and Resh 1999). Groundwater withdrawals can have similar effects as surface water diversions, but unlike direct surface water withdrawals, streamflow depletion is typically lagged and dampened relative to the time at which pumping occurred due to the slow movement of water through the subsurface, making it difficult to predict impacts (Reeves *et al* 2009, Barlow and Leake 2012, Konikow and Leake 2014, Zipper *et al* 2018). The lagged and damping effects will typically be greatest when wells are far from streams or in materials with lower hydraulic conductivity, and lags between pumping and streamflow depletion range widely, from hours to years (Barlow and Leake 2012). Generally, however, depletion will be greater for wells with larger pumping rates, located closer to streams, and situated in hydrogeological substrates with greater hydraulic conductivity (Bredehoeft 2011). Although well location data are exceptionally sparse, limited records from Northern California indicate that wells are preferentially located close to streams (Table S3). The tendency for wells to be drilled near streams, where they have the potential to cause rapid streamflow depletion similar to direct surface water diversions, warrants greater attention and should be addressed in policies that regulate both cannabis and non-cannabis water users.

The difficulty of addressing streamflow impacts from wells is exacerbated by a legacy of California water policy that has limited the state's authority to regulate groundwater use compared to the regulation of surface water resources (Owen *et al* 2019). Furthermore, given the context dependency of groundwater pumping impacts, a universal standard for streamflow protection remains elusive, making it more difficult to craft reasonable and effective statewide policy (Gleeson and Richter 2017). It is important to acknowledge that within groundwater basins, especially large basins regulated under SGMA, the relative demand (and potential impact) from cannabis farms is and will remain small relative to other agricultural sectors, given the much smaller footprint of cannabis farms (Butsic *et al* 2018). However, the use of unregulated groundwater wells for cannabis cultivation outside of groundwater basins, especially where wells are located near streams (Zipper *et al* 2019a), and where farms are clustered (Butsic *et al* 2017), distinguish this form of groundwater use as a potential concern for streamflow depletion, particularly for streams that harbor sensitive species.

Concerns over streamflow depletion are exacerbated by projections of future climate change in California. The prospect of reduced precipitation or changes in precipitation seasonality and variability may have foreseeable consequences for irrigation sources used by cannabis farms. California experienced record drought from 2012–2016 and is currently entering another historically severe drought event (Luković *et al* 2021). Climate projections for California indicate that annual precipitation extremes are likely to become more common (Swain *et al* 2018). While the occurrence of wet years would be welcomed by farms relying on surface water, the potential for increased frequency of drought years raises the threat of annual water insecurity. In other agricultural sectors, drought is known to significantly increase the frequency of well installations in subsequent years (Zipper *et al* 2017). Among cannabis agriculture in California, new evidence suggests that the likelihood of cannabis farms receiving enough precipitation to fill their allotted water rights will decline in the future (Morgan *et al* 2021), further incentivizing wells as a more consistently reliable water source.

The results presented herein could benefit from additional sources of data that are currently unavailable. First, the lack of data on unpermitted cannabis farms precludes our ability to directly evaluate their water use practices. Therefore, we are unable to determine the current extent to which unpermitted farms are using groundwater. Second, given the nascency of California's cannabis water policy, there is only a brief period of permitting record with which to examine how drought and projected increases in climate variability may affect irrigation practices by cannabis farms, as has been explored in other crops (e.g., Ajaz *et al* 2019, Saddique *et al* 2020). However, as the collection of water use data on cannabis farms continues, such analyses should be possible in the future.

Conclusions

Reliable access to irrigation water for cannabis is critical for farms participating in the regulated cannabis industry in California. Yet, methods to obtain water should also seek to avoid streamflow depletion and associated negative effects on aquatic ecosystems, particularly in remote natural areas that harbor sensitive species. While the prospect of regulating groundwater wells in upland areas outside of basins is fraught with legal and technical challenges, researchers and policymakers must engage what is likely to be an emerging issue in the regulated cannabis industry in California. In particular, more research is needed to understand where wells are located relative to streams and the contexts in which groundwater withdrawals cause streamflow depletion. Policies that address groundwater use should also be sensitive to regional variation in water availability and wherever possible, incentivize and facilitate water storage instead of or in conjunction with well use, as even modest storage capacity has the potential to reduce surface water diversions by almost 50% in the dry season (Dillis *et al* 2020). Finally, it should be recognized that, for some farms, wells may be the only viable water source available and therefore approaches to regulate groundwater use must balance concerns of streamflow impacts with the potential benefits of transitioning unpermitted farms to the regulated industry. Cannabis farming will continue to be challenged by water scarcity in California for the foreseeable future and it is important that steps be taken now to guide the development of a viable and environmentally sustainable legal cannabis industry.

Acknowledgments

This work was made possible in part through funding from the Resources Legacy Fund and the Campbell Foundation.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Christopher Dillis  <https://orcid.org/0000-0003-4208-5332>

Van Butsic  <https://orcid.org/0000-0002-6236-7313>

Jennifer Carah  <https://orcid.org/0000-0002-1453-5706>

Samuel C Zipper  <https://orcid.org/0000-0002-8735-5757>

Theodore Grantham  <https://orcid.org/0000-0002-9089-9026>

References

- Ajaz A, Taghvaeian S, Khand K, Gowda P H and Moorhead J E 2019 Development and evaluation of an agricultural drought index by harnessing soil moisture and weather data *Water* **11** 1375
- Barlow P M and Leake S A 2012 *Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow* (No. Circular 1376) (Reston VA: U.S. Geological Survey)
- Barlow P M, Leake S A and Fienen M N 2018 Capture versus capture zones: clarifying terminology related to sources of water to wells *Groundwater* **56** 694–704
- Bates D, Mächler M, Bolker B and Walker S 2014 *Fitting linear mixed-effects models using lme4* *arXiv preprint arXiv:1406.5823*
- Bauer S *et al* 2015 Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds *PLoS One* **10** e0120016
- Bodwitch H, Carah J, Daane K, Getz C, Grantham T, Hickey G and Wilson H 2019 Growers say cannabis legalization excludes small growers, supports illicit markets, undermines local economies *California Agriculture* **73** 177–84
- Bodwitch H, Polson M, Biber E, Hickey G and Butsic V 2021 Why comply? farmer motivations and barriers in cannabis agriculture *Journal of Rural Studies* (In Press) (<https://doi.org/10.1016/j.jrurstud.2021.05.006>)
- Boundary Solutions 2020 National Parcelmap Data Portal
- Bredehoeft J D 2011 Monitoring regional groundwater extraction: the problem *Groundwater* **49** 808–14
- Burns E R, Zhu Y, Zhan H, Manga M, Williams C F, Ingebritsen S E and Dunham J B 2017 Thermal effect of climate change on groundwater-fed ecosystems *Water Resour. Res.* **53** 3341–51
- Butsic V and Brenner J C 2016 Cannabis (*Cannabis sativa* or *C. indica*) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts *Environ. Res. Lett.* **11** 044023
- Butsic V, Carah J K, Baumann M, Stephens C and Brenner J C 2018 The emergence of cannabis agriculture frontiers as environmental threats *Environ. Res. Lett.* **13** 124017
- Butsic V, Schwab B, Baumann M and Brenner J C 2017 Inside the emerald triangle: modeling the placement and size of cannabis production in Humboldt County, CA USA *Ecol. Econ.* **142** 70–80
- Carah J K *et al* 2015 High time for conservation: adding the environment to the debate on marijuana liberalization *BioScience* **65** 822–9

- Chen T and Guestrin C 2016 Xgboost: a scalable tree boosting system *Proc. of the 22nd acm sigkdd international conference on knowledge discovery and data mining* 785–94
- Corva D 2014 Requiem for a CAMP: the life and death of a domestic US drug war institution *International Journal of Drug Policy* **25** 71–80
- Dewitz J 2019 National Land Cover Database (NLCD) 2016 Products: U.S. Geological Survey data release
- Dillis C, Biber E, Bodwitch H, Butsic V, Carah J, Parker-Shames P, Polson M and Grantham T 2021 Shifting geographies of legal cannabis production in California *Land Use Policy* **105** 105369
- Dillis C, Grantham T, McIntee C, McFadin B and Grady K 2019 Watering the Emerald Triangle: Irrigation sources used by cannabis cultivators in Northern California *California Agriculture* **73** 146–53
- Dillis C, McIntee C, Butsic V, Le L, Grady K and Grantham T 2020 Water storage and irrigation practices for cannabis drive seasonal patterns of water extraction and use in Northern California *J. Environ. Manage.* **272** 110955
- Dillis C, Polson M, Bodwitch H, Carah J, Power M and Sayre N 2021 Industrializing cannabis? socio-ecological implications of legalization and regulation in California *Routledge Handbook of Interdisciplinary Cannabis Research* ed D Corva and J Meisel (Philadelphia, USA: Routledge Press)
- Evans JS 2020 *spatialEco*. R package version 1.3-3
- Foglia L, McNally A and Harter T 2013 Coupling a spatiotemporally distributed soil water budget with stream-depletion functions to inform stakeholder-driven management of groundwater-dependent ecosystems *Water Resour. Res.* **49** 7292–310
- Gasith A and Resh V H 1999 Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events *Annual Review of Ecology and Systematics* **30** 51–81
- Gleeson T and Richter B 2017 How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers *River Res. Appl.* **34** 83–92
- de Graaf I E, Gleeson T, van Beek L R, Sutanudjaja E H and Bierkens M F 2019 Environmental flow limits to global groundwater pumping *Nature* **574** 90–4
- Gruère G, Shigemitsu M and Crawford S 2020 Agriculture and water policy changes: Stocktaking and alignment with OECD and G20 recommendations *OECD Food, Agriculture and Fisheries Papers, No. 144*, (Paris: OECD Publishing) (<https://doi.org/10.1787/f35e64af-en>)
- Johnson R and Cody B 2015 *California Agricultural Production and Irrigated Water Use* (Sacramento, California: Congressional Research Service) (<https://fas.org/sgp/crs/misc/R44093.pdf>)
- Konikow L F 2015 Long-term groundwater depletion in the United States *Groundwater* **53** 2–9
- Konikow L F and Leake S A 2014 Depletion and capture: revisiting ‘the source of water derived from wells’ *Groundwater* **52** 100–11
- Larsen L G and Woelfle-Erskine C 2018 Groundwater is key to salmonid persistence and recruitment in intermittent Mediterranean-climate streams *Water Resour. Res.* **54** 8909–30
- Liaw A and Wiener M 2002 Classification and Regression by randomForest *R News* **2** 18–22
- Lovill S M, Hahm W J and Dietrich W E 2018 Drainage from the critical zone: Lithologic controls on the persistence and spatial extent of wetted channels during the summer dry season *Water Resour. Res.* **54** 5702–26
- Luković J, Chiang J C, Blagojević D and Sekulić A 2021 A later onset of the rainy season in California *Geophys. Res. Lett.* **48** e2020GL090350
- Morgan B, Spangler K, Stuienvolt Allen J, Morrisett C N, Brunson M W, Wang S Y S and Huntly N 2021 Water availability for cannabis in Northern California: intersections of climate, policy, and public discourse *Water* **13** 5
- Ojha C, Shirzaei M, Werth S, Argus D F and Farr T G 2018 Sustained groundwater loss in California’s Central Valley exacerbated by intense drought periods *Water Resour. Res.* **54** 4449–60
- Owen D, Cantor A, Nylen N G, Harter T and Kiparsky M 2019 California groundwater management, science-policy interfaces, and the legacies of artificial legal distinctions *Environ. Res. Lett.* **14** 045016
- Perkin J S, Gido K B, Falke J A, Fausch K D, Crockett H, Johnson E R and Sandersn J 2017 Groundwater declines are linked to changes in great plains stream fish assemblages *Proc. Natl Acad. Sci.* **114** 7373–8
- PRISM Climate Group 2018 30-year normals of annual precipitation. Oregon State University
- R Core Development Team 2018 *R: A language and environment for statistical computing* (Vienna, Austria: R Foundation for Statistical Computing) (<https://r-project.org>)
- Reeves H W, Hamilton D A, Seelbach P W and Asher A J 2009 *Ground-water-withdrawal component of the Michigan water-withdrawal screening tool (Scientific Investigations Report No. 2009–5003)* (Reston VA: U.S. Geological Survey) 36
- Saddique Q, Li Liu D, Wang B, Feng P, He J, Ajaz A, Ji J, Xu J, Zhang C and Cai H 2020 Modelling future climate change impacts on winter wheat yield and water use: A case study in Guanzhong Plain, northwestern China *Eur. J. Agron.* **119** 126113
- State of California 2014 Department of Water Resources. Sustainable Groundwater Management Act
- State of California 2019a State Water Resources Control Board. Cannabis Cultivation Policy
- State of California 2019b California State Geoportal. 2019 SGMA Basin Prioritization Map
- Swain D L, Langenbrunner B, Neelin J D and Hall A 2018 Increasing precipitation volatility in twenty-first-century California *Nat. Clim. Change* **8** 427–33
- Tolley D, Foglia L and Harter T 2019 Sensitivity analysis and calibration of an integrated hydrologic model in an irrigated agricultural basin with a groundwater-dependent ecosystem *Water Resour. Res.* **55** 7876–901
- U.S. Geological Survey 2018 USGS TNM Elevation (NED), accessed March 1, 2020
- U.S. Geological Survey 2019 USGS TNM Hydrography (NHD), accessed March 1, 2020
- Wilson S, Bodwitch H, Carah J, Daane K, Getz C, Grantham T and Butsic V 2019 First known survey of cannabis production practices in California *California Agriculture* **73** 119–27
- Zipper S, Carah J, Dillis C, Gleeson T, Kerr B, Rhode M, Howard J and Zimmerman J 2019b Cannabis and residential groundwater pumping impacts on streamflow and ecosystems in Northern California *Environmental Research Communications* **1** 125005
- Zipper S C, Dallemagne T, Gleeson T, Boerman T C and Hartmann A 2018 Groundwater pumping impacts on real stream networks: testing the performance of simple management tools *Water Resour. Res.* **54** 5471–86
- Zipper S C, Gleeson T, Kerr B, Howard J K, Rohde M M, Carah J and Zimmerman J 2019a Rapid and accurate estimates of streamflow depletion caused by groundwater pumping using analytical depletion functions *Water Resour. Res.* **55** 5807–29
- Zipper S C, Gleeson T, Li Q and Kerr B 2021 Comparing streamflow depletion estimation approaches in a heavily-stressed, conjunctively-managed aquifer *Water Resour. Res.* **27** e2020WR027591
- Zipper S C, Smith K H, Breyer B, Qiu J, Kung A and Herrmann D 2017 Socio-environmental drought response in a mixed urban-agricultural setting *Ecology and Society* **22** 39