Eubank Creek, Humboldt County, CA, 2019. Example of stream morphology in the study area. Photo credit: Elijah Portugal, CDFW

Post Mountain, Trinity County, CA. Google Earth aerial images taken in the same location in 2007 and 2016 demonstrating land clearing for cannabis cultivation operations.

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Applied Science to Inform Management Efforts for Cannabis Cultivation, Humboldt, County, California

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Like other forms of commercial agriculture, recent work has shown that land use practices associated with cannabis agriculture can pose a risk to aquatic and terrestrial habitat for threatened and endangered species (Bauer et al. 2015; Carah et al. 2015; Butsic and Brenner 2016; Butsic et al. 2018). Potential impacts from cannabis agriculture vary widely among different types of cultivators, ranging from illegal, clandestine public land trespass grows, privately owned non-compliant cannabis farms, and cumulative impacts associated with privately owned farms in the regulated market (Bodwitch et al. 2018; Schwab et al. 2019).

The focus of much recent work has been investigating impacts from illegal public land trespass grows (Gabriel et al. 2012, 2013, 2018; Thompson et al. 2014) or has not differentiated between private land cultivators based on their level of regulatory compliance (Butsic and Brenner 2016; Wang et al. 2017; Butsic et al. 2018). This paper focuses on the preliminary findings of a larger study examining the impacts of cannabis cultivation on private lands in remote, forested watersheds of northwestern California that have supported decades of illegal cultivation and include both compliant and non-compliant cannabis cultivators.

Clandestine public land trespass grows have been associated with poisoning of terrestrial wildlife (Gabriel et al. 2012, 2013, 2018; Thompson et al. 2014), and both clandestine and non-compliant private-land growers have been associated with illegal forest conversions and habitat fragmentation (Wang et al. 2017; Butsic et al. 2018) to support cannabis cultivation. Commercially available agricultural fertilizers and pesticides not unique to cannabis can degrade water quality and cause additional impacts to sensitive aquatic species (USEPA 1994; Alvarez et al. 2008a,b). Cumulative water diversions to support cannabis agriculture pose a high risk of reducing or seasonally eliminating critical aquatic habitat (Bauer et al. 2015; Dillis et al. 2019; Zipper et al. 2019).

Cannabis farms that are in compliance with current policies established by the State Water Resources Control Board (SWRCB) (2019) attempt to minimize impacts by following best management practices. These include measures that avoid sedimentation and erosion (e.g., minimum setbacks from riparian areas and streams), institute a forbearance period from surface water diversions for cannabis during the low-flow season, and reduce inputs of pathogens and toxicants into streams. With cannabis being a newly legalized industry within the state, policies are continuing to evolve and will presumably require continued assessment and monitoring to ensure that the potential impacts of legal commercial cultivation are minimized.

The cannabis industry (permitted and unpermitted production) nearly doubled in area under cultivation from 2012-2016 in Northern California (Butsic et al. 2018) and the quantity and magnitude of stream diversions associated with this expansion, as well as the potential for other forms of cumulative impacts, requires an objective, data-driven management response from the California Department of Fish and Wildlife (CDFW). To meet the mandate for environmental monitoring and management of the emerging cannabis industry, CDFW is developing the California Environmental Monitoring and Assessment Framework (CEMAF), a statewide monitoring framework to assess potential impacts to aquatic and terrestrial habitat and communities from all forms of outdoor, greenhouse, and mixed light cannabis cultivation and other land uses. To inform the development of CEMAF and to test assessment and analysis methods novel to CDFW, the Fisheries Branch and Water Branch within CDFW initiated a pilot study in the Headwaters Mattole River watershed (Hydrological Unit Code 12 (HUC12): 180101070202) in May 2018 that concluded in October 2019. This research note solely summarizes the methods, analysis and discussion of the cannabis cultivation site mapping portion of the 2018 pilot study. The findings presented here, and the findings of the larger overall pilot study informed the development of CEMAF but are not a product of CEMAF, which is still in development.

We employed high resolution aerial imagery and simple GIS analysis to identify cannabis cultivation sites and assessed their likelihood to impact aquatic and terrestrial habitat at three spatial scales (e.g., individual farm scale, watershed and entire study area). The three spatial scales were selected to meaningfully summarize results for land managers and to scale up the results at the farm scale to the watershed scale and larger to compare the potential for cumulative impacts. For the purposes of this note, we assumed that the five metrics below and related hypotheses would correspond to the likelihood of impacts to the aquatic, and to a lesser extent terrestrial, environment in the study area due to cannabis cultivation.

1) Farm Attributes: size, operation type and presence of a pond. We assumed with all else being equal, that a farm with a larger footprint of disturbance would be more likely to cause impacts to surrounding terrestrial and aquatic habitat than smaller ones. We also assumed that the demographics of farm owners would correspond to farm size and that may influence the ability of a given farm to join the regulated market. The operation type (e.g., outdoor or greenhouse) and presence of a pond were also identified as these features influence the amount of water extracted from the watershed to support cannabis production (Dillis et al. 2019) leading to potential impacts to instream flow.

2) Proximity to critical habitat for steelhead (*Oncorhynchus mykiss*). With all else being equal, we assumed that a farm was more likely to impact aquatic habitat if it was located in close proximity to designated critical habitat for steelhead.

3) Slope: proportion of sites located on steep slopes. The potential for erosion, sediment delivery and runoff containing toxicants from cultivation sites and roads is assumed to be relatively higher when the site or road occurs on steep slopes (e.g., >30%) compared to a low-gradient valley setting (Walling and Webb 1983; Liu et al. 2000; Verstraeten

and Poesen 2001). Excess fine sediment negatively influences growth, reproduction and mortality rates at all trophic levels in the aquatic environment with direct and indirect effects to freshwater fishes (Kemp et al. 2011). Excess sedimentation has been shown to be particularly detrimental to salmonid spawning through filling interstitial spaces in gravel, leading to a decrease in available oxygen in developing redds (Suttle et al. 2004; Sear et al. 2008; Kemp et al. 2011).

4) Compliance: proportion of sites with a temporary permit from California Department of Food and Agriculture (CDFA). We assumed that the likelihood for impacts from an unregulated farm was higher than one in the legal market that is attempting to minimize impacts by adhering to SWRCB cannabis policy land use practices.

5) Road Metrics: We analyzed four additional metrics associated with potential impacts from the road networks within the study watersheds. Long-standing empirical evidence shows that unpaved forest roads are a significant anthropogenic contributor of sediment to the aquatic environment at both the local and watershed scale (Reid and Dunne 1984; Bilby et al. 1989; Luce and Black 1999). The length, location, age, construction practices, amount of use, basin geology, and precipitation characteristics have all been shown to influence the amount of sediment generated from roads, but in general road networks cause a net increase in watershed scale sediment production (Reid and Dunne 1984; Bilby et al. 1989; Wemple et al. 2001). Though paved roads with adequate cut slopes and ditches typically produce 1% of the sediment yield produced by gravel roads under heavy use with all other factors being equal (Reid and Dunne 1984).

We assumed that attributes of the road network in the study watersheds would influence the potential for erosion, sediment delivery and increased peak flows where higher road densities, more road crossings of the stream network and more unpaved surfaces would have a higher likelihood of impacting aquatic and terrestrial habitat. Specifically, we assumed that the potential for road-related sedimentation was higher in locations where the road network was in close proximity to the stream network compared to areas where the road was further away.

METHODS

Study Area

The pilot study took place in coastal Northern California within five small, intermittent tributaries (mean drainage area = 11.45 ± SE 3.37 km^2) to the headwaters of the Mattole River (HUC12:180101070202; Figure 1). The Mattole watershed was selected because of the long history of clandestine cannabis cultivation in close proximity to high value aquatic and terrestrial habitat. Study streams in the Mattole River watershed were selected to possess a range of cannabis cultivation densities and willing landowners to provide access to their farms to meet the objectives of the larger study. All five study watersheds in the headwaters of the Mattole River were included in the aerial imagery/GIS analysis and gauged for hydrological assessment and three of them (Eubank, McKee, and Van Arken) also received biological assessment, though those results are in preparation for a separate technical report and are not presented here. Van Arken Creek was included as a reference watershed where no cannabis cultivation was present.

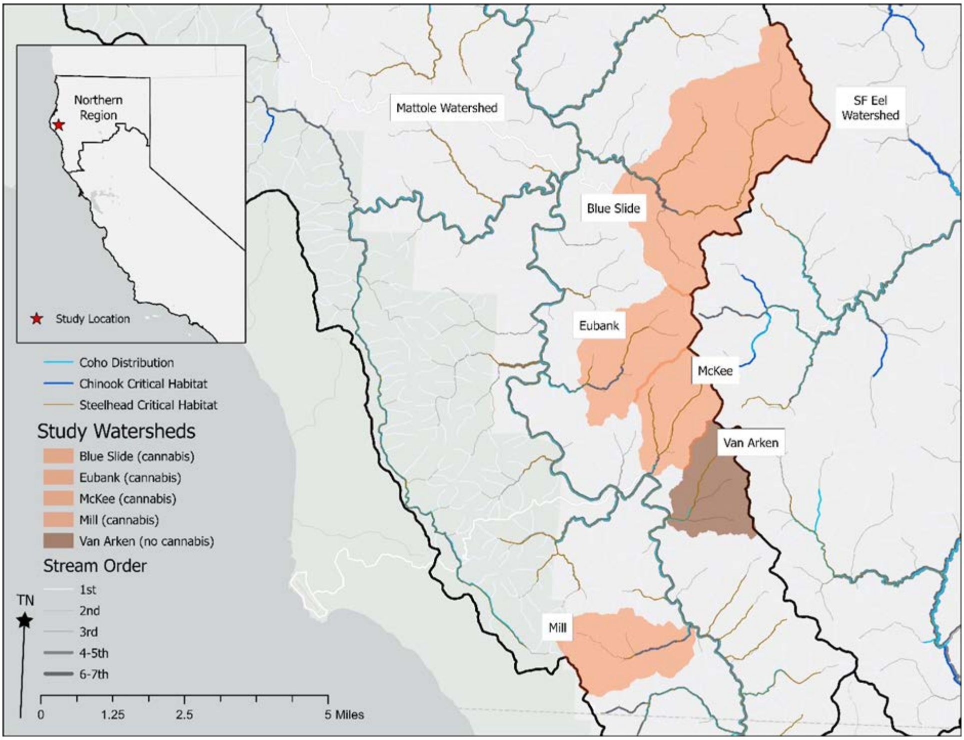

Figure 1. Map of watersheds included in the 2018 pilot study (n = 5). Peach fill indicates watersheds with known cannabis cultivation and brown fill indicates watersheds with no known cultivation.

Aerial Imagery Analysis/Geographic Information System (GIS)

Farm Attributes.—We manually digitized all cannabis cultivation sites (defined as individual greenhouses or outdoor gardens) identifiable from current aerial imagery within the five study watersheds by digitally tracing a polygon boundary around the footprint of each feature. Digitization included both compliant and non-compliant sites and all sites were attributed to a parcel or multiple continuous parcels which were then defined as a farm. A farm is defined as a discrete location that could contain multiple cultivation sites with greenhouses, outdoor gardens, and/or ponds. We followed the digitization methods developed in Bauer et al. (2015) and refined in Butsic and Brenner (2016) and in Butsic et al. (2018). We formalized this process by developing a guidance document for the manual digitization, storage and documentation of cannabis cultivation sites from aerial imagery (CDFW 2020 [mapping guidance doc]). We used both Google Earth (Google Maps 2018) and ESRI's ArcGIS mapping platforms (Esri 2018) to conduct the analysis.

In order to use the most current aerial imagery available to us within the study area, we primarily digitized in ArcGIS using ~ 30 cm resolution Digital Globe imagery (Digital Globe 2018) acquired on 25 April 2018 and 2 May 2018. We were concerned that we would not be able to adequately identify outdoor gardens using imagery acquired in April and May when outdoor plants may not be in place or are too small to individually identify. To address this, we cross-referenced the majority (~ 80%) of all sites identified from the April/May imagery with Digital Globe imagery acquired 9 October 2018, though this imagery did not cover all study watersheds. Thus 20% of sites could not be confirmed by the October imagery alone. This effort was to validate that greenhouses and outdoor gardens identified using the April/May imagery were under cannabis cultivation in October when outdoor cannabis plants attain their maximum size and are easier to identify. If any outdoor gardens identified using the April/May imagery did not show signs of cultivation from the October imagery, that site was deleted. Less than 10% of the outdoor gardens identified in April/May were deleted based on October imagery verification (i.e., 6 outdoor gardens were deleted of the 65 identified using April/May imagery). To address the 20% of sites that could not be verified with October 2018 imagery, we cross-referenced all cannabis sites identified in 2018 with Google Earth imagery from 28 May 2014 to gather more visual evidence that the sites identified from 2018 imagery were also under cannabis cultivation in 2014. This was not to determine a sites longevity but rather to provide more evidence that a site was growing cannabis and not a rural homestead with a large vegetable garden and greenhouse.

It is more difficult to detect outdoor gardens relative to greenhouses which are easily identifiable from aerial imagery. Though outdoor gardens do not appear to be the preferred operation type amongst cultivators in the study area with outdoor gardens only comprising 10.9% of all sites. It was impossible to confirm that all greenhouses identified were solely growing cannabis and not another greenhouse crop. There is evidence to suggest that it is unlikely that the greenhouses identified in the study watersheds are used for anything other than cannabis cultivation. For example, Butsic and Brenner (2016) compared the growth of greenhouses in Humboldt County from 2004–2014 to the growth of the nursery industry during the same period. They found the abundance of greenhouses increased 1900% while the value of nursery products in the county fell by 1.5% (Humboldt County 2015) indicating that greenhouses in Humboldt County were unlikely to be constructed and used for anything but cannabis. Though 2004–2012 is prior to the initiation of this study, the same logic applies in 2018, though it was not possible to verify the status of the non-cannabis nursery industry in Humboldt County from 2014–2018 because those data were not available. In many cases, it was possible to view historical imagery from sites that had been under cannabis cultivation for the last 5–10 years where we observed the transition from outdoor cannabis gardens to greenhouse cultivation.

Ponds associated with cannabis farms were also digitized within all study watersheds to use as input for a water extraction model (Dillis et al. 2019; CDFW, in prep.) though those results are not reported here.

1a) Farms with Ponds.—Dillis et al. (2019) showed that most cultivators in 2017 (n = 608) lacked the amount of storage (e.g., water tanks, bladders, and ponds) needed to meet late summer water demand unless they had a seasonal water source with a pond present. A seasonal water source was defined as rainwater catchment, springs, or surface water. If cultivators had a seasonal water source with a pond for storage, they were predicted to have a positive water storage balance for cultivation sites of up to nearly 0.4 ha (Dillis et al. 2019). As such, we identified all ponds visible during aerial imagery analysis of the study region.

1) Proximity to Critical Habitat

We calculated the distance of each cultivation site to NOAA/NMFS designated critical habitat for steelhead (National Marine Fisheries Service 2005) using the 'Near' tool in ArcGIS Desktop Version 10.5.1. The 'Near' tool provides the shortest geodesic distance and additional proximity information between each cultivation site relative to steelhead critical habitat. We summarized these data at the watershed scale and assumed that the likelihood of impacts to critical steelhead habitat from cannabis land use was relatively higher if the site was located within 45.7 m of critical habitat, which is the riparian setback distance required by the SWRCB (2019) Cannabis Policy of >45.7 m from perennial (Class I) watercourses.

2) Slope

To provide context of the study area's steep mountainous setting, slope rasters were generated from 10 m resolution Digital Elevation Models (DEMs) of each study watershed in ArcGIS to assess 1) mean watershed slope and 2) if each cultivation site occurred on a steep slope (>30%).

3) Compliance

For the purposes of this analysis we considered a farm in regulatory compliance if they possessed a temporary or annual cultivation license from CDFA. We assessed the proportion of sites that had obtained a temporary permit from CDFA using their license data for each parcel in the study watersheds. We then compared the license data with the locations of all cannabis cultivation sites identified from aerial imagery analysis to generate the % compliant metric at the watershed scale.

4) Road Metrics

We used two different methods to quantify road crossing metrics. The first metric examined the mean number of road crossings of NOAA/NMFS designated critical habitat for steelhead combined with locations where the road network was in close proximity (<15.2 m) to critical habitat (hereafter, "critical habitat roads metric"). The second metric did not consider critical habitat designation but included the number of road crossings of the perennial and intermittent stream network combined with the number of locations where the road came in very close proximity to the stream network (<15.2 m; hereafter "all roads metric"). We included the "all roads metric" because significant portions of the stream networks within the study watersheds extend upstream beyond the areas designated as critical habitat for steelhead and are in close proximity to the road network. These upstream portions of the stream network are hydrologically connected to the downstream critical habitat and are vulnerable to road-related sedimentation transported downstream into critical habitat.

We obtained the road network spatial data from Humboldt Counties GIS portal which is updated as needed (Humboldt County Building & Planning 2019). It was beyond the scope of this study to perform detailed road inventories required to generate quantitative predictions of sediment yield from the existing road network in the study watersheds. Instead, we generated four simple GIS metrics to assess the relative likelihood of road-related sedimentation and erosion impacts to sensitive aquatic habitat. These metrics were:

1) Road density (km/km^2),

2) Number of road crossings and locations where the road was <15.2 m from designated critical habitat for steelhead,

3) Number of road crossings and locations where the road was located <15.2 m from the perennial and intermittent National Hydrography Dataset (NHD) stream layer (not designated critical habitat),

4) Proportion of road network that is paved.

RESULTS

1) Farm Attributes

Within the study area at the regional scale, the total area under cultivation in 2018 was low (<1% of total drainage area; Table 1). There were 18.5 ha of cannabis cultivation in all four study sub-watersheds containing cannabis out of a total combined drainage area of 3,8401 ha (0.48% total drainage area). At the watershed scale, the total area under cannabis cultivation was also low (<1% total drainage area; Table 1). Of the watersheds with cannabis cultivation, Eubank Creek had the highest proportion of drainage area under cultivation (0.84%) and Mill Creek had the lowest (0.17%). One hundred and twenty-four farms were identified within the study area with a mean farm size of 0.12 ha.

1a) Farms with Ponds.—At the regional scale 11.4% of farms had a pond present. At the watershed scale, the proportion of ponds ranged from 6.7% (McKee) to 21.4% (Blue Slide; Table 1).

2) Proximity to Critical Habitat

The mean distance (± SE) of cultivation sites to critical habitat for steelhead across all study watersheds was 389.2 ± 65.2 m (Table 1). This is a substantially greater distance than the riparian setback distance of >45.7 m from perennial watercourses. For three of the four study watersheds containing cannabis, the mean distance to steelhead critical habitat was near the regional mean, with the exception of McKee Creek, which was considerably lower (mean distance = 175.3 ± 19.5 m; Table 1) when compared qualitatively. The proportion of sites <45.7 m from critical habitat for steelhead exhibited a similar trend with three of the four study watersheds containing cannabis having relatively low proportions (0-7.9%), while McKee Creek had the highest proportion with 25.8% of sites <45.7 m.

3) Slope

Though the total footprint of cultivation within the study watersheds was low, the location of farms relative to steep slopes (i.e., >30% slope) was moderate with 29.4% (n = 115) of all cultivation sites occurring on steep slopes. At the watershed scale, the proportion of sites considered steep varied from 19% (Eubank) to 36.2% (McKee). Mean basin slope for all watersheds is high (36.1% ± 1.39%). In comparison to the mean basin slope of each study watershed, cannabis sites tended to be located in less steep locations than the average slope conditions available within the watershed. Mckee Creek is an exception to this where mean basin slope and the proportion of farms considered steep were approximately equal.

Table 1. Summary of manual mapping results from study watersheds containing cannabis cultivation. (Note: Van Arken is not included because there is no cannabis cultivation in the watershed.)

Watershed	Drainage Area (km^2)	# Cannabis Farms	# Greenhouses (sites)	# Outdoor Gardens (sites)	Total Area Cultivated (ha)	% Drainage Area Cultivated	Mean Farm Area (ha)	% Farms with Ponds	Cultivation Site mean dist. to Steelhead Critical Habitat (m)	% Cultivation Sites <45.7 m from Steelhead Critical Habitat	% Cultiva-tion Sites >30% Slope	% Compliant
Eubank	6.2	27	146	13	5.2	0.84	0.19 ± .04	7.7	472 ± 22	1.3	19.0	63.0
McKee	5.4	16	55	10	1.9	0.36	0.12 ± .02	6.7	175 ± 20	25.8	36.2	35.3
Blue Slide	20.7	71	257	33	10.4	0.50	1.21 ± .02	21.4	397 ± 20	8.3	27.1	26.3
Mill	6.0	10	35	2	1.1	0.17	0.11 ± .02	10.0	513 ± 45	0.0	35.3	10.0
All Sites†	9.6 ±3.1×	124*	482*	59*	18.5*	0.50×	0.15 ± .01×	11.4×	389 ± 65×	8.8×	29.40×	33.6×

†Value in this row include both sums (denoted with *) and means ± standard error (denoted with ×).

4) Compliance

At the regional scale, 33.6% of all sites possessed either a temporary or annual license from CDFA and were considered compliant for this analysis (Table 1). At the watershed scale, the proportion of compliant sites in 2018 ranged from 10% (Mill) to 63% (Eubank; Table 1).

5) Road Metrics

Road Density.—At the regional scale, road density was 2.8 km/km^2 (Table 2) with notable variability between study watersheds. Van Arken, the reference watershed had approximately 2 times higher road density compared to the regional mean.

Road Crossings.—At the regional scale, the critical habitat roads metric was 2.2 ± 0.6 km/km^2 (Table 2). At the watershed scale, this metric ranged from 1 (Eubank) to 6 (Van Arken). We found that the all roads metric was higher than the critical habitat roads metrics in all study watersheds, with the exception of McKee Creek, where these metrics were equal to one another (Table 2). The regional mean for the all roads metric was 5.3 ± 2.0 km/km^2, which is greater than two times the value of the critical habitat roads metric.

Proportion Paved.— At the regional scale, the mean proportion of paved roads within the study watersheds was 10.9% ± 6.4% indicating that the vast majority of all roads in the study watersheds are unpaved. The regional mean is primarily driven by the high proportion of paved roads in McKee Creek (37.8%) and moderate proportion in Eubank (13.6%), while the rest of the study watersheds were essentially unpaved (0-2.8% paved).

Table 2. Summary of GIS derived metrics associated with potential impacts from the existing road network study watersheds.

Watershed	Road Density (km/km^2)	Road Crossings and Roads within 15.2 m of Critical Steelhead Habitat	Road Crossings and Roads within 15.2 of Stream Network (Perennial and Intermittent)	Proportion Paved
Eubank	2.49	1	2	13.6
McKee	2.24	5	5	37.8
Blue Slide	2.54	5	21	2.8
Mill	1.26	1	3	0.0
Van Arken	5.44	6	12	0.5
All Sites (mean)	2.79 ± 0.63	3.6 ± 0.96	8.6 ± 3	10.9 ± 6.4

DISCUSSION

Aerial imagery analysis of cannabis sites combined with simple GIS metrics represents a tractable methodology to assess relative risk of impacts from cannabis cultivation land-use to aquatic and terrestrial habitat in the study area. However, it was beyond the scope of this study to quantitatively rank each of the metrics in terms of their ability to describe impairment due to cannabis cultivation. The total footprint of cannabis cultivation within the study watersheds was low (<1% of total drainage area; Table 1) and average farm size was low (0.12 ha) with farms not generally located in close proximity to designated critical habitat (mean = 389.2 ± 65.2 m) and with relatively high levels of regulatory compliance (33.6%). This indicates that at the regional scale, the potential impacts from cannabis cultivation in the study area may be low. When viewed at the scale of individual study watersheds or individual farms, the potential for impacts is more variable. The location of many farms is problematic due to the proximity to designated critical habitat (Mckee Creek site mean distance = 175.3 ± 19.5 m), the steep headwaters setting of the study watersheds (mean basin slope = 36.1% ± SE 1.39%), and the presence of unpaved road networks with relatively high road density (2.8 km/km^2) that occur on steep slopes and cross-designated critical habitat.

1) Farm Attributes

The mean farm size in the study area was >2 times the mean farm size reported in Butsic et al. (2018). There are a few likely reasons for this disparity. Butsic et al. (2018) assessed a much larger area with far more farms compared to this study (n = 5906 and 124, respectively). Consequently, they were better able to capture the full range of variability in farm size throughout the cannabis producing regions in Northern California. The difference in farm size may also reflect regional differences in the cannabis industry. The Mattole River Watershed has been a cannabis cultivation hotspot for decades and established, multi-generational cultivators are more likely to have the resources to navigate the regulatory process and sustain larger farms relative to the cultivators that have entered the industry recently during the unregulated "Green Rush" of 2012-2016 (Butsic et al. 2018). Additionally, we were able to use slightly more recent imagery than Butsic et al (2016, 2018) and the trend in increasing farm size he documented would have likely continued in the few years between the studies.

The dominance of greenhouses in our study region (90% of all sites are greenhouses) is much higher than Butsic and Brenner's (2016) findings based on aerial imagery analysis from 2012-2013. They found the proportion of greenhouses to outdoor gardens was approximately equal (54% greenhouses). The discrepancy could be a matter of scale of the studies as mentioned previously, and/or also reflect a difference in the demographics of cultivators with more established growers in the Mattole watershed favoring greenhouses. It could also reflect broader changes in the cannabis industry since 2013 where there was a transition to relatively more greenhouse production from a previously even distribution of outdoor gardens and greenhouses. This is consistent with Butsic et al. (2018) where they documented a 248% increase in the amount of plants grown in greenhouses from 2012-2016 relative to total plant increase (greenhouses and outdoor gardens) of 183%. Greenhouse production allows for a longer growing season, more harvests per year, and potentially higher yields compared to outdoor gardens.

1a) Farms with Ponds.— The vast majority (88.6%) of cultivators in the study area in 2018 likely did not have enough storage to meet late summer water demands as evidenced by the lack of ponds. Consequently, it is also likely that water extraction for cannabis occurred during the critical low flow period of July through October 2018. We also assume that well use occurred during the low flow period though it was beyond the scope of this study to determine the total number of well users and the magnitude and frequency of groundwater diversion. We also did not examine the level of hydrologic connection between groundwater and surface water in the study watersheds. The magnitude and intensity of water extraction during the low flow period cannot be verified with absolute certainty because we could not inventory all water sources or storage infrastructure for all cultivators but our findings are consistent with Dillis et al. (2019) who showed that most cultivators (n = 608) enrolled with the North Coast Regional Water Quality Control Board lacked the amount of storage (e.g., from water tanks, bladders, and ponds) needed to meet late summer water demand unless they had a seasonal water source with a pond present.

The difference in the location and density of ponds amongst study watersheds may relate to characteristics of the underlying lithology which has been shown to influence a watersheds ability to store water as groundwater in the winter and slowly release that water as baseflow in the late summer (Davenport et al. 2002, Lovill et al. 2018). For example, Blue Slide creek had the highest proportion of sites with ponds (21.4%) compared to the regional average (11.4%) and is underlain by a mélange rock type with lithology associated with low levels of groundwater storage. With relatively less groundwater available in late summer in Blue Slide Creek relative to other study watersheds underlain by rock types that can support higher levels of groundwater storage (Hahm et al. 2019), a pond is necessary to store surface and groundwater collected in the wet winter months to meet late summer plant demand.

2) Proximity

The mean distance of cultivation sites to critical habitat for steelhead across all study watersheds was 8 times greater distance than the 45.7 m riparian setbacks required by SWRCB Cannabis Policy (2019) for perennial (Class I) watercourses. An exception to this was McKee Creek, possessing the highest proportion of sites (25%; n = 17) located <45.7 m from critical habitat for steelhead. Four out of five study watersheds possessed a very similar proportion of available steelhead habitat within the drainage network. Again, this is evidence of the variability of potential impacts from cannabis cultivation when viewed at multiple spatial scales.

3) Slope

High mean basin slope of the study watersheds coupled with underlying lithology that is highly erosive (Davenport et al. 2002) in a climate with high intensity winter precipitation events creates a combined physiographic setting that is naturally prone to mass wasting and transport of sediment into stream networks. In addition to the physiographic setting, the study area experienced decades of anthropogenic impacts to the watershed-scale hydrologic and sediment routing processes from large-scale forest conversions and road development primarily to support commercial timber extraction prior to large-scale cannabis cultivation. This resulted in a landscape that is vulnerable to additional anthropogenic impacts from cannabis cultivation, particularly in steep locations. When roads and cannabis farms are located on steep slopes or land conversions to support cannabis, there is an elevated risk of sediment-related impacts to aquatic habitat in the study area.

The distance to the stream network also influences the likelihood of impacts to aquatic habitat from mass wasting or toxicant runoff initiated from a cannabis farm located on a steep slope. The sites that are on steep slopes (>30%) and located within close proximity to the stream network (<45.7 m) are at the highest risk for impacting nearby aquatic and riparian habitat though the proportion of sites that met that criteria was very low (4.1%; n = 22). In general, it appears that cultivators tend to locate their farms on less steep locations relative to available slope conditions in the watersheds.

4) Compliance

The trends in compliance we identified from aerial imagery analysis revealed the different demographics of cannabis cultivators in this region. Generally, cannabis cultivators in the headwaters of the Mattole have a much higher level of regulatory compliance than the statewide mean (33.6% of sites = compliant). This is approximately three times higher than anecdotal estimates from state cannabis regulators of approximately 10% compliance among the total cannabis industry in California and 30 times higher than a recent report from the California Growers Association (California Growers Association 2018) asserting that 1% of the state's cannabis cultivators have joined the legal market.

The watershed with the highest level of compliance, Eubank Creek (63%), also had the largest mean farm size (0.19 ± 0.04 ha) and the largest proportion of the watershed under cultivation (0.84%). These combined metrics may reveal a difference in the demographics of cultivators in the region where the largest farms tend to be owned by cultivators with more financial resources and motivation to join the regulated market (Polson and Petersen-Rockney 2019, Schwab et al. 2019, Wilson et al. 2019). This finding is consistent with Butsic et al. (2018) who found that large farms were less likely to be abandoned than small farms and that smaller farms are less likely to join the regulated market. Specifically, Butsic et al. (2018) found that farm abandonment between 2012-2016 was best predicted by farm size, with smaller farms (i.e., ≤50 plants) twice as likely to be abandoned relative to large farms (i.e., ≥200 plants).

The variability in rates of compliance amongst study watersheds was likely driven by a combination of physical and demographic factors. For example, McKee Creek had the highest proportion of farms on steep slopes (36.2%) and the highest proportion of farms within 45.7 m of critical steelhead habitat (25.8%) which is three times higher than the regional mean. These attributes make the permitting process more difficult for cultivators to become compliant in McKee Creek relative to Eubank Creek and the difference in the rates of compliance between the watersheds is apparent (Eubank = 63%; McKee = 35.3%). Eubank Creek had the largest mean farm size (0.19 ± 0.04 ha) and the lowest proportion of sites located on steep slopes (19.0%), and the second lowest proportion of sites within 45.7 m of critical habitat for steelhead (1.3%; Table 1). These factors increase the likelihood of obtaining a permit because the sites are considered lower risk and do not require sediment and erosion plans by the SWRCB's (2018) Cannabis Policy.

5) Road Metrics

Road density within the study watersheds is >4 times the road density considered an 'acceptable' level (0.6-0.7 km/km^2) to sustain a naturally functioning landscape that supports large terrestrial predators (Forman and Alexander 1998). This threshold has been used in recent studies examining impacts of roads on terrestrial organisms (e.g., Cai et al. 2013, Boulanger et al. 2014). The National Research Council (2005) identified a threshold range of road density between 2.0-3.0 km/km^2 and at road densities greater than the threshold, alterations to the runoff regime and flow routing processes at a watershed scale are pervasive and peak flows typically increase (National Research Council 2005). Increased peak flows often lead to a decrease in instream habitat quality and quantity (Poff et al. 1997). All study watersheds except Mill Creek, had road densities equal to or greater than 2.0 km/km^2, indicating that peak flows have likely been altered from baseline conditions in three of the four study watersheds.

One major caveat of the current study is that the highest road density and number of crossings within 15.2 m of critical steelhead habitat occurred in the reference watershed, Van Arken Creek. This reflects the recent history of timber production as the dominant land use in that watershed as opposed to cannabis cultivation in the others. In Van Arken Creek, legacy impacts to hydrological and sediment routing processes from commercial timber production are likely still impacting the quantity and quality of instream habitat (CDFW, in prep).

Other studies have shown that the amount of sediment yield to the stream network associated with road crossings is widely variable based on the construction methods, surface type, and condition (Wemple et al. 2001). As such it was beyond the scope of this study to rank the likelihood of impacts from each road crossing. Despite this, the total number of crossings may still be a reasonable proxy to assess the relative likelihood of increased sediment yield and erosion potential at the watershed scale.

CONCLUSIONS/RECOMENDATIONS

Aerial imagery analysis to identify cannabis cultivation sites combined with simple GIS metrics associated with: 1) farm attributes, 2) proximity to critical habitat, 3) site and watershed slope, 4) regulatory compliance, and 5) attributes of the road networks provide the basis for developing a screening tool for rapidly assessing the relative risk of impacts to the aquatic and terrestrial environment from large-scale cannabis cultivation without the need for extensive field visits. The GIS metrics presented here are not comprehensive, and more robust metrics could be developed and employed statewide that assess the risk of cannabis-related impacts associated with natural intrinsic watershed characteristics (e.g., geologic setting as it relates to groundwater availability, climate/hydrologic setting, vegetation, presence of species of special concern), and anthropogenic drivers like recent land conversions for cannabis or the total number of surface water diverters and well users in a given watershed. With repeat cannabis site mapping in the same location, a land conversion metric could be generated that assesses the relative risk of cannabis impacts due to the history and magnitude of land conversions for cannabis cultivation. Similarly, hydrologic metrics could be generated to assess the risk for dewatering a given watershed based on the hydrologic setting (i.e., estimates of unimpaired flow) relative to total water users employing a water budgeting approach (Zipper et al. 2019). The metrics described here could also be refined. For example, our %compliant metric could be bolstered to account for all state and local permits required in a given county and not solely based on CDFA licenses. The road-related sedimentation metrics could also be significantly bolstered by rapid, field-based road assessments to investigate the condition of road crossings and unpaved roads close to the stream identified in the GIS analysis.

In the absence of more detailed metrics or some level of field validation, we have shown that potential impacts from cannabis cultivation in our study area are variable based on the spatial scale of inquiry, the actual farm locations relative to sensitive habitat, and intrinsic watershed characteristics (e.g., steep slopes) that make a given farm more likely to impact the aquatic environment. The use of geospatial information to identify land use types and analyze associated impacts is well-established and here, we use geospatial data to explore metrics related to cannabis cultivation. The methods we describe will be used to help with the development of CEMAF, a robust statewide monitoring framework to help CDFW scientists assess the impacts of cannabis cultivation on aquatic and terrestrial ecosystems.

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