

The spatial overlap of small-scale cannabis farms with aquatic and terrestrial biodiversity

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Abstract

The rapid expansion of cannabis agriculture in the Western United States provides a rare opportunity to study how an abrupt change in land-use policy affects local biodiversity. There is broad speculation that cannabis production on private land is expanding and having negative effects on aquatic and terrestrial ecosystems, yet there exist little empirical data to evaluate this concern. In this study, we mapped and characterized outdoor cannabis production during the first season of legal recreational production (2016) in a large legacy cannabis-producing region of Southern Oregon, Josephine County. We descriptively compared cannabis farms to all available private parcels based on proximity to rivers/streams and undeveloped land and their overlap with carnivore richness. Using publicly available satellite imagery, we found approximately 1.34 km² (331 acres) of cannabis cultivation within Josephine County during the first season of legal recreational production. Most cannabis production areas were small (median size 414 m²), spatially clustered at all observed scales, and recently established (67% were not visible in 2013–2014 pre-legalization). When compared with all available private parcels, cannabis was preferentially located in forested areas, undeveloped land and slightly closer to rivers. Within riparian areas, farms were slightly closer to rivers with predicted occurrence of coho salmon (*Oncorhynchus kisutch*). While projected carnivore richness was similar between cannabis and all private parcels, projected fisher (*Pekania pennanti*) occupancy was more than five times higher on cannabis farms, with a median occupancy of 0.69 (interquartile range: 0.24–0.87). Our results establish a baseline for cannabis land cover at the time of early recreational legalization and rapid expansion and can be used to predict future patterns or ecological consequences of cannabis development in other production areas. Understanding the potential ecological impact of cannabis is increasingly important as legalization expands and may also offer insights into other rural land-use change frontiers.

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KEYWORDS

agricultural frontier, carnivore richness, coho salmon (*Onchorhynchus kisutch*), fisher (*Pekania pennanti*), land-use change, marijuana, Oregon

1 | INTRODUCTION

Land-use change is one of the oldest and most pervasive threats to global biodiversity (Ellis et al., 2013; Foley et al., 2005), yet it often occurs over time spans that obscure pattern (Turner, 2005; Turner, Gardener, & O'Neill, 2001) or in tandem with multiple development drivers that are difficult to disentangle (Meyfroidt, 2015; Turner, 2005). An exception to this is when abrupt changes in law or regulation accelerate development, creating what is known as a “policy-induced rapid land use change frontier” (le Polain de Waroux et al., 2018). The acceleration of development at these frontiers enables researchers to assess how land-use change affects biodiversity or ecosystem function over short time periods (Turner, 2005). One such unique opportunity to study land-use change frontiers has emerged recently in the Western United States with the legalization of cannabis production and use (Butsic, Carah, Baumann, Stephens, & Brenner, 2018).

Over the past decade, 17 states and the District of Columbia in the United States have legalized recreational cannabis, or marijuana (*Cannabis sativa* or *C. indica*), and the rate of recreational legalization has increased over that time. This policy change has initiated rapid development of cannabis cultivation, particularly in areas with a history of illicit or medical cannabis farming (Butsic et al., 2018; Butsic & Brenner, 2016). Note that because of the complex policy background of cannabis and its quasi-legal status (Short Gianotti et al., 2017), this expansion occurs across types of cultivation including licensed and unlicensed producers. As with any development frontier, the rapid expansion of recreational cannabis is likely to come with ecological costs. Indeed, cannabis production has sparked considerable conservation concern for its potential effects on water, land, and wildlife (Carah et al., 2015; LaChance, 2019; Wartenberg et al., 2021). These effects may occur in part through (1) water withdrawals that lower freshwater availability (Bauer et al., 2015; Dillis et al., 2020; Zipper et al., 2019), (2) road construction or use of pesticides that lower freshwater quality (Carah et al., 2015; Portugal & Hwan, 2020), (3) clearing or fencing of undeveloped land that removes or degrades wildlife habitat (Butsic et al., 2018; Butsic & Brenner, 2016; Wang, Brenner, & Butsic, 2017; Wengert et al., 2021), (4) toxicants or poaching that directly kills animals and poses particular risk to terrestrial carnivores like the

fisher (*Pekania pennanti*; Gabriel et al., 2012; Thompson et al., 2014; Gabriel et al., 2015, 2018; Rich, McMillin, Baker, & Chappell, 2020), and (5) human disturbance (from increased human presence, use of security or grow lights, or noise from generators and equipment) that alters animal behavioral cues (Parker-Shames, Xu, Rich, & Brashares, 2020; Rich, Baker, & Chappell, 2020; Rich, Ferguson, Baker, & Chappell, 2020). These five impact pathways likely vary depending on surrounding context, production practices, and license status but provide a general guideline for potential ecological effects (Wartenberg et al., 2021).

Much of the existing research on ecological effects of cannabis have focused on illicit production on public lands (e.g., Carah et al., 2015; Gabriel et al., 2012; Levy, 2014). However, private-land production is quickly becoming a dominant source of cannabis in the western United States while illegal public-land production in the region either appears to be declining (Klassen & Anthony, 2019), shifting, or possibly increasing in some areas with increased enforcement (Wengert et al., 2021). Private-land cannabis cultivation appears to generally follow one of two development trajectories (Dillis et al., 2021). The first pathway consists of many, smaller farms in rural areas with a history of illicit or medical cultivation (i.e., “the legacy pathway”). The second path is dominated by fewer, larger farms in new areas more conducive to large-scale, industrial farming (i.e., “the industrial pathway”). Note that although the legacy pathway is characterized by historical growing practices, this form of production can also expand with emerging development frontiers. Research on these development trajectories in California suggests that, although both trajectories are expanding, the legacy pathway may require policy intervention if it is to fully transition to, and persist in, the legal industry (Bodwitch et al., 2019; Dillis et al., 2021). Proponents often argue that smaller scale styles of farming are more sustainable (Bodwitch et al., 2019), sometimes drawing parallels to industries such as craft vineyards (e.g., Hilty & Merenlender, 2004; Kremen & Merenlender, 2018). However, these farms are also often located in more rural, biodiverse watersheds close to protected wilderness and managed timberlands that could be at environmental risk from expanding development (Butsic et al., 2018; Carah et al., 2015). As land managers and policymakers decide where to prioritize cannabis farming, there is a growing need to contextualize the potential effects of the legacy pathway in ecologically sensitive regions.

In Josephine County, Oregon, the co-occurrence of cannabis agriculture within the highly biodiverse

Klamath-Siskiyou Ecoregion has created a natural experiment to examine how the post-legalization expansion of small-scale, private-land farms might affect freshwater and terrestrial biodiversity. In this study, we ask: What was the development pattern of cannabis land use in Josephine County during the first year of recreational legalization, and how might cannabis production overlap with sensitive ecological features?

To address these questions, our objectives were to (1) map and characterize the spatial configuration of cannabis farms in Josephine County, Oregon, in an early stage of cannabis legalization and (2) examine the proximity of cannabis production to undeveloped land cover, freshwater, sensitive fish species (e.g. coho salmon [*Oncorhynchus kisutch*], Chinook salmon [*Oncorhynchus tshawytscha*], and Steelhead [*Oncorhynchus mykiss*]), and terrestrial carnivore richness (e.g. fishers, coastal marten [*Martes caurina humboldtensis*], ringtail [*Bassariscus astutus*], cougar [*Puma concolor*], bobcat [*Lynx rufus*], gray fox [*Urocyon cinereoargenteus*], and coyote [*Canis latrans*]). We anticipated that due to the cultural dominance of historical growing practices, cannabis production in this region would be comprised of relatively small-scale farms representative of the legacy industry pathway (Dillis et al., 2021), but most farms would be new since legalization. Based on research from California pre-legalization (Butsic et al., 2018; Butsic & Brenner, 2016), we expected that cannabis in our study area would also be clustered at the subwatershed level. Concerning proximity to ecologically sensitive areas, we expected that cannabis agriculture would be located in more undeveloped lands, closer to freshwater streams or rivers, and closer to sensitive fish species compared with the surrounding context of all private-land parcels. The proposed mechanisms behind these predictions are summarized in Table 1 and draw on the five hypothesized pathways of effect for cannabis on the surrounding environment listed earlier (Wartenberg et al., 2021). Finally, we quantified spatial overlap of cannabis farms with projected terrestrial carnivore distributions. We focused on carnivores because previous studies have described this group as particularly sensitive to cannabis cultivation (Carah et al., 2015; Gabriel et al., 2015; Parker-Shames et al., 2020; Rich, Baker, & Chappell, 2020; Rich, Ferguson, et al., 2020; Thompson et al., 2014) and because this group includes species of regional conservation concern such as the fisher.

2 | METHODS

2.1 | Study area

Our study focused on Josephine County in Southern Oregon (4250 km²). Josephine County was an ideal location

to measure cannabis dynamics of legacy areas and to gain broader insights on the ecological outcomes of cannabis legalization. Josephine County had a long history of illicit and medical cannabis cultivation and an active presence in the growing legal industry in Oregon (Klassen & Anthony, 2019; V. Smith, Powell, Mungeam, & Emmons, 2019). In 2014, Oregon became one of the first US states to legalize recreational cannabis. Southern Oregon has become known as a prime destination for outdoor cannabis production (V. Smith, Powell, et al., 2019), and Josephine County had the highest number of applications for licensed producers relative to population size in the state (0.38 per 100 inhabitants; Oregon Liquor Control Commission, 2019). Widespread cultivation of cannabis started in the region during the 1960s (Corva, 2014) and is now viewed as one of the county's main economic drivers (Parker-Shames, unpublished interviews).

Josephine County is also located in a biodiversity hotspot. The study area is part of the Klamath-Siskiyou Ecoregion, one of the most biodiverse temperate forest regions and an area of increasing conservation focus (D. Olson et al., 2012; D. M. Olson et al., 2006). The Klamath-Siskiyou Ecoregion straddles the Oregon-California border and contains several regions identified as critical climate change refugia (D. Olson et al., 2012; D. M. Olson et al., 2006). The study area contains several protected areas including state and federal protected lands (68.8% of the county is state or federal land), several federally threatened and endangered species including northern spotted owl (*Strix occidentalis caurina*) and coho salmon (*O. kisutch*), and state-sensitive species such as fisher (*P. pennanti*).

2.2 | Mapping cannabis farms

To characterize the spatial distribution of cannabis farming, we hand-digitized cannabis production sites across Josephine County using high-spatial-resolution Google Earth images taken after statewide legalization (e.g., Figure 1d). We based our methods on those previously used to map cannabis production in regions of Northern California (Butsic et al., 2018; Butsic & Brenner, 2016). We used publicly available satellite imagery for May or July 2016, the first year with a full growing season after recreational legalization went into effect in July 2015.

Next, we characterized the farms themselves. Digitizers counted the number of plants visible in outdoor gardens, recorded whether there was a visible fence surrounding each cannabis production site, and recorded whether each site was new (i.e., whether it was visible in the previous imagery year of 2013 or 2014). To estimate the number of plants produced in greenhouses, we used

TABLE 1 Summary of layers used for spatial analyses

Layer	Used for	Related pathways	Source	Year	Resolution
Digital Elevation Model (DEM)	Elevation	Loss/degradation of habitat (3)	Oregon Department of Forestry	2008	10 m
Land cover	Developed/undeveloped classification	Loss/degradation of habitat (3)	NLCD (Dewitz, 2019)	2013	30 m
Forest structure	Canopy cover and stand age	Loss/degradation of habitat (3)	GNN (LEMMA Team, 2020)	2016	30 m
Carnivore richness	Average carnivore richness for fisher, marten, ringtail, cougar, bobcat, gray fox, and coyote combined	Loss/degradation of habitat, direct mortality, and behavioral shifts (3–5)	Barry (2018) and Moriarty et al., unpublished data (Appendix S5)	2016	3 × 3 km grid
Individual carnivore distributions	Projected probability of occupancy for fisher, ringtail, cougar, bobcat, gray fox, and coyote individually	Loss/degradation of habitat, direct mortality, and behavioral shifts (3–5)	Barry (2018) and Moriarty et al., unpublished data (Appendix S5)	2016	3 × 3 km grid
Rivers/streams	Proximity to freshwater	Freshwater availability/quality (1, 2)	NHDplus (US Geological Survey, 2018)	2018	Vector data
Fish habitat	Proximity to coho, chinook, and steelhead habitat	Freshwater availability/quality (1, 2)	Oregon Fish Habitat Data, OFHD (Bowers, 2020)	2020	Vector data

Note: Related pathways refer to the five hypothesized ecological effects of cannabis that could potentially affect the given layer (see text): (1) water availability from withdrawals, (2) water quality from contamination, (3) loss or degradation of habitat from clearing/fencing, (4) direct animal mortality from toxicants or poaching, and (5) behavioral shifts from human disturbance.

Abbreviations: GNN, Gradient Nearest Neighbor; LEMMA, Landscape Ecology, Modeling, Mapping, and Analysis; NHD, National Hydrography Database; NLCD, National Land Cover Database.

180 instances where we could count the number of plants through the see-through top of greenhouses and divided this count by greenhouse area. This yielded an average of one plant per 7.23 m² of greenhouse area, which we then used to estimate greenhouse plant counts. See supplement (Appendix S1) for full mapping procedure.

To test the accuracy of image-based data collection, we visited approximately 30 farms between 2017 and 2019 to verify and refine our mapping protocol after a pilot mapping process. Because systematic ground verification for all grow sites was not possible, we used a qualitative confidence score to represent digitizers' relative certainty about each mapped site (based on characteristics such as plant size, color, shape, and use of individual planter boxes). For consistency, we thoroughly checked all mapped polygons and associated scoring using the same person who conducted on-the-ground site verification (PPS). We used only high-confidence sites for these analyses, but see supplemental materials for a comparison to the full data set (Appendix S2 and S3). Finally, we used only sites with more than four plants for analyses because we were focused on the cannabis industry rather than plants grown for personal consumption (Oregon law permitted four plants per household for personal use).

2.3 | Describing the spatial configuration of cannabis farms

To generate a baseline characterization of cannabis production post-legalization, we grouped cannabis production in two ways: (1) by the individual digitized polygons (site) and (2) by the surrounding/containing parcel (farm). We used 2018 county tax lot information for parcel boundaries (parcel lines and zoning are unlikely to be different between years; Josephine County 2018). We characterized cannabis farm size, use of fences, and new production using multiple per-site and per-farm metrics (see Table 2). We joined farm-level data to parcels in ArcGIS Pro (Esri Inc, 2020), and we calculated all other summaries using R (R Core Team, 2020).

The distribution and clustering of rural development can change the ways in which land-use change affects local biodiversity. First, to assess the relationship between scale and spatial clustering of cannabis cultivation, we used a Ripley's K analysis (with an isotropic edge correction) on cannabis sites with the "spatstat" package in R (Baddeley, Rubak, & Turner, 2015; Ripley, 1977). Then, to identify the location of cannabis clusters, we conducted a Getis Ord Gi* hotspot analysis (Ord & Getis, 2010) to test for statistically significant clustering

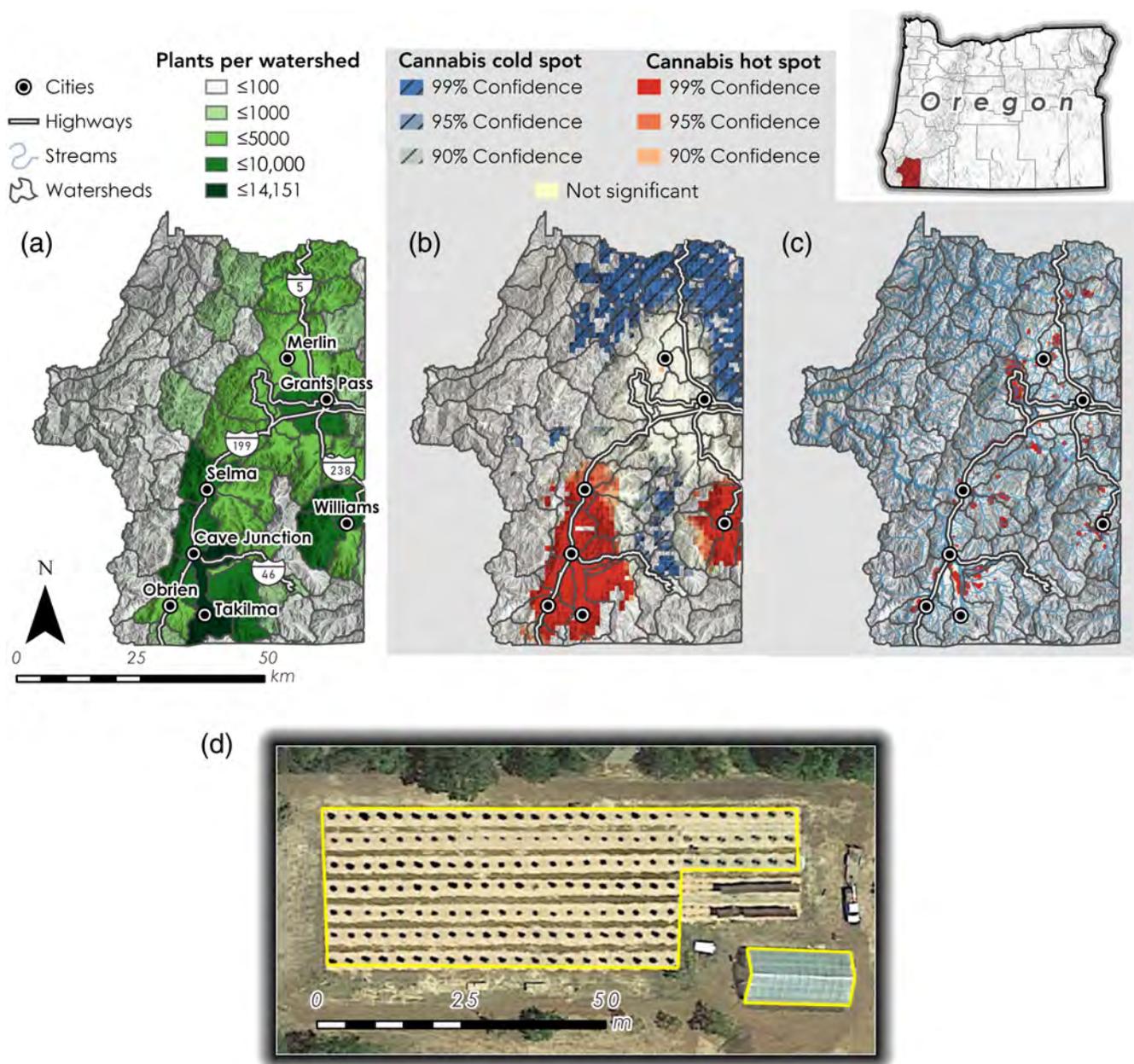


FIGURE 1 Distribution of cannabis in Josephine County. (a) Plants per subwatershed; (b–c) cannabis hotspots (in red) at two different scales: (b) County (excluding public lands) and (c) individual subwatersheds with at least 30 sites. Hotspots are generated using the Getis-Ord G_i^* analysis and indicate significant clustering. (d) Example of what an outdoor garden and greenhouse look like from aerial imagery with digitized polygons around the cultivated area and greenhouse

of cannabis farms on private land at the county level and individual subwatershed level (USGS Hydrologic Unit Code 12) based on methodology from Butsic and Brenner (2016). To conduct the Getis Ord analysis, we used the optimized hotspot analysis tool on farm centroids in ArcGIS Pro. For the county-level analysis, we excluded public tax lots from the study area. For the individual watershed-level analysis, the optimized hotspot analysis required at least 30 points per watershed to test for statistical significance, so we only used 25 out of 73 watersheds to meet this requirement.

2.4 | Quantifying spatial metrics of conservation concern

To assess the potential ecological effects of cannabis at the landscape scale, we quantified spatial proximity of cannabis to landscape features, fish populations, and carnivore distributions (Butsic et al., 2018). This proximity does not directly infer effect but rather infers whether the configuration of cannabis may increase the opportunities for negative environmental outcomes. We focused on spatial metrics that might approximate some of the five

TABLE 2 Summary of mapped cannabis in 2016 Josephine County for outdoor gardens, greenhouses, all sites (gardens + greenhouses), and all farms (parcel-level summaries)

	<i>n</i>	Plant count	Median number of plants per group (IQR)	Total cultivated area in km ²	Median area in m ² (IQR)	Fenced (%)	New (%)
Outdoor ardens	2593	91,922	26 (14–48)	1.20	282 (114–629)	55.5	58.5
Greenhouses	1317	23,760	14.4 (8.4–22.5)	0.14	85.8 (49.8–134)	40.7	73.4
All sites	3910	115,682	21 (12–42)	1.34	163 (73.5–428)	50.5	63.6
All farms	2227	115,682	41.5 (19–61)	1.34	414 (161–811)	59.0	67.4

Note: For farms, percentages are for farms containing at least one site that is fenced or new. Abbreviation: IQR, Interquartile range.

main hypothesized effects of cannabis farming on local environments (Table 1).

To approximate the potential loss of wildlife habitat, we assessed cannabis production in developed versus undeveloped lands. We extracted elevation and 2013 land cover at the centroid of each farm and then grouped land-cover classes into developed (developed and cultivated) and undeveloped (herbaceous, forest, shrubland, and wetland) categories (Table 1). The National Land Cover Database (NLCD) Cultivated category includes hay, annual crops such as corn or perennial crops such as orchards and vineyards; given the resolution of the NLCD data set compared to average farm size, this is unlikely to include cannabis pre-recreational legalization.

To approximate the potential degradation of forested habitat, we assessed the forest structure on farms used for cannabis production (Table 1). To do so, we extracted canopy cover and stand age at the centroid of each farm (but see supplement for other metrics; Appendix S4).

To approximate the potential effects on carnivores, we examined the overlap of cannabis with projected carnivore richness and individual carnivore species distributions. We extracted the average carnivore richness and individual carnivore occupancy value at the centroid of each farm (Table 1). For carnivore richness and individual carnivore distributions, we used projected model data for Southern Oregon, from Barry (2018) and Moriarty et al. (unpublished data; see Appendix S5 for description of occupancy and richness methods). Within our study area, the richness layer represents the total number of carnivores expected in a given grid cell for the following species: fisher, coastal marten, ringtail, cougar, bobcat, gray fox, and coyote. For individual species, we used calculated distribution data from projected occupancy, and this represented the average probability that a given area would be occupied by that species. Marten projected occupancy was almost entirely absent in this region and was not included in individual species summaries.

Finally, to approximate the potential effects of freshwater extraction or declines in freshwater quality due to cannabis production, we assessed the proximity of cannabis to freshwater rivers or streams and fish habitat for potentially sensitive species. For vector data with the proximity analysis (Table 1), we calculated the distance from the centroid of each cannabis farm to the nearest river and fish habitat in R using the “simple features” package (Pebesma, 2018). For rivers, we used the National Hydrography Database (NHD Plus). We filtered out canals/ditches and underground aqueducts (*F* code > 42,000; US Geological Survey, 2018). For fish habitat data, we used Oregon Fish Habitat Distribution data for coho salmon, fall- and spring-run Chinook salmon, and winter- and summer-run Steelhead (Bowers, 2020). We then calculated summaries of proximity and overlap metrics in R. In order to inform the interpretation of the fish habitat data, we also extracted the stream order (level of stream branching, starting at headwaters) of the nearest stream to each cannabis site and summarized results in R.

The conservation effect of these metrics for cannabis likely depends on how they compare to the potential effect of surrounding land uses and available land for development (i.e., the landscape baseline). Therefore, we contextualized the proximity metrics by comparing cannabis farms to all private-land parcels in the county. We used all private parcels instead of parcels without visible, high-confidence cannabis because we were mainly interested in how cannabis production fits into the surrounding landscape context of available private lands. See the supplement for a more local comparison in which we calculated the proximity and overlap metrics (Table 1) for all parcels within a buffer around each cannabis site. For buffer size, we used the average home range of fishers from Southern Oregon (specifically, the range for females of 16.27 km²; T. Smith, 2021; Appendix S6).

TABLE 3 Proximity metrics for cannabis farms and all private-land parcels

	Cannabis	Private land
Number of parcels	2227	41,158
Elevation (m): Median ^a	1388 (1185–1503)	1059 (948–1300)
Land cover: % undeveloped	68%	43%
Forest structure: % forested	68%	43%
Forest structure: Median canopy cover	49% (31–65)	52% (35–67)
Forest structure: Median stand age	76 (61–100)	77 (63–98)
Rivers (m): Median distance	94 (47–177)	140 (61–294)
Coho (m): Median distance	538 (229–1126)	811 (341–1541)
Chinook (fall; m): Median distance	807 (309–1718)	1194 (542–2186)
Chinook (spring; m): Median distance	12,147 (3762–27,819)	2291 (1015–7918)
Steelhead (winter; m): Median distance	458 (190–969)	590 (265–1147)
Steelhead (summer; m): Median distance	1724 (415–18,877)	683 (297–1518)
Carnivore richness: Median number of species	2.6 (2.5–2.9)	2.5 (2.4–2.8)
Bobcat projected occupancy: Median probability of occupancy	0.37 (0.32–0.46)	0.36 (0.31–0.45)
Cougar projected occupancy: Median probability of occupancy	0.51 (0.46–0.55)	0.49 (0.44–0.53)
Ringtail projected occupancy: Median probability of occupancy	0.49 (0.30–0.59)	0.24 (0.21–0.40)
Gray fox projected occupancy: Median probability of occupancy	0.61 (0.20–0.92)	0.92 (0.88–0.93)
Fisher projected occupancy: Median probability of occupancy	0.69 (0.24–0.87)	0.12 (0.11–0.34)

^aFor median results, interquartile range (IQR) is given in parentheses.

3 | RESULTS

3.1 | Characterization and spatial configuration of cannabis farms

Outdoor cannabis production across Josephine County in 2016 was generally small scale but also pervasive and suggested that recreational legalization greatly expanded the industry locally. We mapped nearly 4000 individual gardens and greenhouses on 2220 different farms, all identified as highly likely to be cannabis (Table 2; Figure 1a; for results from the full data set, see Appendix S2 and S3). Most sites (63.6%) were new since legalization (Table 2). Most production was in outdoor gardens (66.3%), but a greater proportion of greenhouses was new (73.4%; Table 2). Farms contained an average of 1.76 individual sites, with a maximum of 14. The average size of individual sites and farms was small (outdoor garden median

area 282 m² or 0.07 acres) but highly variable in terms of cultivated area and number of plants (Table 2). The average parcel size for farms was 0.098 km² (24.2 acres); 99.6% of detected farms were on private-land parcels. Out of all private-land parcels in the county, 5.7% contained a farm identified as highly likely to be cannabis.

Cannabis sites were clustered at multiple spatial scales. Ripley's K analysis indicated that cannabis sites were clustered at all observed spatial scales (Appendix S7). At the county level, the Getis-Ord Hotspot maps identified two regional hotspots (in red) near Williams in the south-east, and in the Illinois Valley in the south-west (Figure 1b). The subwatershed analysis indicated that even within these larger regional hotspots, there were pockets of more and less intensive production (Figure 1c). Both the county and subwatershed hotspots seem to follow primary roads or river networks.

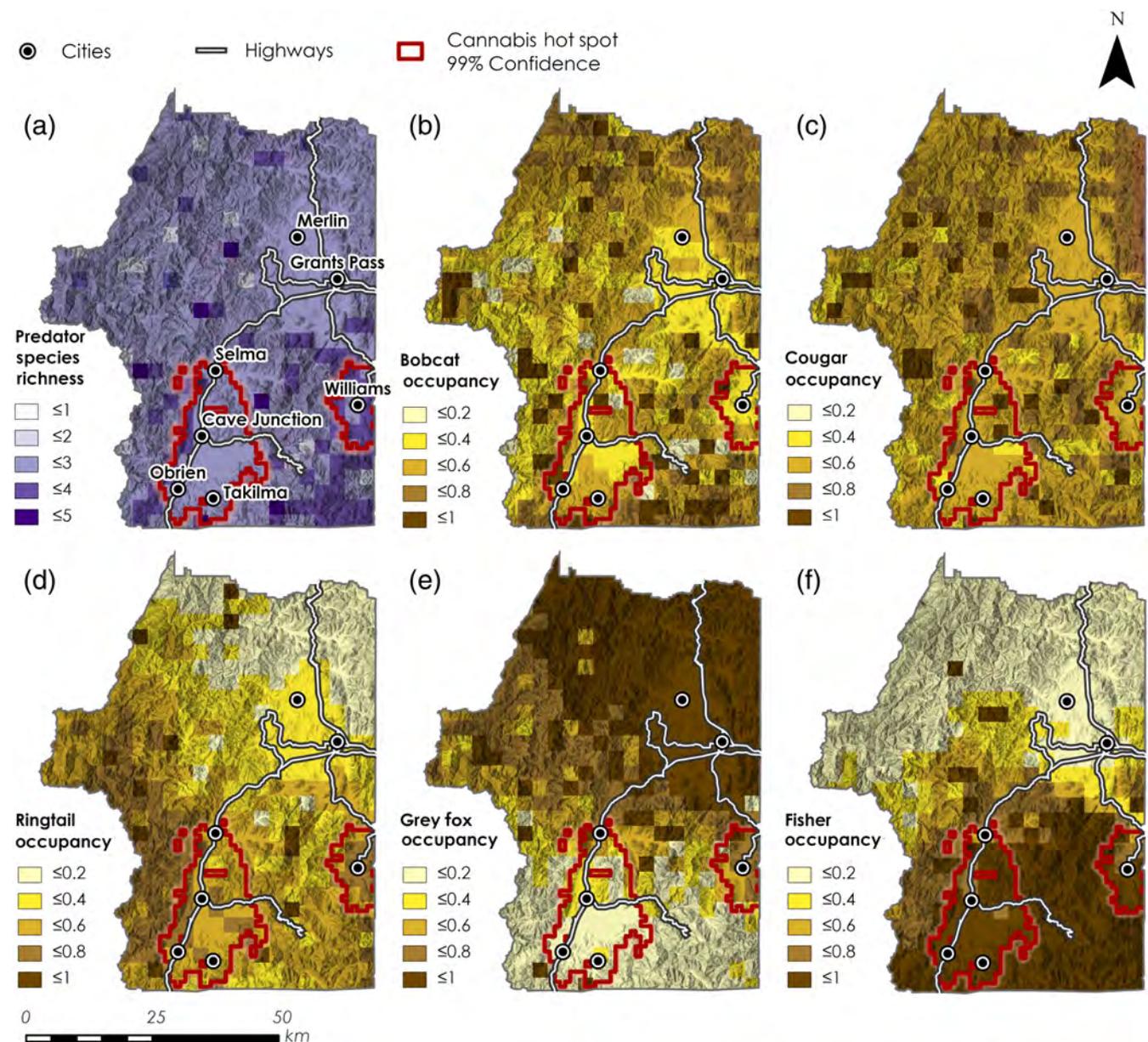


FIGURE 2 Projected carnivore richness (estimated number of carnivores present in a cell) and individual projected occupancy (average probability that a grid cell would be occupied by the given species) in relation to regional cannabis production hotspots

3.2 | Spatial relation of cannabis farms to measurements of conservation concern

Overall, cannabis was produced on more undeveloped and forested parcels compared to all available private lands as a whole (Table 3). The most common land cover for individual outdoor gardens was shrubland (29%), followed by cultivated (25%) and forest (21%). Greenhouse cannabis production occurred in areas already cultivated with other crops (29%), followed by shrubland (26%) and forest (22%). At the farm scale, however, where outdoor and greenhouse production was combined, forest was the most common land cover type (32%). The predominance of cannabis in forest and undeveloped land

covers was also supported by the Gradient Nearest Neighbor (GNN) data on forest structure. Although the GNN data set uses a broader categorization for forest, it also indicated that cannabis was disproportionately grown in forested areas (Table 3). Nevertheless, the forest structure (canopy cover and stand age) of farms was similar to that on all available private parcels (Table 3).

Cannabis farms occurred in areas with intermediate carnivore richness, similar to all available private parcels (Table 2; Figure 2). However, at the individual species level, cannabis farms overlapped with higher projected fisher (median 0.69) and ringtail (0.49) occupancy and lower gray fox occupancy (0.61; Figure 2). These differences were consistent across land cover, forest structure,

and zoning. However, median fisher occupancy values were larger on high elevation (>1500 m) parcels, and a greater proportion of cannabis farms (25.5%) were at higher elevations compared with private (5.3%) parcels. There was no difference in richness between existing or new cannabis farms, and no difference at the species level except for gray fox, which had a slightly higher median occupancy on existing farms (0.80) compared with new farms (0.60).

Cannabis was located slightly closer to rivers compared with all available private parcels, though the interquartile range (IQR) intervals overlap (Table 3). There were also a higher proportion of cannabis farms located within 15 m (50 ft) of a river or stream, compared to private parcels (8.3% vs. 5.9%). However, the proximity of farms to threatened fish species was mixed. For example, although there was a large variation in distances and overlap of IQR intervals, on average, cannabis was nearly 1.5 times closer to coho salmon habitat than all private parcels, yet more than five times farther from spring chinook habitat. The variation in proximity to fish habitat may be in part due to the proximity of cannabis to smaller streams by order (Appendix S8).

4 | DISCUSSION

This study is one of the first landscape-scale assessments of small-scale outdoor cannabis farming and its potential broad-scale ecological effects in a rural biodiversity hotspot. Our results suggest two main conclusions. First, private-land cannabis farming in Josephine County, Oregon, in 2016 was common and spatially clustered, expanded post-recreational legalization (67.4% of farms were new), and yet only covered a small portion (0.0003%) of the total land area. This supports our expectation that cannabis farming in Josephine County would exhibit characteristics typical of the legacy development pathway but that these farms would largely be new post-legalization. Second, our spatial proximity results highlighted areas of overlap or proximity of cannabis farms and sensitive habitats and species. Compared to the surrounding context of all available private-land parcels, cannabis was more frequently located in forested areas and undeveloped land, closer (though perhaps not significantly so) to rivers/streams and coho salmon habitat, and in areas of high value as fisher habitat. These results provided mixed support for our expectation that cannabis production would be in areas that increase its potential ecological impact.

Recent research on public-land production in the broader region (Wengert et al., 2021) highlights similarities and differences between public- and private-land

production. For example, both seem to be located relatively close to rivers and streams, with ~50% canopy cover, and in relatively young stands (less than 120 years; Wengert et al., 2021). However, while we may presume that all productions on public lands represent new clearing for production, our results indicate that 32% of farms are on already developed and unforested parcels. Additionally, public lands provide critical refuges for many of the region's carnivores, which may help explain why public-land production appears to overlap more with carnivore habitat than our results for private-land production (Wengert et al., 2021). Perhaps most importantly at a landscape scale, farm size and total extent appear to be much smaller for legacy pathway private-land cannabis mapped in this study compared to estimates of public-land production practices (Bauer et al., 2015; Wengert et al., 2021).

Despite the differences between public- and private-land cannabis production, private-land cannabis farming still has characteristics that warrant continued research and planning. Our results suggest that legacy pathway cannabis farming could be compatible and comparable with existing rural land use in Josephine County. In order to ensure this continues to be the case, however, further attention should be given to conservation outreach, policies to support small-scale farming, and attention to land-use practices on farms, particularly those that may affect carnivores and coho salmon. As the industry continues to expand, policymakers and conservationists need to clarify landscape-level strategies to ensure a sustainable future.

Care should be taken when interpreting these results, since cannabis agriculture takes many forms and often exhibits regional differences in production practices that may influence its ecological impact (Wartenberg et al., 2021). Our study, by nature of our mapping approach, evaluated outdoor production on private lands. We were unable to quantify whether the farms we mapped were illegal or licensed medically or recreationally, nor how many farms we may have missed by farmers effectively concealing their crop. Given our mapped sites included 2227 farms in 2016 compared to the 43 recreationally licensed locations in 2016 (Oregon Liquor Control Commission Public Records Request 2020), it is likely that most of the farms we georeferenced were not licensed. If this is the case, the lack of effort to conceal crops is notable. We suspect because cannabis was pervasive (6% of private parcels), that enforcement would not have been feasible (Corva, 2014). Therefore, we were confident that our study accurately quantified the distribution of private-land cannabis production because of the visibility of both licensed and unlicensed farms from aerial imagery. Further, our data likely do not

capture all of the cannabis being grown in Josephine County as we were unable to quantify concealed farms on public-land or indoor cannabis production. Instead, our study offers critical insights into the ecological consequences of the growing industry in legacy production regions.

4.1 | Potential ecological effects of outdoor cannabis

The overall cultivated area of private-land cannabis agriculture at the landscape scale in Josephine County in 2016 appears to be similar to small-scale rural development already occurring regionally. For example, in a county of 4250 km² (~1 million acres), the total cannabis cultivation area was only 1.34 km² (331 acres; or up to 1.57 km², 388 acres including all confidence levels, see Appendix S2). This small size is similar to other agricultural production in the county: in 2017, Josephine County produced 2.98 km² (733 acres) of grapes and 0.48 km² (118 acres) of vegetables (USDA Census of Agriculture, 2017). Cannabis in Josephine County was also considerably smaller in scale than other legacy cannabis-producing regions in Northern California in 2016, where averages ranged from 53 to 119 plants per site, compared with the median of 21 found in our study (Butsic et al., 2018). While we do not have comparative research on the ecological effects of other agriculture in the study area, small-scale agriculture in rural areas often creates a landscape mosaic that supports species richness (Kremen & Merenlender, 2018; Mendenhall, Karp, Meyer, Hadly, & Daily, 2014). The ability of small-scale cannabis farming to function like agriculture in other working lands systems, however, requires a deeper understanding of land-use practices associated with cannabis production. Specifically, to be ecologically sustainable, small-scale private-land cannabis farms would need to create a significantly smaller ecological footprint than public-land cannabis (Carah et al., 2015; Levy, 2014).

Although the area of cultivation for cannabis in Josephine County was small, this study did not evaluate the edge effects of cannabis cultivation, nor take into account other forms of disturbance associated with the sites, such as clearing beyond the cultivated area, road construction, or water storage development. Therefore, the actual overlap and potential ecological effect from cannabis farming in the region are likely to be larger than what was documented in this study. Our understanding of these broad-scale impacts would be enhanced in future studies that may be able to assess the fine-scale response of wildlife on and surrounding cannabis farms.

While our study does not address direct effects of cannabis production, we did identify spatial relations of cannabis development that could pose unique risks to terrestrial and freshwater ecosystems. We found that cannabis production was clustered in its distribution, which is consistent with research from Northern California (Butsic et al., 2018; Butsic & Brenner, 2016). This clustering could be an ecological concern if cannabis is occurring disproportionately in sensitive ecological areas. Similarly, the proliferation of fences associated with cannabis (59% of mapped farms had a visible fence) could be a concern for habitat fragmentation as the industry expands (McInturff, Xu, Wilkinson, Dejid, & Brashares, 2020). The overlap results indicate that cannabis may be grown disproportionately in forests and at higher elevations, which suggests cannabis could be associated with greater land clearing than other development on private parcels. However, the forests where cannabis was grown did not appear to be denser or older than comparable parcels.

Our results indicate a large overlap of cannabis farms with areas of high projected fisher occupancy. This overlap was greater on cannabis farms than private land generally but could be due to a higher proportion of cannabis farms located at higher elevations (>1500 m). However, elevation alone does not explain this overlap. Fisher occupancy was projected to be higher on cannabis farms than the areas immediately surrounding them (Appendix S4). This suggests that even at fine scales, farms are appearing in areas of potential for high-quality habitat for fisher. What this overlap may mean for fisher populations is unclear, given the lack of research on the impacts of private-land cannabis production. Private-land cannabis has not been documented to have the same negative effects on fishers as public-land production, and in particular, pesticide and toxicant use appears to be lower on private-land farms, according to self-reported farmer surveys (Wilson et al., 2019). However, anecdotal reports and local news stories raise concerns for these private-land farms as well, and many grower organizations have emphasized a need for stronger environmental norms among farmers. Given the remaining uncertainty, these results emphasize the potential need for conservation attention to private-land farms as well.

Surprisingly, the individual species differences did not add up to differences in overall carnivore richness, which was relatively consistent across the study area. This raises the possibility that the differences in carnivore distributions might be driven by competitive interactions (Green et al., 2018), though finer scale research would be needed to disentangle the drivers of these species distribution patterns in relation to cannabis production.

Regarding potential interactions between cannabis production and freshwater ecosystems, the picture was also somewhat mixed. There were a number of farms (8.3%) within 15 m (50 ft) of rivers and streams, but this was not surprising, given the high density of rivers and streams in the study area. On average, most farms were only slightly closer to rivers and streams than the surrounding context of all private-land parcels. Cannabis was located on average 273 m closer to coho salmon habitat than private parcels overall, 387 m closer to fall-run chinook, and 132 m closer to winter-run steelhead, though the IQR intervals overlap. This proximity to freshwater in Josephine County was also generally closer than observed in other legacy cannabis regions (Butsic et al., 2018). For example, the proportion of sites in Josephine County within 500 m of coho habitat (47.7%) was more than twice the proportion in Northern California (17.9%; Butsic et al., 2018). Butsic et al. (2018) used intrinsic potential data rather than direct fish population data, which may overestimate fish populations (Sheer et al., 2009), so this difference could be even more extreme. Coho salmon spawn in smaller upstream tributaries that may be particularly susceptible to drought or water withdrawals (Bauer et al., 2015; Brown, Moyle, & Yoshiyama, 1994). This proximity to coho may be explained by the large number of cannabis sites in proximity to small, headwater streams (Appendix S8), which could further indicate potential threat to other species that depend on these habitats, such as headwaters-dwelling amphibians. Therefore, this proximity to fish habitat could be an ecological concern if farms are drawing water from small rivers or shallow wells during the dry season (Zipper et al., 2019).

Whether metrics summarizing the proximity of farms and sensitive habitats result in actual ecological harm largely depends on the individual land-use practices occurring on cannabis farms. There is a rich history of different approaches to cultivating cannabis (Corva, 2014; Wilson et al., 2019), which could lead to variation in how cannabis affects ecosystems. Unfortunately, we still do not have a complete picture of cannabis land-use practices, nor their mechanisms underlying their ecological effects. So far, available published research suggests that much of small-scale private-land cannabis production may not be as ecologically damaging as previously believed (Bodwitch et al., 2019; Parker-Shames et al., 2020; Wartenberg et al., 2021), though a consensus has not been reached, and effects may vary over time. Given our current knowledge, therefore, the snapshot of private-land cannabis in 2016 in Josephine County does not on its own indicate widespread ecological effects. There could however be an increased concern for local biodiversity if cannabis development expands in size or intensity while remaining in the

same spatial configuration—located in forested vegetation and in proximity to a few key sensitive carnivore and fish species. Certainly, the large number of new farms in the first year of legalization (67.4%) suggests a rapidly expanding industry. This concern suggests a need to consider development pathways and future trajectories that sustain conservation values.

5 | CONCLUSIONS

This study presents a baseline understanding of cannabis production post-legalization in a legacy production region. The ecological metrics and maps presented here could be useful tools to begin prioritizing conservation and development trade-offs in a complex and rapidly changing industry. Landscape-scale cannabis management for conservation is increasingly urgent, particularly as cannabis legalization expands to more states, and federal legalization is being considered. Additionally, cannabis agriculture may offer important insights for other emerging development patterns that occur over longer time spans or policy-induced rapid land-use change frontiers in other regions. For example, development patterns of cannabis have similarities with small-scale slash and burn agriculture in parts of South America (le Polain de Waroux et al., 2018) or wealthy exurban development at wildland–urban interfaces in regions of Southern California (Radeloff et al., 2005; J. A. Smith, Duane, & Wilmers, 2019). Ultimately, policy shifts around cannabis and their resulting development impacts offer an exciting opportunity to study rapid land-use change and its potential consequences for biodiversity.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest for this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon request from the corresponding author, PPS.

The spatial data are not publicly available due to their containing sensitive information that could compromise the privacy of people living in the study area.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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