Cannabis, an emerging agricultural crop, leads to deforestation and fragmentation

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Early assessment of environmental impacts from emerging agriculture is a scientific challenge that – if poorly executed – limits sound policy making. Here, we present an approach for evaluating and forecasting the effects of emerging and expanding land uses on natural habitats. By analyzing landscape change per unit area, the effects of emerging land uses can be compared with established benchmarks. We apply this approach to study forest fragmentation in northern California, comparing the effects of cannabis agriculture – a booming commodity worldwide that affects diverse ecosystems – to those of timber harvest from 2000 to 2013. We found that although timber has greater impacts on the landscape overall, cannabis leads to far greater changes in key metrics on a per-unit-area basis. Thus, despite its small current land-use footprint, if changes are not made in the spatial pattern of its expansion, the boom in cannabis agriculture will likely create substantial threats to the surrounding environment. Future research, land management, and agricultural policy must account for these threats.

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Agricultural expansion is a leading cause of forest loss, biodiversity decline, and carbon emissions, and can also degrade habitat quality by fragmenting natural landscapes (Tscharntke *et al.* 2005; Sayer *et al.* 2013; Leal *et al.* 2016). Such expansion can diminish core habitat, increase edge effects, and alter the spatial configuration of forest, threatening species that rely on intact forest landscapes (Fahrig 2003; Fischer *et al.* 2006; Chaplin-Kramer *et al.* 2015) and imperiling ecosystem stability (Tscharntke *et al.* 2005; Leal *et al.* 2016).

Regulations on agriculture can, if well designed, mitigate impacts on natural landscapes and ecosystems, but regulations and environmental assessments usually come after crop production is well established (Payraudeau and van der Werf 2005). By then, major land-use conversion and other impacts may have already taken place (Chaplin-Kramer *et al.* 2015). There is, therefore, an urgent need for rapid analyses that can measure landscape change stemming from emerging agricultural activities, assess those changes at multiple scales, and forecast the potential environmental consequences of their expansion to help inform sound land-use policy (Clark *et al.* 2001; Chaplin-Kramer *et al.* 2015; Leal *et al.* 2016).

Our goal in this study was to develop and apply an efficient approach for assessing landscape changes resulting from new agricultural activities early in their emergence. We use this approach to examine the landscape impacts of cannabis (*Cannabis sativa* or *Cannabis indica*) agriculture, a rapidly emerging new form of land use with environmental impacts that are not well characterized but are suspected to be substantial (Carah *et al.* 2015; Butsic and Brenner 2016). Cannabis, as either a medicinal or recreational drug, is now legal in several countries and over 30 US states. Legal markets for cannabis in the US today are worth more than $7.6 billion (USD) annually, and this value is projected to grow to $21 billion by 2020 (ArcView Market Research 2016).

One area of high production is the "Emerald Triangle" of northern California, which is also home to a large timber industry and several endangered species, including the Coho salmon (*Oncorhynchus kisutch*) and northern spotted owl (*Strix occidentalis caurina*; Mooney and Zavaleta 2016). Expansion of cannabis production has contributed to environmental damage, including rodenticide poisoning of forest mammals (Gabriel *et al.* 2012; Thompson *et al.* 2014) and dewatering of streams due to improper irrigation techniques (Bauer *et al.* 2015). Moreover, the placement of cannabis farms in remote locations may produce disproportionate impacts on the environment, including greater risks of forest fragmentation, stream modification, soil erosion, and landslides (Butsic and Brenner 2016). While the overall size of most cannabis farms (or "grows") is small (<0.5 ha), the large number of grows and their distribution on the landscape have generated concerns over their impacts on forest habitat (Carah *et al.* 2015). Thus, as with many other emerging land uses and expanding agricultural activities (Chaplin-Kramer *et al.* 2015), the spatial pattern of cannabis agriculture may increase its environmental impacts.

We present a simple analysis to quantify the landscape change resulting from an emerging agricultural crop (cannabis), by comparing its per-unit-area effects on landscape fragmentation to those of an established agricultural industry (timber harvest). Our approach employs pattern metrics common in landscape ecology and

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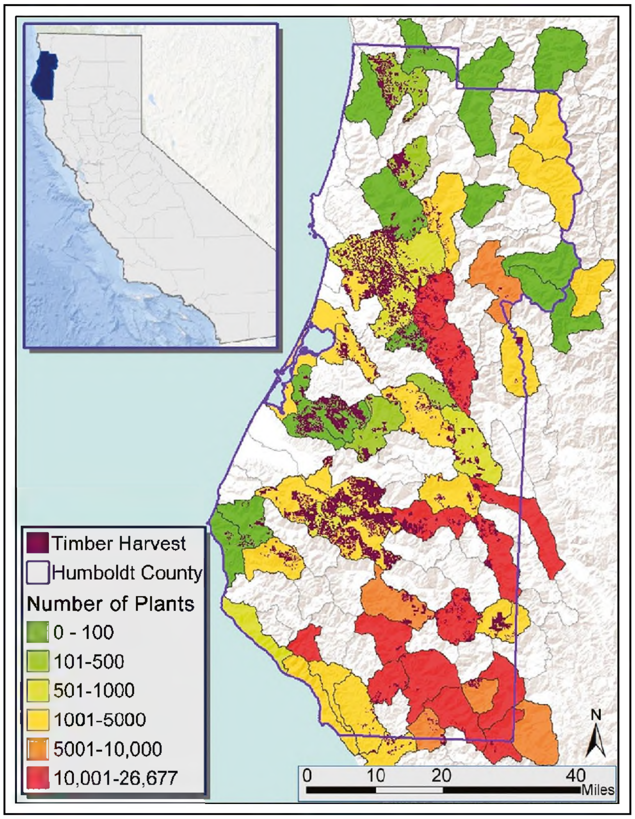

***Figure 1.** Map of our study area in Humboldt County, California, including the number of cannabis plants in each watershed and areas of timber harvest from 2000 to 2013.*

compares per-unit-area fragmentation effects of these two land-use activities. In doing so, we can control for differences in their total areas and isolate the effects that their distinct spatial patterns have on natural habitats.

Using forest change data from 2000 to 2013 combined with data on areas of cannabis grows and timber harvest in 2013, we investigate how cannabis expansion has affected forest fragmentation in Humboldt County, California. Specifically, we (1) evaluate the total direct effects of cannabis production and timber harvest on forest fragmentation at the county scale, (2) test for differential effects of cannabis agriculture among individual watersheds, and (3) quantify the per-unit-area impacts of cannabis grows relative to those of timber harvest. In applying our approach to the recent rapid expansion of cannabis cultivation, we test its effectiveness for identifying the impacts of emerging agriculture while also addressing real-world concerns about ongoing impacts of cannabis production.

Methods

Study area

Our study area consists of 62 randomly selected watersheds in or bordering Humboldt County, California (Figure 1; see Butsic and Brenner 2016 for comparative statistics). This area is located along the Pacific coast and is considered the leading cannabis-producing region in the US, if not the world (Butsic and Brenner 2016). Regional land cover is predominantly mixed conifer and hardwood forest, with pockets of open rangeland. Timber production contributed about $71.3 million in direct sales in Humboldt County in 2015, down from $81.5 million in 2014, according to the most recent Humboldt County crop report (Humboldt County 2015). In comparison, the wholesale value of cannabis production is likely over $300 million per year as of 2012, although no official data exist (Butsic and Brenner 2016). The value of cannabis production has therefore outpaced that of timber extraction in our study region, and ongoing changes in the laws regulating cannabis production and consumption across the world may make this an increasingly lucrative crop that displaces traditional land uses.

Data

We used three major datasets in our analysis, spanning from 2000 to 2013. This time frame represents an era of nearly unregulated cannabis expansion for which reliable spatial data are available for forest harvest and cannabis production. First, to track forest change from 2000 to 2013, we used GIS data layers of forest cover developed by Hansen *et al.* (2013), downloaded from Global Forest Watch (GFW; data.globalforestwatch.org). This dataset includes a forest cover map from 2000 and forest losses and gains for the duration of our study period, from which we constructed a map of forest cover for 2013.

Second, we rasterized (converted a vector file of polygons to a raster file of grid cells) a previously developed dataset containing shapefiles of cannabis grows in Humboldt County (Butsic and Brenner 2016; WebPanel 1) and then applied a 10-m buffer around each grow site (the area containing recognizable cannabis plants) after identifying the appropriate buffer size (WebPanel 1). This dataset was developed by heads-up digitizing Digital Globe imagery (www.digitalglobe.com) using Google Earth, and we performed internal and external validation to confirm the reliability of the resulting data prior to downstream analysis (WebPanel 1). Our database documents over 4400 cannabis grows, including outdoor plots and indoor greenhouses (Figure 2), with the average grow containing 67.3 ± 75.1 (mean ± standard deviation [SD]) cannabis plants and the largest grow containing 960 plants.

Finally, to differentiate between timber harvest and other forms of forest loss, we used data from the California Department of Forestry and Fire Protection (CAL FIRE) Forest Practice GIS database (ftp://ftp.fire.ca.gov/forest). In California, a timber harvest plan (THP) must be approved by the state before commercial harvest can begin. Therefore, we classified any forest loss in a site with a registered THP as timber harvest and

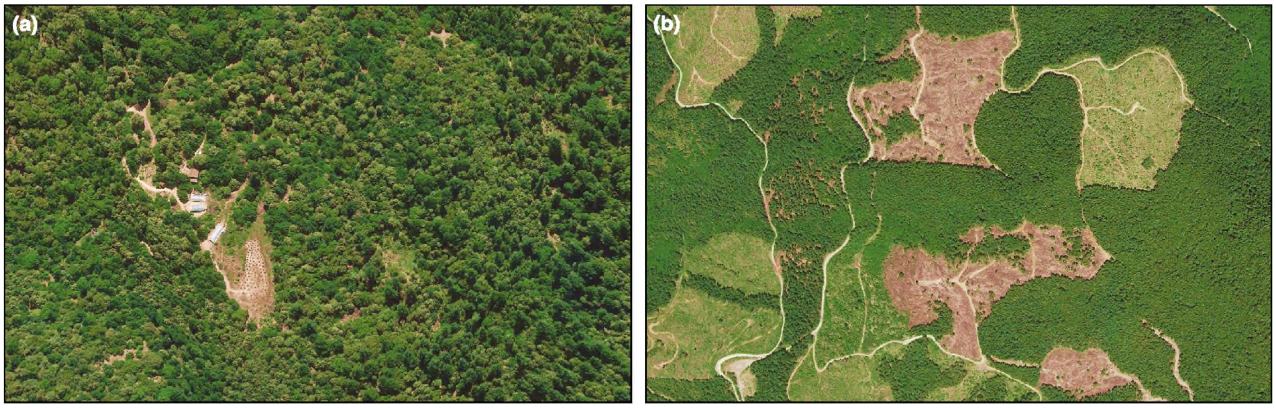

Figure 2. *Satellite images of representative cannabis grows (a) and timber harvest (b) in northern California (Google Earth Engine). (a) Clearing with greenhouses (upper left in clearing) and rows of cannabis plants (lower right in clearing), surrounded by a buffer area; (b) a typical pattern of large areas of clear-cuts for timber harvest and various stages of regrowth.*

constructed a map of timber harvest areas. Forest losses on sites with no THP were not designated as timber harvest; these are generally due to natural disturbance events but could result from illegal harvests, although there is no evidence of illegal timber harvest in Humboldt County (WebPanel 1). During the period of our study, timber harvest was a mix of clear-cuts and selective harvest in our study area.

Because cannabis plants could potentially be identified as forest cover from remote-sensing data, we examined whether any cannabis grows were misidentified as forest by the GFW dataset by examining whether any grid cells in our study area were classified as forest cover (on the 2013 forest cover raster) but were identified as containing cannabis grows (on our cannabis raster). These cells were subtracted from the 2013 forest cover raster prior to further analysis. To avoid attributing deforestation to these grows, we also tested whether any grows occurred in areas already deforested in 2000; these cells were not counted in analyses of the effects of cannabis agriculture on forest fragmentation.

In our final dataset, we had four rasters of forest cover (WebFigure 1), all of equal extent and cell sizes (0.9 arc seconds, ≈ 30 m): (1) forest cover for year 2000 from GFW (Y2000), from which landscape changes were calculated; (2) forest cover for year 2013 from GFW adjusted for cannabis grows misidentified as forest (Y2013), which most accurately reflects the actual state of forest cover in 2013; (3) Y2013 with cells containing cannabis grows reclassified as forest (Y2013-CG), which represents the landscape as if cannabis agriculture had not taken place; and (4) Y2013 with cells containing timber harvest reclassified as forest (Y2013-TH), which represents the landscape as if timber harvest had not taken place. The rasters excluding cannabis grows and timber harvest (Y2013-CG and Y2013-TH, respectively) allowed us to identify their effects on forest fragmentation by comparing the landscape pattern metrics on these hypothetical landscapes with those from Y2013.

Analysis of landscape metrics

We calculated several common landscape metrics in R using the SDMTools package (VanDerWal *et al.* 2014), which returns a variety of class-level and patch-level metrics based on the popular software FRAGSTATS (McGarigal *et al.* 2012). For each raster, we calculated a set of class metrics (WebTable 1), including the proportion of the landscape containing forest cover, patch area (total, mean, and SD), total length of patch edges, patch perimeter-to-area ratio (mean and SD), patch core area (total, mean, and SD), patch fractal dimension, patch shape index (mean and SD), landscape division index (McGarigal *et al.* 2012), and dominance of perforation (see discussion section) versus fragmentation (ε_d; Bogaert *et al.* 2002). The patch shape index is a measure of how much a patch deviates from a perfect circle (shape index = 1), where values >1 indicate increasing shape complexity (Forman and Godron 1986). The landscape division index is interpreted as the probability that two randomly chosen pixels are not in the same patch (McGarigal *et al.* 2012). Dominance of perforation versus fragmentation (ε_d) ranges from 0 to 1, with values closer to 1 indicating a dominant pattern of fragmentation and values closer to 0 indicating dominance of perforation (Bogaert *et al.* 2002).

We performed the landscape metrics analysis on all four forest cover layers (Y2000, Y2013, Y2013-CG, and Y2013-TH) for our entire study area and for 62 individual watersheds (WebFigure 1). The watershed-scale analysis, in which we used the USGS Watershed Boundary Dataset (http://nhd.usgs.gov/wbd.html) to "mask" individual watersheds on the forest cover layers, allowed us to investigate whether watersheds in Humboldt County were differentially affected by cannabis production and timber harvest. For both scales of analysis, we calculated the total change in each landscape metric from 2000 to 2013 (Y2000 versus Y2013) and the changes attributable to cannabis grows (Y2013 versus Y2013-CG) and timber harvest (Y2013 versus Y2013-TH). On the basis of these statistics, we also calculated the changes in landscape metrics from 2000 to 2013 as a percentage of their original values in 2000 and the proportions of those changes that were attributable to cannabis grows and timber harvest. Finally, because timber harvest currently covers a much greater area than cannabis, we calculated the effects of timber harvest and cannabis grows per unit area (WebFigure 1). In other words, we divided the total effects of cannabis grows and timber harvest by their respective total areas to quantify changes in landscape metrics resulting from the conversion of one unit of forest to either product (WebPanel 1). This allowed us to identify how the spatial patterns of cannabis grows and timber harvest produced different impacts on the landscape, irrespective of their total areas.

Results

Landscape change at the county scale

Our entire study landscape covered roughly 8067 km^2. Timber harvest covered a total area of 207.7 km^2, whereas cannabis grows occupied 6.2 km^2. Of these, 1.9 km^2 of cannabis grows were in areas not forested in 2000, and 4.1 km^2 were found in cells identified as forest on the 2013 GFW layer (Hansen *et al.* 2013). A total of 35 raster cells (<0.03 km^2) were identified as both timber harvest and cannabis grows.

Forest covered 79% (6375 km^2) of the landscape in 2000 but declined to 74.2% (5986 km^2) in 2013, representing a loss of almost 389.5 km^2 (Table 1; WebTable 2). Timber harvest was responsible for 53.3% of this loss, while cannabis grows accounted for 1.1% (4.2 km^2). Consistent with a landscape-wide pattern of forest fragmentation, we observed large changes from 2000 to 2013 in a variety of metrics (Table 1; WebTable 2), including the number of forest patches (53% increase), mean patch area (39% decrease), mean core area (42% decrease), total edge length (34% increase), and patch fractal dimension (43% increase). Perimeter-to-area ratio (6% increase), patch shape index (2% decrease), and landscape division index (2% increase) all displayed potentially important levels of change as well (Table 1; WebTable 2).

For all metrics, a much greater proportion of the total change resulted from timber (26.2% to 67.7%) as compared to cannabis (0.5% to 8.4%) (Table 1; WebTable 2). However, timber covered 33.5 times more area on the

Table 1. Changes in landscape metrics for forest patches over our entire study area from 2000 to 2013

		Total		*Per unit area*	
Metrics	*Total change (%)*	*Change due to CG (%)*	*Change due to TH (%)*	*Change due to CG/km^2 (%)*	*Change due to TH/km^2 (%)*
N_{forest}	53.4	0.5	39.6	0.088	0.191
P_{forest}	–6.1	1.1	53.3	0.174	0.257
Patch area (km^2)					
total	–6.1	1.1	53.3	0.174	0.257
mean	–38.8	0.4	31.6	0.066	0.152
SD	–25.2	0.5	40.2	0.077	0.194
Total edge length (km)	34.4	3.1	33.3	0.501	0.160
P/A					
mean	6.0	0.7	28.6	0.119	0.138
SD	–4.2	0.7	37.1	0.120	0.179
Core area (km^2)					
total	–11.5	2.3	42.9	0.365	0.207
mean	–42.3	0.7	30.6	0.107	0.148
SD	–29.7	0.9	39.3	0.143	0.189
Shape index					
mean	–2.1	–2.3	57.9	–0.364	0.279
SD	9.9	8.4	26.2	1.362	0.126
Fractal dimension	43.1	2.9	38.5	0.462	0.185
Landscape div index	2.1	0.8	67.7	0.128	0.326

Notes: We calculated the total overall changes on the landscape, the total changes due to cannabis grows (CG) and timber harvest (TH), and the per-unit-area changes due to cannabis grows (CG/km^2) and timber harvest (TH/km^2). Metrics included the number of forest patches (N_{forest}), the proportion of the landscape containing forest cover (P_{forest}), forest patch area (Patch area), total length of patch edges (Total edge length), perimeter-to-area ratio (P/A), patch core area (Core area), patch shape index (Shape index), patch fractal dimension (Fractal dimension), and landscape division index (Landscape div index). Definitions for the landscape metrics are available in WebTable 1, and raw values for all metrics on each raster are available in WebTable 2 and WebTable 4.

landscape. The metrics upon which cannabis agriculture had the greatest impact were total edge length (3.1%), total core area (2.3%), shape index (2.3%), and fractal dimension (2.9%) (Table 1; WebTable 2). For one metric, the direction of change caused by cannabis was different from that caused by timber harvest: cannabis increased patch shape complexity, while timber harvest had the opposite effect (Table 1; WebTable 2). We also found that cannabis grows generated a pattern indicative of greater landscape perforation ($\varepsilon_d = 0.346$) as compared to timber harvest ($\varepsilon_d = 0.424$), which produced a pattern of both perforation and fragmentation reflective of the combination of clear-cutting and selective harvesting in our study area (Figure 2).

Landscape change at the watershed scale

Across individual watersheds, the impacts of cannabis agriculture and timber harvest were highly heterogeneous. For example, 11 watersheds did not have any timber harvest, and 13 watersheds had no cannabis grows (WebTable 3). For seven metrics analyzed in detail, cannabis had larger total impacts on fragmentation in 15 to 17 watersheds, whereas timber had greater impacts in 44 to 47 watersheds (WebTable 3). Comparisons of changes caused by timber and cannabis revealed significant differences between their impacts on total edge length, total core area, mean patch area, fractal dimension, and the landscape division index (WebTable 3).

Landscape change per unit area

When we calculated the impacts of cannabis agriculture and timber harvest at equivalent per-unit-areas (controlling for their total areas), we found that 1 km^2 of cannabis agriculture generates very similar effects on forest fragmentation to 1 km^2 of timber harvest (Table 1; WebTable 4). Their effects on perimeter-to-area ratio and mean patch core area were remarkably similar, as were the magnitudes of their effects on patch shape index, although, as before, patch shape index changed in opposite directions (Table 1; WebTable 4). Timber harvest had a greater per-unit-area effect on the number of patches, patch area, and the landscape division index compared to cannabis agriculture, but cannabis grows resulted in 1.5 times greater loss of core area, 2.5 times greater change in fractal dimension, and a threefold greater increase in edge length than timber harvest per unit area (Table 1; WebTable 4).

Discussion

Early assessments of emerging agricultural practices are critical for forecasting their potential environmental impacts and mitigating these impacts through sound policy making (Girvetz *et al.* 2008). Here, we found considerable landscape change in Humboldt County over a 13-year period (Table 1; WebTable 2), resulting in not only forest loss but also conversion from large, contiguous forest patches to smaller, fragmented patches with more exposed edge and reduced core areas (Figure 2). All of these changes potentially have negative consequences for biodiversity and ecosystem function (Fahrig 2003; Fischer and Lindenmayer 2007). Although timber harvest was the primary driver of changes at the landscape scale, this was primarily because it disturbed an area 33.5 times greater than that of cannabis agriculture (Table 1; WebTable 2). After quantifying the per-unit-area impacts of these two industries (change per square kilometer), we found that their effects were often similar, and in some cases cannabis had a greater impact (Table 1; WebTable 4).

How their impacts differed reflects the different spatial patterns of the two land uses. Timber harvest, which affects large stands of forest, causes greater patch and landscape division and more forest loss per unit area, whereas cannabis grows, which are typically more isolated and placed away from roads in forest interiors, generate proportionately greater losses of core area and greater increases in forest edge and shape complexity (Figure 2; Table 1; WebTable 4). Thus, cannabis grows tend to cause perforation of forest patches, reducing their interior core areas by creating holes or gaps that generate more edge areas (forest areas bordering other landcover classes) and lead to greater irregularity in patch shape (patches that are more uneven, less circular, and less intact). Timber harvest, on the other hand, breaks up the forest into smaller, more isolated fragments but actually creates patch shapes that are more regular, probably because of the systematic, regulated practice of timber harvest in this region. The impacts of cannabis agriculture in the future will therefore depend on the spatial pattern of its expansion and the degree to which this land use expands in large parcels versus smaller, dispersed grows.

Although the current footprint of cannabis production has relatively minor landscape impacts, our per-unit-area analysis reveals it could cause extensive habitat modification when scaled up to meet increasing demand. Current California law caps the size of outdoor cannabis production to 1 acre (0.4 ha) per parcel. This maximum size restriction was put in place to prohibit the development of industrial-scale outdoor cannabis operations. An unintended consequence of this law may be the continued spread of small farms, which may perforate or fragment intact landscapes. Given that most grows in Humboldt County already occur on parcels less than 100 ha, this may lead to even further fragmentation.

The effects of cannabis production were highly heterogeneous across the study area and some of these environmental impacts have already been observed in individual watersheds. In roughly one-quarter of the study's watersheds, cannabis caused greater landscape change than timber harvest, including a >12% increase in forest edge and a >3% core habitat loss in certain watersheds

(WebTable 3). This observation is consistent with previous findings that cannabis grows are spatially clustered, leading to greater effects in some areas (Butsic and Brenner 2016). Thus, cannabis agriculture is already the primary driver of change in many of the remote, forested watersheds where it is most prevalent, and many species of conservation concern may experience the effects of habitat degradation at local scales such as watersheds (Vos *et al.* 2001; Leal *et al.* 2016). As many countries move toward liberalized policies surrounding cannabis consumption, our results point to a need for regulation and monitoring of cannabis production as it expands to meet growing demand. The environmental impacts of cannabis agriculture will depend upon the land-management practices, competing land uses, and local laws and economics surrounding cannabis for any particular location (Carah *et al.* 2015), but in all cases methods like the one introduced here will help to evaluate those impacts.

Our method assumes that the effects of emerging land uses are scalable and more-or-less linear. In other words, landscape impacts should increase in roughly the same way as the total footprint of the land use increases. This might not hold true in all cases but, if anything, would likely lead to underestimation of future impacts, which are unlikely to diminish during agricultural expansion (Rudel *et al.* 2009; Chaplin-Kramer *et al.* 2015). Additionally, the total impacts of cannabis agriculture at our study site could be underestimated by looking only at forest fragmentation. Most harvested timberland is replanted and therefore does not represent forest loss over longer timescales. Likewise, timber practices in Humboldt County are changing, with many of the largest landowners committing to using selective harvest techniques in the future. The longer-term impacts of cannabis agriculture, on the other hand, are still unknown. Given favorable markets (Arcview Market Research 2016), cannabis grows could persist, representing long-term, or even permanent, forest losses. This seems especially likely in our study area, where the value of cannabis crops has exceeded the value of timber harvest during recent years (Humboldt County 2015; Butsic and Brenner 2016); increasing demand and movements toward decriminalization should lead to even faster expansion of cannabis production in this region.

Our analysis also conservatively estimates the spatial extent of impacts around grow sites. Our 10-m buffer accounts for clearings but not impacts farther afield. These buffers often include access roads, trails, latrines, agrochemical storage sites, and waste dumps (MW Gabriel, pers comm). Many of these features, along with impacts such as agrochemical runoff, loss of water in streams, disturbance to wildlife by humans or domestic animals, and energy consumption (Carah *et al.* 2015), are invisible in satellite imagery and detectable only through fieldwork. Moreover, most of these impacts are generally not associated with activities like timber harvest. Finally, our analysis excludes an unknown number of clandestine cannabis production sites concealed under closed forest canopy. Thus, the overall environmental impacts stemming from the expansion of cannabis agriculture, as currently practiced, probably go far beyond forest fragmentation and may be cause for concern, further investigation, and policy response.

Conclusion

The rapid analysis of the early impacts of an emerging agricultural crop we present here is the kind of work that needs to be employed more often and earlier in the process of agricultural development (Clark *et al.* 2001; Rudel *et al.* 2009). By comparing landscape-scale and per-unit-area impacts of cannabis to those of an established industry (timber harvest), we present an efficient tool for forecasting the ecological consequences of agricultural expansion. Methods like this are needed for evaluating and predicting the effects of new land uses and for developing effective strategies to manage them (Clark *et al.* 2001; Vos *et al.* 2001).

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References

Arcview Market Research. 2016. The state of legal marijuana markets (4th edn). www.arcviewmarketresearch.com. Viewed 4 Sep 2017.

Bauer S, Olson J, Cockrill A, *et al.* 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. *PLoS ONE* **10**: e0120016.

Bogaert J, Van Hecke P, and Ceulemans R. 2002. The Euler number as an index of spatial integrity of landscapes: evaluation and proposed improvement. *Environ Manage* **29**: 673–82.

Butsic V and Brenner JC. 2016. Cannabis (*Cannabis sativa* or *C indica*) agriculture and the environment: a systematic, spatially-explicit survey and potential impacts. *Environ Res Lett* **11**: 44023.

Carah JK, Howard JK, Thompson SE, *et al.* 2015. High time for conservation: adding the environment to the debate on marijuana liberalization. *BioScience* **65**: 822–29.

Chaplin-Kramer R, Sharp RP, Mandle L, *et al.* 2015. Spatial patterns of agricultural expansion determine impacts on biodiversity and carbon storage. *P Natl Acad Sci USA* **112**: 7402–07.

Clark JS, Carpenter SR, Barber M, *et al.* 2001. Ecological forecasts: an emerging imperative. *Science* **293**: 657–60.

Fahrig L. 2003. Effects of habitat fragmentation on biodiversity. *Ann Rev Ecol Evol Syst* **34**: 487–515.

Fischer J and Lindenmayer DB. 2007. Landscape modification and habitat fragmentation: a synthesis. *Global Ecol Biogeogr* **16**: 265–80.

Fischer J, Lindenmayer DB, and Manning AD. 2006. Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes. *Front Ecol Environ* **4**: 80–86.

Forman RTT and Godron M. 1986. Landscape ecology. New York, NY: Wiley.

Gabriel MW, Woods LW, Poppenga R, *et al.* 2012. Anticoagulant rodenticides on our public and community lands: spatial distribution of exposure and poisoning of a rare forest carnivore. *PLoS ONE* **7**: e40163.

Girvetz EH, Thorne JH, Berry AM, and Jaeger JAG. 2008. Integration of landscape fragmentation analysis into regional planning: a statewide multi-scale case study from California, USA. *Landscape Urban Plan* **86**: 205–18.

Hansen MC, Potapov PV, Moore R, *et al.* 2013. High-resolution global maps of 21st-century forest cover change. *Science* **342**: 850–53.

Humboldt County. 2015. Humboldt County crop and livestock report. http://humboldtgov.org/623/Agricultural-Commissioner. Viewed 4 Sep 2017.

Leal CG, Pompeu PS, Gardner TA, *et al.* 2016. Multi-scale assessment of human-induced changes to Amazonian instream habitats. *Landscape Ecol* **31**: 1725–45.

McGarigal K, Cushman SA, and Ene E. 2012. FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. www.umass.edu/landeco/research/fragstats/fragstats.html. Viewed 4 Sep 2017.

Mooney HA and Zavaleta E. 2016. Ecosystems of California. Berkeley, CA: University of California Press.

Payraudeau S and van der Werf HMG. 2005. Environmental impact assessment for a farming region: a review of methods. *Agric Ecosyst Environ* **107**: 1–19.

Rudel TK, Defries R, Asner GP, and Laurance WF. 2009. Changing drivers of deforestation and new opportunities for conservation. *Conserv Biol* **23**: 1396–405.

Sayer J, Sunderland T, Ghazoul J, *et al.* 2013. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *P Natl Acad Sci USA* **110**: 8349–56.

Thompson C, Sweitzer R, Gabriel M, *et al.* 2014. Impacts of rodenticide and insecticide toxicants from marijuana cultivation sites on fisher survival rates in the Sierra National Forest, California. *Conserv Lett* **7**: 91–102.

Tscharntke T, Klein AM, Kruess A, *et al.* 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. *Ecol Lett* **8**: 857–74.

VanDerWal J, Falconi L, Januchowski S, *et al.* 2014. SDMTools: species distribution modelling tools: tools for processing data associated with species distribution modelling exercises. https://cran.r-project.org/web/packages/SDMTools. Viewed 4 Sep 2017.

Vos CC, Verboom J, Opdam PFM, and Ter Braak CJF. 2001. Toward ecologically scaled landscape indices. *Am Nat* **157**: 24–41.

Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1634/suppinfo