Cropland heterogeneity drives frequency and intensity of pesticide use

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Abstract

Agricultural landscapes across the planet have replaced natural habitat with crop production that is less diverse at field and landscape scales. Loss of cropland heterogeneity can increase pest colonization rates and decrease predation rates, thereby exacerbating pest pressure and leading to increased use of pesticides. Linking landscape pattern, crop pest pressure, and pesticide use is emerging as critical step for understanding the benefits, and potential trade-offs, of diversified agriculture. We advance this work by exploring how cropland heterogeneity drives pesticide use, and whether this effect is modified by pesticide class (i.e. fungicide, herbicide or insecticide). We focus on a diverse growing region, California’s Central Valley, and use spatial auto-regressive models to test for consistent class-based differences in the relationship between pesticide use and cropland heterogeneity (i.e. mean field size and landscape-level crop diversity). We find reduced pesticide use, in terms of both frequency and intensity of application, in diversified, spatially-heterogenous landscapes. Additionally, we see (a) more consistent responses of fungicides and insecticides to landscape pattern, (b) pesticide use increases as cropland becomes more homogenous with respect to crop identity, and (c) this effect is more consistent for perennial crops than annual crops. The modifying influence of pesticide class is largely consistent with expectations from ecological theory. Our results support increasing focus on whether enhancing the heterogeneity of the crop mosaic itself can benefit biodiversity, ecosystem services, and human well-being.

1. Introduction

Agricultural landscapes are shaped by market forces influencing farmers’ choices of what, where and how to produce (Bowman and Zilberman 2013). Expanding demands from a growing human population have resulted in the conversion of natural habitat to often homogenous expanses of input-intensive, yet high-yielding land use. This trend of landscape simplification is expected to increase pest pressure on crops by homogenizing cropland and limiting habitat for the natural enemies of crop pests, thereby leading to further reliance on agrochemical inputs. Already, approximately 2.7 billion kg of pesticides are applied to agriculture each year globally (Atwood and Paisley-Jones 2017), with annual expenditures exceeding US$58 billion (Chen 2017). These chemicals threaten both human (Bouchard et al 2011, Kim et al 2017) and ecosystem health (Pimentel et al 1992, Dale and Polasky 2007, Hallmann et al 2014). With 20%–30% of yield lost to pests and pathogens globally (Savary et al 2019), the challenge for holistic pesticide policy is to balance food security with the risks imposed by agricultural pesticide use (Möhring et al 2018). Understanding the links between landscape simplification, pests and pesticide use is an important pathway towards meeting effective usage-reduction goals.

Field-level pest dynamics are often tied to land use practices at larger spatial scales (Thies and Tscharntke 1999, Landis et al 2000). There are multiple mechanisms, potentially operating in parallel,
that underpin landscape effects on pests, including: resource concentration (Root 1973, Hambäck and Englund 2005), landscape complementarity (Dunning et al 1992, Landis et al 2000), and dispersal facilitation (Tscharntke et al 2007, O’Rourke and Petersen 2017). Evidence for these effects supports agricultural diversification strategies meant to enhance natural enemies by increasing habitat heterogeneity through various ‘ecological intensification’ approaches (Fahrig et al 2011, Schellhorn et al 2015, Kleijn et al 2019). These mechanisms and associated agroecological actions are supported by numerous case studies, yet pest responses to them are far from uniform; indeed, recent reviews indicated that impacts on pest populations range from strongly negative to positive (Chaplin-Kramer et al 2011, Karp et al 2018). It is unsurprising then that relatively few studies have examined whether naturally-sourced biocontrol leads to reduced pesticide use.

The evidence base for landscape effects on pesticide use is similarly equivocal, yet considerably less rich. Some studies report more insecticides are applied in simplified landscapes (Meehan et al 2011, Yang et al 2015, Larsen and Noack 2017), while others report significant variability in landscape effects over space and time (Larsen 2013, Meehan and Gratton 2016). Meehan et al (2011) put forth two hypotheses by which landscape pattern could influence insecticide use: (a) insecticide application responds to increased arthropod pest pressure due to simplification-driven reduction in natural enemy abundance and diversity, (b) insecticide application responds to increased pest pressure due to homogenous cropland resulting in greater host crop connectivity facilitating pest colonization. However, this previous work focused on whether insecticide use responds to landscape pattern. The ecological mechanisms that underpin the spatial dynamics of non-arthropod pests (e.g. plant pathogens and weeds) are far less studied, and the landscape effects on fungicide and herbicide use are unknown (Plantegenest et al 2007).

These pest-centered pathways are reasonable, but predicated on the assumption that farmers apply pesticides primarily in reaction to observed or expected damages. Farmers are not uniform in their responses to pest pressure, and biocontrol decisions can vary by operation, motivation, and socioeconomic constraints (Chaplin-Kramer et al 2019). Prophylactic or calendar-based applications are common, and likely to be influenced by exogenous variables, such as crop identity or value, then by pest pressure. These factors will also shape the relationship between landscape simplification and pesticide use. Moreover, the diverse pests afflicting agricultural production, from arthropods to weeds to fungal pathogens, are likely to respond in distinct ways to landscape heterogeneity. Therefore we may expect divergent landscape responses for different pesticide classes.

The majority of studies of landscape effects on pest control services have focused on overall landscape composition or amount of semi-natural habitat (Bianchi et al 2006b, Rusch et al 2016). How heterogeneity of cropland itself affects beneficial arthropods is still not well understood (Aguilera et al 2020). Cropland heterogeneity can be decomposed into composition-based measures—the number and amount of different crop patches (e.g. crop diversity, proportional coverage of specific crops)—and configuration-based measures—the shape and spatial arrangement of crop patches (e.g. mean field size, edge density) (Fahrig et al 2011). Research into cropland heterogeneity have been limited by two challenges. First, accurate and detailed spatial information on the extent of different crop types (as opposed to an aggregate ‘cropland’ land use class) is uncommon. Second, it can be difficult to disentangle collinearity between cropland composition and configuration. Nonetheless, recent studies have made advances investigating multiple aspects of cropland heterogeneity, finding largely additive effects of cropland diversity and field size on farmland biodiversity (Monck-Whipp et al 2018, Redlich et al 2018, Martin et al 2019, Sirami et al 2019).

Most pesticide use studies have examined a single metric of landscape simplification: county-level proportional cropland area. This coarse, composition-based metric may not capture important aspects of agricultural landscapes. In highly diverse agricultural systems, such as California’s Central Valley or regions dominated by small-holder farms, landscape-level crop diversity or mean field size may be important drivers of pests, their natural enemies, and ultimately pesticide use. Moreover, aggregating compositional information at coarse spatial scales (e.g. counties, large grid cells) precludes analysis of cropland configuration, forcing analyses to scales beyond those of some underlying ecological processes.

We adopt an econometrics approach (Rosenheim and Gratton 2017) and use a large public database to explore fine-scale spatial dynamics of pesticide use in California’s Central Valley. We build on previous work investigating landscape-scale drivers of pesticides use, but with four additional insights. First, we test whether pesticide use is affected by cropland configuration in addition to composition. Second, we explore whether pesticide use is influenced by cropland self-similarity—defined as the proportion of the landscapes surrounding a crop field that is composed of the same crop. Third, we explore multiple dimensions of pesticide use, including application intensity (kg ha\(^{-1}\)) and application frequency. Finally, we perform these analyses for multiple classes of pesticides, not just insecticides. Leveraging detailed pesticide use information from almost 8000 individual agricultural fields we ask:
(a) Do cropland diversity and field size affect field-level pesticide use frequency and intensity?
(b) Does self-similarity in crop land use drive field-level pesticide use?
(c) Does pesticide class influence these landscape effects on pesticide use?

2. Methods

2.1. Study area
California accounts for approximately 20% of United States agricultural pesticide use (Atwood and Paisley-Jones 2017). We focus our analysis in three counties in California’s Sacramento River Valley, USA: Colusa, Yolo and Solano. These counties cover 7993 km² with 3046 km² total crop area that is characterized by a diversity of production, from vineyard to orchard to row crops (California Department of Food and Agriculture (CDFA) 2017; www.cdfa.ca.gov/statistics/). In 2017, a total 125 different crop commodities were grown in the region, worth over $1.78 billion. The native vegetation is oak woodland, chaparral and riparian forest with most remnant natural habitat concentrated around the borders of agricultural lands or along waterways.

2.2. Data sources
We obtained pesticide use data from the California Department of Pesticide Regulation (CDPR) Pesticide Use Report (PUR) for 2017. The PUR database records field identity, crop identity, date of application, weight of each active ingredient (AI) applied, and treated acres. We enriched this database by joining to a statewide web-based GIS (CalAgPermits), allowing us to map agricultural applications through field identity to a specific spatial location. Together this creates a spatialized PUR. The PUR data are internally checked for errors, however, about 2% of records are found to have some type of reporting error when checked by CDPR (Yanga and Steinmann 2018), nonetheless the PUR data are considered highly accurate and the most detailed pesticide data in the world. We further filtered this dataset by eliminating the following:

- records of adjuvants, as the chemical identity of these are proprietary and their modes of action are unknown (35% of all records)
- records where application extent is not measured in units area (e.g. m² for greenhouses; <0.0001% of all records)
- records where the method of application was not aerial or ground (e.g. fumigation; <0.0001% of records)
- records with extreme application rates (i.e. kg ha⁻¹ >6 standard deviations away from AI-specific averages; <1% of all records)
- records for focal-fields that planted more than one crop (<5% of all focal fields).

This yields 7627 unique fields with 52 789 application records on 105 different crop commodities, which we summarize as explained below. To explore landscape effects on pesticide application we used landcover data from two sources. First, we retrieved the 2017 Crop Data Layer (CDL; United States Department of Agriculture (USDA) 2017) and resampled its resolution to 10 m² pixel size. Second, we used the spatialized PUR to create crop land use rasters (10 m² pixel size).

2.3. Landscape composition and configuration
We derive two focal landscape variables that characterize land use composition and configuration surrounding each field: crop diversity and mean field size. For each focal field, we identified the centroid and created concentric radii of 1000, 2000 and 3000 m. Using the spatialized PUR crop landcover, we calculated cropland diversity as the Shannon diversity index for all crop types within each radius. This variable approaches 1 as the number of different crop types increases and the proportional distribution of area among crop types becomes more even. We focus on crop diversity at the commodity level (i.e. sweet corn and fodder corn are separate ‘species’), because crop management practices are commodity-specific, rather than taxon-specific. However, we also conducted analyses for crop diversity at the taxonomic species- and family-level. Because we filtered intercropped fields, this variable does not consider within-field crop heterogeneity. Using the spatialized PUR, we calculated mean field size as the summed hectares across all patches, divided by the total number of patches within an each radius.

We also calculated three measures of land use as control variables: proportion semi-natural area (SNA), PUR coverage, and land quality (table S1 (available online at stacks.iop.org/ERL/16/074008/mmmedia)). We calculated the proportion of SNA using the CDL as the proportional sum of the following land use types: Shrubland, Barren, Deciduous Forest, Evergreen Forest, Mixed Forest, Grass/Pasture, Woody Wetlands, and Herbaceous Wetlands. Next, the spatialized PUR depicts only cropland that received pesticide application; non-agricultural or non-sprayed focal fields are not represented. This leads to some areas containing more spatial information than others. To address this difference in sample coverage we calculated the proportion of each radii that contained crop use information and use this as our PUR coverage variable. We investigated the distribution of land use not accounted for in the spatialized PUR by masking and summarizing the CDL in areas that do not contain spatial information in the PUR. We found that the majority of the area not covered by the PUR (87%) belongs to natural land use classes or is developed. Finally, we extracted a measure of land quality for each field from the California Department of
Conservation’s Farmland Mapping and Monitoring Program (FMMP; www.conservation.ca.gov/dlrp/fmmp). This statewide GIS categorizes farmland into quality classes based on previous land use, water availability, and soil quality.

To explore the response of pesticide use to the homogenization of landscapes by specific crops, we used the spatialized PUR to quantify landscape self-similarity. We define landscape self-similarity as the proportional area of a crop type surrounding a focal field that shares the same crop identity. As there are over 125 crops represented in this region, we focused on focal fields belonging to the top eight crops, which represent >85% of all 2017 PUR cropland. For each focal field, we identified its crop commodity type and calculated the area that is covered by the same crop. We then subtracted the area of the focal field from this extent and divided by the total area in each of the three radii above to derive the proportional extent of similar landcover around each focal field.

2.4. Pesticide use
To characterize pesticide use within each field we calculated two response variables that capture different dimensions of pesticide application: application frequency and application intensity. For each compound, we used pesticide property databases (PPDB and PAN) to classify whether the primary target of an AI are fungal pathogens (fungicides), arthropods (insecticides, including growth regulators), or weeds (herbicides). Henceforth, we consider individual pesticides based on their AIs, rather than their product (brand) names. Less than 1% of all field-applications belonged to pesticide classes not represented by these groupings (e.g. rodenticides, molluscicides) and we removed these records from the dataset. For application frequency, we counted the number of applications within each pesticide class for a given focal-field. Given a strongly right-skewed distribution, we log transformed application frequency. We adopted a common measure of pesticide intensity, the rate of application (Steinmann 2018), calculated as the amount of AI by extent of application (kg ha\(^{-1}\)). Grouping by focal-field, pesticide class, and crop, we then summarized application intensity across application days and AIs. Owing to large differences in toxicity, the amount of AI applied can vary by orders of magnitude (e.g. mean rate of the insecticide diazinon = 2.42 kg ha\(^{-1}\) vs the insecticide abamectin = 0.02 kg ha\(^{-1}\)), yielding a large range in application intensities across AIs. Therefore, we log transformed application intensity as well.

\[
\ln\left(\text{Frequency}_{ij}\right) = \beta_{0ij} + \beta_{1ij}\text{CropDiversity}_{2km} + \beta_{2ij}\text{FieldSize}_{2km} + \beta_{3ij}\text{SNAproportion}_{2km} + \beta_{4ij}\text{PURcoverage}_{2km} + \beta_{5ij}\text{CropID} + \beta_{6ij}\text{FMMPClass} + \epsilon_{ij}
\]

\[
\ln\left(\text{Intensity}_{ij}\right) = \beta_{0ij} + \beta_{1ij}\text{CropDiversity}_{2km} + \beta_{2ij}\text{FieldSize}_{2km} + \beta_{3ij}\text{SNAproportion}_{2km} + \beta_{4ij}\text{PURcoverage}_{2km} + \beta_{5ij}\text{CropID} + \beta_{6ij}\text{FMMPClass} + \epsilon_{ij}
\]

thus, the use of pesticide class i on parcel j is a function of crop diversity and mean field size. We also include four control variables (table S1): (a) proportion SNA to account for the influence of other natural areas in the landscape (b) PUR coverage to account for differences in amount of crop use information in the landscape, (c) focal field crop identity to account for crop-specific differences in pesticide use, and (d) focal field FMMP class account for differences in agricultural land quality.
Second, we tested the effect of landscape self-similarity on pesticide use using multiple generalized least squares (GLS) models. We focused our analyses on the eight crops that represent 86% of cropland area. Our response variables are the two pesticide use metrics. Our predictor is the proportion of like-landcover for these eight crops. We constructed separate models for each combination of pesticide use metric, pesticide class and crop type. Because we test multiple univariate models, we use a Benjamini and Hochberg (1995) false discovery rate procedure to correct for multiple testing and present adjusted P-values.

Third, we explored whether crop value explained patterns of pesticide use using GLS models. We follow Rosenheim et al (2020) and use the CDEA-reported USD $ per hectare value of each crop as the predictor of pesticide frequency and intensity. We included an interaction term between value and pesticide class to see if the slope of this relationship depended on pesticide class.

All analyses were conducted in R (R Development Core Team 2018); spatial autocorrelation tests were implemented with the ‘spdep’ package (Bivand 2018), SAR models were fit via maximum likelihood using the ‘spatialreg’ package (Bivand 2013), SUR models with spatial errors were fit via maximum likelihood using the ‘spsur’ package (Mínguez et al 2018). GLS models were fit using the ‘nlme’ package (Pinheiro and Bates 2010).

3. Results

Across 7627 agricultural fields in Colusa, Yolo, and Solano counties applications of 65 distinct fungicides, 76 distinct herbicides, and 81 distinct insecticides occurred in 2017. A few compounds such as sulfur, glyphosate, and lambda-cyhalothrin dominate applications, whereas most compounds are applied infrequently (figures 1(a), (c) and (e); table S1).

Similarly, most fields only applied one or two fungicide, herbicide or insecticide Alts (figures 1(b), (d) and (f)).

These compounds were used on 105 different crop commodities belonging to 22 plant families. Overall, our study region is characterized by both heterogeneous cropland and pesticide use that exhibits substantial spatial variability (figure 2).

Field-level pesticide use is affected by landscape composition and configuration, but the magnitude and direction of this relationship depends on pesticide class (figure 3). For mean field size models the frequency (figure 3(a)) and intensity (figure 3(c)) of fungicide and insecticide use increased as landscapes became dominated by larger fields. Mean field size did not affect herbicide use. For cropland diversity models, the frequency (figure 3(b)) of fungicide and insecticide use decreased with increasing cropland diversity, although fungicide frequency was marginally affected (P = 0.06). The intensity of insecticide use decreased, whereas intensity of herbicide use increased with cropland diversity (figure 3(d)). Cropland diversity did not affect the intensity of fungicide use. When calculated at the taxonomic species- or family-level crop diversity did not affect pesticide use, other than herbicides (table S3). Insecticide use decreased with the amount of SNA (figure S2). The frequency and intensity of herbicide use increased with proportion SNA and cropland extent (figure S2). Application frequency and intensity of all pesticide classes increased with crop value (figure S3). For spatial SUR models, crop identity was a significant term, indicating that pesticide use patterns are crop-dependent. We explore this dependency further below.

Eight crops represent 86% of crop area: rice (29%), almonds (21%), walnut (8%), processing tomatoes (8%), alfalfa (7%), wine grapes (5%), wheat (5%), and sunflower (3%). Not every pesticide class was applied to each crop, for example
Figure 2. Regional variation in crop diversity (a) and the intensity (log(kg ha$^{-1}$)) of fungicide (b), herbicide (c) and insecticide use (d).

wheat received no fungicide or insecticide application. Generally, pesticide use increased with landscape self-similarity. Fungicide and insecticide use responded consistently to landscape self-similarity, increasing as landscapes became more homogenous. For the five crops that received fungicide applications (tomatoes, rice, grapes, alfalfa, walnut and almonds), both frequency and intensity of use increased for all but rice (figures 4(a) and (d)). For the seven crops that received insecticide applications, the frequency of use increased for all seven (figure 4(c)) and the intensity (figure 4(f)) increased for all except sunflower, walnuts and rice. The response of herbicide use to landscape self-similarity was less consistent. For the eight crops that received herbicide applications, the frequency of herbicide use (figure 4(b)) increased for alfalfa. The intensity of herbicide use (figure 4(e)) increased for alfalfa and decreased for almonds. Overall, significant relationships were observed more frequently for perennial crops (73%; 16/22 regressions) than annual crops (33%, 6/18 regressions).

4. Discussion

Overall, we find reduced pesticide use frequency and intensity, in diversified, spatially-heterogenous landscapes. This striking result is in many regards consistent with expectations. Landscape simplification can increase pest pressure over large spatial extents, increasing pest-induced yield loss and intensifying the need for pesticides. Previous research has focused on insecticide application patterns (Meehan et al 2011,
Growers applied insecticides, and to a degree fungicides less frequently in landscapes with greater crop diversity. Cropland diversity influenced the intensity of use (kg ha\(^{-1}\)), with insecticide intensity decreasing and herbicide intensity increasing as landscapes diversified. The configuration of fields also influenced use patterns. In landscapes with smaller average field size we found the frequency and intensity of fungicide and insecticide use decreased, while herbicide use was unaffected. These results are consistent with theoretical work (O’Rourke and Jones 2011) and empirical studies that find positive relationships between landscape simplification and insecticide use, whether within a county (Larsen and Noack 2017, 2020) or across counties (Meehan et al 2011, Meehan and Gratton 2016). Like these previous studies, this work suggests that increasing cropland heterogeneity could decrease local insecticide use. We extend this previous research by showing that this relationship is explained by cropland self-similarity and modified by pesticide class. We discuss these factors below.
Figure 4. The effect of cropland self-similarity on pesticide use frequency (a)–(c) and intensity (d)–(f). Crop types are listed in order of increasing areal extent within two groups: annuals (no shading) and perennials (gray shading). Separate models tested whether the frequency (a) or intensity (b) of fungicide (red), herbicide (blue) or insecticide use (yellow) on focal fields changed when surrounding landcover was increasingly dominated by cropland sharing the same identity as the focal field (i.e. landscape self-similarity). Note, not all pesticide classes were applied to every crop (e.g. fungicides or insecticides on wheat). Points represent regression coefficients from generalized least square models. Points above zero indicate that pesticide use increased. Filled points represent coefficient estimates that are significant at $P = 0.05$ after a Benjamini–Hochberg adjustment. Error bars are 95% confidence intervals of unadjusted $p$-values.

Pesticide use increased as cropland became increasingly homogenous with respect to crop identity, corroborating our finding that crop diversity generally reduces pesticide use. The agricultural region we assessed is spatially heterogenous in its crop composition, with over 120 different crop commodities grown. Nonetheless, spatial dominance of crops played an important role in explaining patterns of pesticide use. For the eight crops representing the majority (86%) of arable land in this region, we found that cropland self-similarity generally increased pesticide use. Agricultural landscapes are increasingly characterized by large proportions of arable land dominated by a few crop types (Bennett et al. 2012). Our findings are consistent with a long history of research showing that pest outbreaks (Altieri 1999, Bianchi et al. 2006b, Letourneau et al. 2011, Redlich et al. 2018), but unique in showing that pesticide use increases as cropland homogenizes.

Pesticide class moderated the effect of cropland heterogeneity. On balance, there is more support for landscape effects on fungicide and insecticide use than herbicides. By simply ‘vote-counting’ across results (including composition, configuration and self-similarity) we find significant changes in pesticide use in 71% of fungicide results (10/14 possible effects) and 83% of insecticide results (15/18), compared to 20% of herbicide results (4/20). Moreover, the direction of response for fungicides and insecticides is consistent (e.g. use increased with increasing field size), whereas herbicide use showed diverging responses to cropland heterogeneity. How far a pest spreads through a landscape and whether or not it persists depends upon not only the crop mosaic within the landscape, but the underlying ecology of the organism. Considering the life history of target organisms can help elucidate similarities and differences in pesticide use.

The conceptual basis of landscape-moderated effects on agricultural pests is largely grounded in meta-population theories, with an evidence bias towards arthropod pests involving colonization dynamics of pests and their natural enemies and the maintenance of enemy-free space (Bowman et al. 2002, Segoli and Rosenheim 2012). Larger field sizes or monocultures create larger areas of enemy-free space, where arthropod pests are expected to persist within the crop itself (e.g. navel orange worm within almond) and/or where natural enemies either disperse more slowly or rely on alternative resources that tie them to non-crop habitats. Diversified agriculture can also exert regulating effects on arthropod pests from the bottom—by limiting detection of preferred host plants (i.e. associational resistance; Tahvanainen and Root 1972, Andow 1991, Agrawal et al. 2006).

Root’s (1973) prediction that specialist herbivores are more likely to find and remain on their host plants...
in larger monocultures is upheld as a main mechanism and its empirical support is reviewed elsewhere (Bianchi et al 2006b, Letourneau et al 2011, Rusch et al 2016, Daniese et al 2019).

Linking plant pathology and landscape ecology has received considerably less attention, especially for economically important crop diseases (Plantagegenest et al 2007, Meentemeyer et al 2012), despite the well-recognized influence of landscape configuration on animal disease dynamics (Ostfeld et al 2005, Jousimo et al 2014). Crop diversity and field size may disrupt pathogen spread by altering the spatial structure of susceptible hosts. If crops possess differential susceptibilities, then epidemiological theory would predict slower spread across a heterogeneous crop mosaic (Gilligan 2008). In microcosm experiments of mixed radish and mustard populations, Otten et al (2005) found the inclusion of less susceptible hosts slowed the spread of damping-off (Rhizoctonia sola) epidemics. The reduction in pesticide use in diversified landscapes with smaller field sizes that we observed is supported by metapopulation theory which predicts occupancy of insect pests should decrease with field size and isolation, as well as epidemiological theory which predicts decreased spread of fungal pathogens as the density of susceptible hosts (crop fields) decreases.

What of weeds and herbicide use? Landscape perspectives of weed prevalence are emerging. Generally, weed diversity is higher in complex landscapes than in simple ones (Petit et al 2013), with the ‘species pool hypothesis’ (Zobel 1997) typically evoked to explain these results (Gabriel et al 2005). Cropland heterogeneity increased herbicide use. Our study system harbors a diversity of habitats, likely resulting in a larger regional species pool and greater potential for seed rain from these alternate source habitats. Furthermore, unlike insects and pathogens, weeds do not require specific hosts and are more general in their life history requirements, thus the spatial dynamics of resource concentration and host susceptibility are likely to play less of an important role. Finally, field-level management (e.g. tillage) that affects local seedbanks is assumed to drive the dominance of agricultural weeds (Cardina et al 2002), further supporting the lack of landscape effects on herbicide use that we observe.

Crop attributes can also moderate these landscape effects. As cropland became more homogeneous, herbicide use generally increased, yet this relationship is more consistent for perennial crops than annuals. At landscape scales, spatial dominance of perennials could drive pesticide use because these landscapes provide consistent habitat and refugia, thereby allowing pest populations (especially host-specific arthropods and pathogens) to persist or build up over time. Perennial crops are also more likely to harbor perennial weeds (Gaba et al 2014), thereby sustaining propagule rain. These results underscore the importance of considering cropland diversity across multiple dimensions. Indeed, temporal diversity achieved through rotation of annual crops is an enduring management strategy that aims to limit the accumulation of agricultural pests by disrupting resource availability. There is also uncertainty in the timing of application because pest arrival is a stochastic event. Examining within-year temporal heterogeneity of application could reveal when and where pesticide use inefficiencies may occur (Skevas et al 2012). Although it is beyond the scope of the present study, consideration of how pesticide use is influenced by spatio-temporal dynamics of crop diversity in this system would be a valuable future direction.

Our ecoinformatics approach allowed us to leverage a high volume of data to test for landscape effects on pesticide use across an entire agricultural region. Recent research has shown that the ability to consistently detect pest and pesticide responses to landscape pattern requires sample sizes that are much larger than those typical of landscape pest-control studies (Meisner and Rosenheim 2014, Paredes et al 2021). Nevertheless, a drawback of this approach is that our inferences are based on correlative evidence. There are likely other factors driving pesticide use. However, without manipulative experiments or data on natural enemies or alternative hosts, we can only speculate as to why pesticide use changed in landscapes with greater cropland heterogeneity. Like others (e.g. Larsen and Noack 2020), we assume that patterns of pesticide use reflect patterns pest pressure. There is evidence to suggest that pest control behavior is typically responsive (Wilson and Tisdell 2001, Sexton et al 2007, Waterfield and Zilberman 2012), wherein farmers are basing use decisions on pest densities or damage thresholds (Paredes et al 2021), rather than routine application. Like others (Rosenheim et al 2020), we found that pesticide use increases with crop value (USD $ ha$ ) However, other currently unmeasured cultural factors may also play a role, such as information exchange networks or risk tolerance (Pannell 1991, Reisig et al 2012, Chaplin-Kramer et al 2019). Our spatial regression techniques and the inclusion of crop identity and land quality as a fixed effect may account for some of these factors. However, if these unmeasured aspects of pesticide use behavior are not spatially structured or crop specific we cannot preclude their potential influence.

Here we assessed pesticide use patterns, however we do not account for their toxicity. Better understanding spatial variation in levels of hazard and exposure, in other words the landscape of pesticide risk, is a critical next step. Future work could model the exposure of specific organisms to different pesticides using spatially explicit frameworks, and combine these outputs with known toxicities. Doing
so would permit fine-scale evaluation of pesticide risk, thereby aiding crop management plans to better integrate pest management with biodiversity conservation.

Developing sustainable agricultural practices that are resilient and less reliant on synthetic pesticides is a primary goal of integrated pest management. This research shows that pathways towards this goal operate at scales beyond focal-field considerations and should account for cropland context. Previous conservation biocontrol research largely focused on the positive bottom-up effects of integrating semi-natural habitat into agricultural landscapes (Dainese et al. 2019). Here we show that keeping land in production, but increasing crop diversity and decreasing average field size could reduce landscape-wide pesticide use. For example, based on our log-linear model, for every 10 ha increase in mean field size we expect the intensity (kg ha⁻¹) of insecticide and fungicide use to increase by approximately 7% (11–14% CI). Reduced pesticide use through field size planning could present a real cost-saving opportunity for producers. Of course, smaller field sizes can incur both direct (working time, fuel consumption) and opportunity costs (yield area, farmland valuation) (Gonzales et al. 2007, Latruffe and Piet 2014). However, smaller farms, on average, have higher yields, have greater crop and non-crop biodiversity at the farm and landscape scales and benefit from increased biodiversity-mediated ecosystem services (Martin et al. 2019, Ricciardi et al. 2021). The degree to which ecological-economic trade-offs are mediated by field size is still largely ignored by both policy and research (Clough et al. 2020), and further work is needed to understand the economics of cropland configuration.

The benefits of reduced pesticide use are numerous, including mitigating biodiversity loss (Pimentel et al. 1992, Dudley et al. 2017), decreasing exposure-related health impacts to farm workers (Weichenthal et al. 2010, Kim et al. 2017), limiting toxicological effects for downstream communities (Winchester et al. 2009, Larsen et al. 2017), and direct cost-savings for producers (Sexton et al. 2007). Recent calls to overhaul regulation and environmental risk assessment of pesticides (Topping et al. 2020) advocate for a socio-ecological systems approach, rather than single product, single crop assessments. Integral to this approach is an explicit consideration of how multiple pesticides integrate across different agricultural landscapes to determine risk. Here we show that cropland with greater crop diversity and smaller field size experience less frequent and less intense pesticide use. In addition to increasing and conserving natural habitat, diversifying existing cropland is another option for realizing multiple socio-ecological benefits from reduced pesticide use.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.cdpr.ca.gov/docs/pur/purmain.htm.

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