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Identifying the landscape drivers of agricultural insecticide use leveraging evidence from 100,000 fields

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Agricultural landscape intensification has enabled food production to meet growing demand. However, there are concerns that more simplified cropland with lower crop diversity, less noncrop habitat, and larger fields results in increased use of pesticides due to a lack of natural pest control and more homogeneous crop resources. Here, we use data on crop production and insecticide use from over 100,000 field-level observations from Kern County, California, encompassing the years 2005–2013 to test if crop diversity, field size, and cropland extent affect insecticide use in practice. Overall, we find that higher crop diversity does reduce insecticide use, but the relationship is strongly influenced by the differences in crop types between diverse and less diverse landscapes. Further, we find insecticide use increases with increasing field size. The effect of cropland extent is distance-dependent, with nearby cropland decreasing insecticide use, whereas cropland further away increases insecticide use. This refined spatial perspective provides unique understanding of how different components of landscape simplification influence insecticide use over space and for different crops. Our results indicate that neither the traditionally conceived "simplified" nor "complex" agricultural landscape is most beneficial to reducing insecticide inputs; reality is far more complex.

pesticides | biological control | landscape simplification | landscape complexity | crop diversity

Agriculture has increased to meet the demand of a growing and wealthier population that demands more, and more resource intensive, calories (1). The doubling of agricultural production in the past 40 y has been fueled by technological improvements as well as higher levels of pesticide and fertilizer inputs (2). Although this increase in food production has contributed to vast improvements in nutrition and reductions in hunger worldwide (2, 3), the ecological and environmental consequences of these inputs are straining the long-term viability of agricultural systems (1) and the human and natural communities that surround agricultural production (4, 5).

Agricultural intensification at both local (on-farm) and landscape (regional) scales has been the workhorse behind production increases. Farms have become specialized on fewer, high-yielding crops grown in shorter rotation cycles on larger fields (6). In aggregate, agricultural landscapes have become more simplified with less noncrop habitat and fewer crop types in production (6). Aggregate food production from intensification has undoubtedly increased, reducing the pressure of agricultural land expansion into natural habitats to meet the growing food demand (7). However, there are numerous unintended consequences of agricultural intensification for biodiversity (8–10), water quality, and other ecosystem services (5, 11).

Modern agricultural systems rely on agrochemicals to reduce pest damage, thereby minimizing crop loss (12). However, many of these chemicals have adverse environmental and ecological effects. Pesticides, broadly, and insecticides, in particular, have been linked to biodiversity declines in numerous taxa in both temperate and tropical regions (13, 14), as well as declines in water and air quality. Further, off-site pesticide contamination and pesticide resistance are important externalities of pesticide use that have consequences for both chronic and infectious human diseases.

Pesticide use is fundamentally about controlling pest damage. Crops can vary substantially in average insecticide use based on value or susceptibility to pest damage. However, given the set of crops in production, ecologists are seeking means to reduce excess insecticide use by manipulating on-farm and landscape characteristics. Because insect pests and natural enemies often have large dispersal ranges and varied habitat needs, the focus has been on if and when complex landscapes reduce pest abundance or, conversely, if and when simplified landscapes lead to more pest problems (15). However, ecological field studies seeking to inform more sustainable pest control practices face an enormous challenge. Pest community composition and pest damage may be intricately linked to landscape composition, habitat configuration, and the focal crop type in ways and at spatial scales that are difficult to address in field experiments. As a result, the evidence tying simplified habitats to insecticide use is often specific to one crop and pest combination (e.g., ref. 16) and is equivocal overall (15, 17).

Data-driven approaches have proven useful in elucidating the larger scale patterns in the relationship between landscape-level agricultural intensification and insecticide use (18, 19). However, these studies have been limited in spatial resolution of both crop (20) and insecticide data (21). Thus, the majority of research has focused on one aspect of landscape simplification, namely, cropland extent measured as the proportion of county in cropland. In highly simplified agricultural regions that are dominated by one or a couple of crops, county-level cropland may serve as an appropriate metric for intensification. However, in highly diverse agricultural regions, landscape-level crop diversity, in addition to cropland extent, may be an important driver of pests and enemies (22, 23). Further, cropland extent may act on both local (field size) and landscape (landscape composition) scales. Disentangling such

Significance

Ecological theory predicts simplified agricultural landscapes composed of large-scale, homogeneous cropland will have increased pest problems due to fewer natural enemies and concentrated host plants, which will result in increased pesticide use and associated environmental degradation. Using detailed data from Kern County, California, for 100,000 field-year observations, we parse apart how different components of landscape simplification affect insecticide use. We find insecticide use decreases with increases in crop diversity and increases with field size, whereas the effect of cropland extent depends on the spatial scale. This refined spatial perspective provides unique understanding of how different components of landscape simplification influence insecticide use, and indicates that neither the traditionally conceived "simplified" nor "complex" agricultural landscape is most beneficial to pest control.

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complexities requires refined data on crops and insecticides at large spatial scales, information that is currently absent for much of the world.

Here, we take advantage of unique field-level crop and pesticide data for ∼100,000 field-year observations in the agriculturally diverse Kern County, California, from 2005 to 2013 to understand if crop diversity ("diversity"), field size, and cropland extent drive insecticide use. Kern County is situated in the southern San Joaquin Valley and is California's second ranked county by agricultural production value, with an annual agricultural output of ∼6 billion dollars (24). Although the leading crops by value are grape varieties and almonds, over 200 different commodities are produced (24). We first conduct the analysis pooling all crops to understand general patterns in insecticide use and landscape simplification using panel data analyses that control for regional differences in insecticide use as well as for year shocks in pest control. Because crops are not planted haphazardly, we then use crop-specific controls (i.e., crop dummy variables or "fixed effects") to parse the effect of crop diversity from the differences in crop composition that may be inherent to landscapes with high or low levels of crop diversity. Using these models, we evaluate if crop diversity, field size, or cropland extent drives insecticide use. Further, we test whether the effect of diversity is dependent on the classification and taxonomic level at which diversity is measured. More taxonomically similar crops may be expected to share more pests, yet taxonomically similar crops can be used for very different products (e.g., wine grapes, table grapes) that are associated with different levels of pesticide use and different timing of planting and harvesting. We therefore calculate diversity at different taxonomic levels to understand better which, if any, is most relevant for pest control decisions. Finally, we probe crop-specific relationships, focusing on almonds, grapes, oranges, pistachios, carrots, and wine grapes, which account for over 80% of insecticide use in Kern County. For each of these crops, we again evaluate the influence of diversity, field size, and cropland extent on the magnitude of pesticide applications.

Results

In general, we find that increasing crop diversity reduces insecticide use per hectare, whereas increasing field size increases insecticide use. These relationships, as well as the relationship between cropland extent and insecticide use, are strongly influenced by crop type.

We conducted all analyses at the field scale. There are ∼13,000 fields active per year, with crop diversity, cropland extent, field size, and insecticides varying regionally (Fig. 1). Crop diversity was calculated as the Simpson's Diversity Index (SDI) of all crops within a 2,500-m radius of the focal field (∼1,963-ha area) and did not include the focal field. SDI was calculated at different taxonomic levels (species, genus, and family) or commodity levels (commodity and agricultural class). Unless otherwise noted, the results discussed below are from models based on SDI at the species level. To facilitate comparison, all covariates were standardized.

For models including all crops ("all-crop" models), we found the largest (absolute) effect of crop diversity on insecticide use in the pooled ordinary least squares (OLS) model, followed by the fixed effects model with region and year controls, and then by the fixed effects model with crop and year controls (Fig. 2 and Table S1). Throughout, we are following the econometric use of the term fixed effects to describe panel data models with dummy or indicator variables for each crop, year, or region. Similar to demeaning of the dependent variable, this method uses only the variation in the data that is not explained by differences in pesticide use between years, regions, or crop types (i.e., the model is identified by "within" variation). In contrast, the pooled OLS model clumps all observations together and does not distinguish unobservable differences in crops, years, or regions. However, crops differ dramatically in average insecticide use (Table 1), and failing to control for these differences may bias the statistical estimation. In other words, the effects observed may be driven by differences in crop types in highly diverse versus less diverse areas, not by diversity per se. To control for the possibility that farmers plant low-insecticide crops in highly diverse crop landscapes, we included crop type dummy variables (crop fixed effects) to compare how insecticide use varies with cropland diversity, extent, and field size for a given crop (*Methods*). We also tested models with regional fixed effects to account for (roughly) time-invariant characteristics, such as soil quality or cultural norms, that are shared by all fields in a region. Here, region was defined by the 93-km^2 Public Land Survey Township. Annual variability in insecticides (e.g., prices, technologies), diversity, or weather (e.g., historic drought) could also be important determinants of the relationship between landscape characteristics and insecticides. As such, we included year dummy variables in both the crop and region fixed effects models.

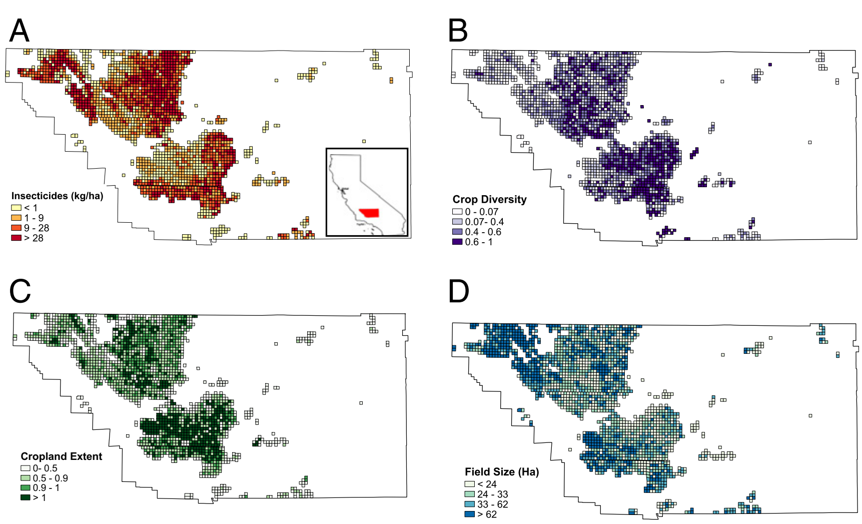

Fig. 1. Map of insecticides (*A*), crop diversity calculated at species (*B*), cropland extent (*C*), and mean field size (*D*) by a 2.6-km^2 Public Land Survey (PLS) section. For all maps, darker colors indicate larger values and the four colors represent quartiles in the distribution.

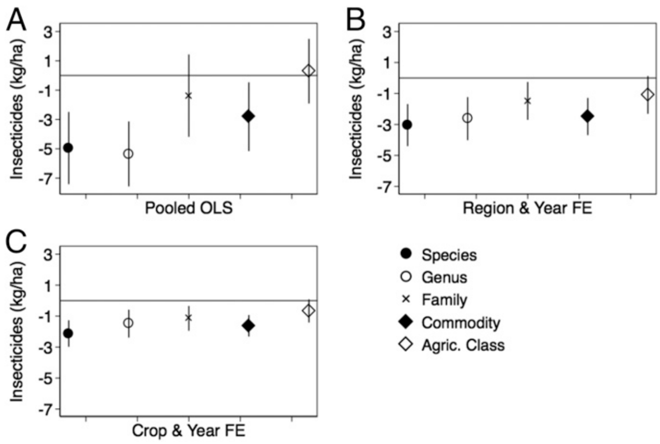

Fig. 2. Effect of crop diversity on insecticides is influenced by crop-specific characteristics and the taxonomic scale at which diversity is calculated. Including crop fixed effects (FE; dummy variables) (*C*) dramatically reduced the magnitude of the estimated coefficient relative to the pooled OLS model (*A*), and relative to the model with regional (93-km^2 PLS Township) and year fixed effects (*B*), indicating that diversity and crop type are correlated. Generally, the estimated effect of diversity, calculated as the diversity of crops grown within a 2,500-m radius of the focal field, decreased in magnitude as the grouping at which diversity was calculated became more aggregated. For all figures, the *y* axis is the size of the slope coefficient (change in insecticide use, in kilograms per hectare). The symbols indicate the point estimate of that relationship for each of the five "taxonomic" diversity metrics. Error bars indicate the 95% confidence interval. Error bars that cross the horizontal zero line indicate a nonsignificant relationship. Agric., agriculture.

Across the different all-crop models, the estimated effect of diversity decreased with taxonomic level. The effect of diversity calculated at the species or genus level had an estimated relationship roughly twice the magnitude as diversity calculated at the family level (Fig. 2). For diversity calculated at the species level, an increase in diversity of 1 standard deviation (SD) resulted in reduced insecticide use of about −5.0 kg/ha, −3.0 kg/ha, and −2.1 kg/ha for the pooled OLS, region, and year fixed effects model and for the crop and year fixed effects model, respectively (Table S1). Average field level insecticide use across all crops and years is 16.1 kg/ha; thus, a 2.1-kg/ha reduction is equivalent to a 13% decrease in average use. For all models, the coefficients for diversity calculated at genus and commodity followed a similar pattern to the coefficients for diversity calculated at the species level. In contrast, the larger aggregations of family and agricultural class had diversity coefficients of smaller magnitude relative to species (Fig. 2 and Table S1).

For cropland extent, defined as the proportion of area in agriculture within a 2500-m radius of the focal field, increasing extent was nonsignificant in all models, with coefficients smaller than 1 kg/ha in magnitude (Fig. S1). In contrast, field size led to a consistent increase in insecticide use regardless of statistical approach, with an increase in field size of 1 SD resulting in an ∼1- to 2-kg/ha increase in insecticides (Table S1).

To explore the heterogeneity over space, we evaluated diversity and cropland extent in five concentric circles of 500-m distances from the focal field, creating five annuli at distances of 0–500 m, 500–1,000 m, 1,000–1,500 m, 1,500–2,000 m, and 2,000–2,500 m. We again included crop and year fixed effects. The average field size was 33 ha; thus, the smallest annuli was about 2.5-fold greater in area than the average field and contained an average of about three surrounding fields, whereas the largest annuli was nearly 60-fold greater in area and contained an average of 21 surrounding fields. We find an important distance component to our results. Cropland extent significantly decreases insecticide use by 1 kg/ha in the 0- to 500-m annuli, yet trends toward a positive and marginally not significant relationship of similar magnitude at 2,000–2,500 m. Crop diversity hints at a nonlinear pattern over space, with diversity decreasing insecticide use at 500 m and 1,500 m, but not at 1,000 m. After 1,500 m, the relationship is smaller, it is marginally not significant at 2,000 m, and it is nonsignificant at 2,500 m (Fig. 3 and Table S2).

The relationship between landscape simplification and insecticides could alternatively be affected by economic changes that ultimately drive the simplification. For example, larger farms (i.e., cultivated area under one owner) could lead to both landscape simplification and increased use of insecticides because a single owner decides the area to plant, what to plant, and treatment levels. To test the impact of farm structure on insecticide use, we tested models that included a covariate for the proportion of the surrounding area owned by the owner of the focal field. However, including this variable did not change the patterns we observed for crop diversity, field size, or cropland extent, indicating that ownership was not driving our results. Other economic factors, such as crop and pesticide prices, certainly also affect pesticide use; however, because the relevant prices become observable only after the land use decision, they add to the noise but do not bias the estimates. Nevertheless, we also evaluated crop-by-year fixed effects models to account for year shocks that may be unique to individual crops (e.g., prices, pests). Doing so did not change the patterns observed in the crop and year fixed effects model (Table S1).

To account for the possibility that different crops had different relationships between diversity (extent or field size) and insecticides, we reran the models for the top six crops representing about 83% of insecticides used. We again included year fixed effects, in this case,

Table 1. **Summary statistics for the top 10 commodities ordered by area**

Crop	Crop area, 10^3 ha	Insect., kg/ha	Insect. rank	Diversity rank, 2,500 m
Almond	74	34	8	48
Alfalfa	39	1	35	35
Pistachio	32	16	20	54
Cotton	31	2	32	39
Grape	27	49	3	45
Wheat	23	0	49	36
Carrot	20	24	16	22
Orange	18	34	7	47
Corn, fodder	15	1	39	25
Wine grape	13	38	6	42

Rankings for insecticides (Insect.) and diversity (calculated at species level) are based on the top 55 crops in production (those crops with at least 405 ha or 1,000 acres in production), with a rank of 1 being the highest possible insecticides or diversity in this sample. Overall, it is evident that there is large, crop-specific variation in average insecticide use. It is also evident that top insecticide crops tend to have low surrounding diversity.

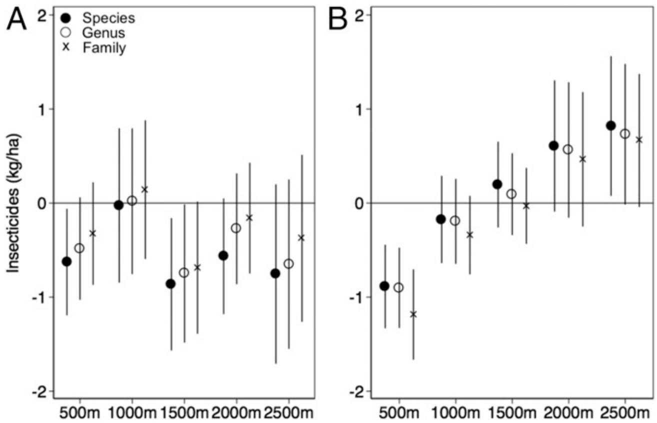

Fig. 3. Effect of crop diversity (*A*) and cropland extent (*B*) is heterogeneous over space. Diversity hints at an inverted U-shaped curve with diversity in the 1,000- to 1,500-m annuli having similar effects as diversity nearby (<500-m annulus), whereas for cropland extent, the magnitude of the relationship trends from nearby extent decreasing insecticide to more distant cropland increasing insecticides. The *y* axis is the size of the covariate–insecticides relationship. Crop and year fixed effects are included.

to account for year-specific shocks shared by all fields of the focal crop (e.g., new pests, crop prices). As anticipated, there was substantial heterogeneity across the different crops. The largest negative and significant relationship between diversity and insecticides was observed for grapes, where an increase in species diversity of 1 SD reduced insecticide use by nearly 8 kg/ha (Fig. 4 and Table S3). Diversity surrounding almonds and pistachios also significantly reduced insecticide use on those crops by ∼2 kg/ha and ∼4 kg/ha, respectively. For oranges and wine grapes, the diversity relationship was negative, but not statistically significant, and less than 2 kg/ha in magnitude, and for carrots, the relationship was near zero. Surprisingly, the crops for which diversity had little effect on insecticides were also the crops for which surrounding cropland extent led to an increase in insecticides. Here, wine grapes and oranges were the only crops with nearly significant ($P = 0.06$ and $P = 0.11$, respectively) increases in insecticides as a result of increasing cropland extent (recall that with individual crop analyses, statistical power is substantially reduced relative to the all-crop model). Thus, for a given level of crop diversity, an increase of 1 SD in cropland in the 2500-m radius area surrounding wine grapes or oranges resulted in an additional 6–8 kg/ha of insecticides. However, for crops such as grapes and pistachios, the coefficients were near zero and nonsignificant. Carrot was the only crop of the top six to have a negative coefficient (i.e., cropland extent decreases insecticides), although this negative coefficient was not significant. Interestingly, despite wine grapes having the largest increase in insecticide as a result of surrounding cropland, they had a sizeable (∼3.6 kg/ha) significant decrease in insecticides as field size increased. For all other crops, field size led to an increase in insecticide use, which was significant for almonds (∼2.5 kg/ha) and pistachios (∼2.4 kg/ha).

Finally, to confirm that neither pesticide outliers nor decisions on model functional form were driving our results, we repeated the main analysis removing the top 1% of pesticide use and evaluated the effect of a logged dependent variable specification. Our results were robust to both modifications (Fig. S2 and Table S4).

Discussion

Landscape complexity has long been shown to increase natural enemy abundance, and, as such, it has been considered a mechanism of ecological pest control (6, 25). However, how different aspects of landscape complexity function with respect to chemical pest control has remained poorly understood. In part, the lack of conclusive evidence is due to the complexity of ecological and economic factors, as well as crop-specific heterogeneity, annual conditions, and/or regional characteristics (26). Using a combination of crop-specific, region-specific, and year-specific controls, we parsed apart the individual effects of crop diversity, cropland extent, and field size on insecticide use.

In general, we find diversity reduces insecticide use. However, interestingly, including crop type fixed effects modifies the diversity–insecticides relationship substantially, indicating that crop types with lower insecticide requirements are planted in areas of higher crop diversity. This correlation may explain the ambiguous literature regarding diversity. For example, our results suggest that in a random sample of fields within an agricultural landscape, crop diversity would be correlated with lower insecticide use because high-diversity areas are composed of low-insecticide use crops.

Ecological diversity can function at multiple taxonomic and spatial scales. Here, we observed a larger effect of diversity at the species or commodity scale than at larger aggregations. At first, this result seems surprising. The suggested mechanism for the impact of landscape simplification on insecticide use is its impact on habitat suitability for pests and their natural enemies. This suitability is largely determined by the suitability of the crop as a habitat, but also by the timing of the planting, pest control, and harvesting decisions that may interrupt species interactions and population demographics. Even within one species, agricultural practices can be very different depending on the agricultural product, such as the difference between wine and table grapes. We suggest here that diversity at lower taxonomic levels better captures the biological and management differences relevant to pest control.

With respect to the spatial scale, we observed that diversity within 2,500 m significantly decreases insecticide use, yet this effect is heterogeneous over varying distances. A large effect of surrounding diversity was observed in the nearest annuli, 0–500 m from the focal crop. Nearby fields would be expected to have a stronger influence on insect and enemy spillover than farther away fields, holding the diversity in other annuli constant. However, the relationship between diversity and insecticides does not appear to change linearly with distance. Rather, our results tentatively suggest the existence of an inverted U-shaped relationship, where diversity at 1,000–500 m is also statistically important with similar magnitude, whereas further annuli tend to be less so. More robust spatial analysis is necessary to confirm this result. A nonlinear response of pests to distance has been

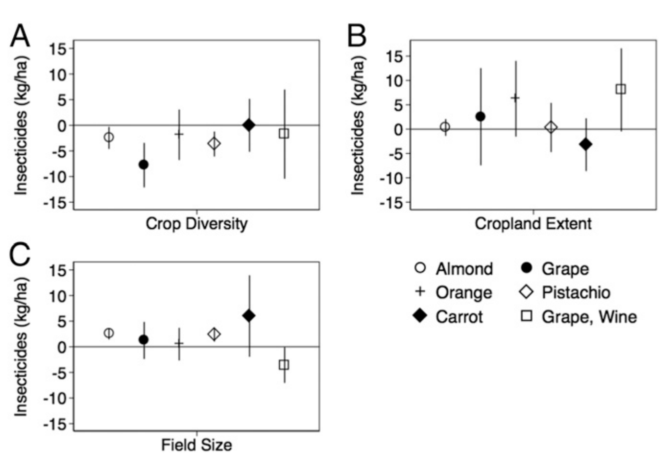

Fig. 4. Components of landscape simplification by top insecticide use crops. Diversity (*A*) and extent (*B*) have variable effects on insecticide use. Crops with a strong response to diversity have muted responses to extent, and vice versa. (*C*) For all but wine grapes, field size increased insecticide use, but this relationship was only significant for almonds and pistachios.

noted elsewhere (27) and may reflect dispersal characteristics or patch use of different pests, although the existence and exact underlying causes of this pattern deserve further attention.

Evaluating individual crops hints at underlying mechanisms for the relationship between landscape characteristics and insecticides. We find large differences in the slope of the relationship between diversity and insecticides among the top six insecticide-use crops, with almonds, grapes, and pistachios having large decreases in insecticides (3–8 kg/ha) in highly diverse landscapes, whereas oranges, carrots, and wine grapes show a smaller and nonsignificant response. The underlying mechanisms could be related to the specialist or generalist nature of the specific crop pests. For example, a crop for which the most damaging pest was a specialist would benefit from surrounding diversity, because diversity would dilute available host crops. Thus, we would expect diversity to reduce insecticides, whereas cropland extent would have little effect. In contrast, if the pest were a generalist, diversity would be expected to have little effect, but extent would be important because other crops would function as suitable hosts. Indeed, we find some evidence of this tradeoff, where crops with strong responses of insecticides to diversity have weak responses to extent, and vice versa.

Beyond diversity, we find surrounding cropland extent decreases insecticide use on the focal field by ∼1 kg/ha when situated nearby (<500-m distances) yet increases insecticides by ∼1 kg/ha when located at larger distances (>2,000 m). This spatial trend is particularly interesting, given the ambiguous literature between cropland extent and insecticides (28). This result could indicate that having other managed systems nearby results in fewer source populations of pests in the immediate surrounding, whereas having widespread cropland in the landscape leads to a concentration of pests [i.e., resource concentration hypothesis (29)] or a lack of natural enemies [enemies hypothesis (22, 29, 30)] within the broader agricultural region. If so, the spatial location of additional cropland is important. In practice, this result implies that reducing insecticides per production area does not require reducing agriculture broadly, but coordinating crop types and crop locations in the nearby surroundings. Of course, farmers do not plant crops haphazardly, and policy mechanisms that sought to leverage this relationship by incentivizing coordination of crop area via agri-environmental programs (e.g., US Department of Agriculture Cropland Reserve Program) would need to subsidize the lost revenue from planting crops with lower expected revenue. Further, as with diversity, the benefits of manipulating surrounding cropland extent would be crop-specific.

Manipulating regional diversity and cropland extent requires coordination among multiple growers, and thus field size may be easier to modify through policy levers. We find large fields use more insecticides per area, even after controlling for crop type and regional attributes. From an ecological perspective, it is surprising to observe different effects of cropland extent compared with field size because both attributes are expected to increase the likelihood of pest problems (and thus pesticides) by inhibiting natural enemy spillover or facilitating pest movement. However, from an economic or human behavior perspective, there are important underlying differences between large expanses of the same crop under multiple owners compared with a single owner. For example, if pests are mobile and the population is shared between more than one farm, farmers may be more willing to spray on large fields because the influence of surrounding growers' management decisions would be reduced (31). Thus, for a given pest distribution across space, the underlying spatial configuration of field size and ownership may be an important and understudied factor for how pests translate into pesticide use.

Of course, landscape characteristics are dwarfed by individual crop attributes. For example, for diversity to drive application rates on oranges to be similar to application rates of carrots, diversity would need to increase by ∼10 SDs. Although improved seeds and integrated pest management may reduce application rates on a given crop, differences between crop types in their susceptibility to insect pests and the value lost due to pest damage are, at least in part, intrinsic characteristics. What ecologists are seeking to understand is not whether forcing substitution of carrots for oranges will reduce insecticides but rather, given demand for the suite of crops in production, what modifications can be made on-farm and in the nearby surroundings such that pest numbers are reduced, thereby reducing insecticides and improving yields.

Increasing agricultural production to meet future demand is a major challenge of the 21st century, with important consequences for human and environmental health. Ecological discussions on how best to achieve a sustainable and abundant global food supply centers, in large part, on how to allocate land to agriculture and how intensively to produce on agricultural land to balance high yields with acceptable levels of off-farm externalities, such as biodiversity loss and contamination of nearby human and natural communities. The simplified and contentious land-sparing/land-sharing dichotomy has persisted, in part, due to the difficulty of disentangling different components of a model landscape for a variety of different ecosystem services, including pest control. Here, we illustrate that, indeed, the effect of "landscape simplification" depends on different components of simplification, the spatial scale, and the focal crop. Although land sparing/sharing may be a convenient division, to achieve major gains in insecticide reduction will necessitate crop-specific and spatially informed management.

Methods

Data. Pesticide and crop data for 2005–2013 are publicly available from the Kern County Agricultural Commissioner's (CAC) Office Spatial Data (www.kernag.com/gis/gis-data.asp). The Kern CAC Office data include field-level observations of crop type, area, and dates the field is active, as well as field-level pesticide use, including pounds of chemicals used (converted to kilograms here), area, and date sprayed. Our outcome variable was kilograms of insecticide used per cropland hectare, and our covariates of interest were crop diversity, cropland extent, and field size. We defined insecticides as any pesticide that is used as an insecticide or insect growth regulator based on the California Pesticide Use Reports Data. Data processing details are described in *SI Methods*.

We calculated crop diversity using SDI, $SDI = 1 - \sum p_i^2$, where p_i is the proportional abundance of crop i in the surrounding area. We defined surrounding area using a circular area with radius of 2,500 m (∼1,963 ha). Only fields that were active contemporaneously with the focal field were included in the diversity calculation. Field size was the size of the focal field, and cropland extent was total agricultural land within a circular area with a radius of 2,500 m from the focal field centroid.

We calculated SDI at the commodity (e.g., broccoli, cauliflower, grape, wine grape), species, genus, family, and agricultural class (e.g., leafy stem vegetable) levels. Species, genus, family, and agricultural class were inferred from commodity. Commodities composed of multiple species (genus or families) were excluded from analyses that calculated diversity at the ambiguous taxonomic level (e.g., winter squash would be excluded from the species analysis but included in all others). Although commodity types are a less relevant category from an ecological standpoint, they contain important information about the product and its use, which may determine insecticide use.

To explore the heterogeneity in the effect of diversity and cropland extent over space, we further parsed the 1,963-ha area into five concentric circles with radii of 500 m, 1,000 m, 1,500 m, 2,000 m, and 2,500 m, and calculated the diversity and proportion of cropland in each annulus (e.g., 0–500 m, 500–1,000 m, 1,000–1,500 m from the focal field). We calculated diversity as fields whose centroid fell within a given annulus. There were ∼3 surrounding active fields in the first annulus from 0 to 500 m, 9 within 500–1,000 m, 13 within 1000–1,500 m, 18 within 1,500–2,000 m, and 21 within 2,000–2,500 m.

To improve the comparison between different land use characteristics, all covariates were scaled by their SD. Thus, each coefficient represents how a change of 1 SD in the variable of interest affects insecticides (kilograms per hectare), holding all else constant.

In essence, analyzing all crops together measures the relationship between diversity (extent or field size) and insecticide use averaged across crops. However, this average can mask important heterogeneity. Thus, we separately analyze the top six crops representing over 80% of insecticide use. These crops are almonds, grapes, oranges, pistachios, carrots, and wine grapes.

Statistical Approach. We evaluate the effect of crop diversity, extent, and field size on insecticide use for ∼13,000 fields over the period of 2005–2013 for a total

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of about 100,000 field observations. We use a fixed effects panel data approach to control for unobserved heterogeneity between crops, regions, and year. Throughout, we are following the econometric use of the term fixed effects to describe models with dummy or indicator variables for each crop, region, or year. We use the terms fixed effects and "dummy variables" interchangeably. In the experimental ideal, different levels of surrounding diversity would be assigned to identical fields, and we could then evaluate insecticide use on the field with low surrounding diversity relative to the field with high surrounding diversity. Although this ideal is, of course, infeasible, we can approximate it by leveraging a time series of observations on a spatial unit and compare that unit with itself in years where diversity is higher versus lower than average. In essence, this model is the fixed effects panel data model with dummy variables for each region. In comparing a spatial unit with itself, the potential for confounding due to omitted variables is minimized because time-invariant characteristics, such as historical land use, slope, and soil quality, drop out of the model. A parallel logic applies to addressing time shocks. For example, technological advancement in seeds, stricter pesticide regulation, or weather anomalies (i.e., drought) could confound our estimates of the effect of diversity. Because we have observations over space and time, we can account for shocks shared by all observations in a given time period by differencing using the year average diversity and insecticide use. Finally, this approach can be used to address crop-specific heterogeneity that is difficult to observe. For instance, almonds are sprayed with 34 kg of insecticides per hectare, whereas alfalfa receives 1 kg/ha (Table 1). Although some of the variation that differentiates these treatment rates could be due to observable factors, some causes of the variation that leads almonds to be sprayed more than alfalfa, even if they were grown on the identical plot with identical surrounding diversity, are due to crop-specific characteristics (e.g., value, pest thresholds).

Here, we use a combination of region, time, and crop fixed effects to identify if and to what extent diversity, cropland extent, and field size drive insecticides. A field is uniquely defined based on permit-location-crop-year, and, as such, fields change over time. Thus, we account for (*i*) all time constant effects that are shared by fields within a given Public Land Survey Township, a 93-km^2 region; (*ii*) all time shocks shared among fields; and (*iii*) all time constant differences between crop types.

Crop-specific pesticide or crop prices may vary from year to year, which would not be covered in the year dummy variables and could confound our estimation. However, to do so, prices would need to be correlated with the diversification decision; otherwise, they only contribute to noise. We argue that this correlation is unlikely because the planting decision is made before crop prices are known. Nevertheless, we test models with crop-by-year dummy variables as well as individual crop models that account for crop-specific year shocks. If pests spill over between fields, the benefit of pest control decreases as fields become smaller because an individual farmer has less control over the pest population spilling over into her field (31). Similarly, we would anticipate that the benefit of pest control would increase with the more fields that an owner held in proximity because she would retain more of the value of her pest control action. To account for the possibility that this economic driver was confounding our estimation, we test models that include a covariate for the proportion of the surrounding area owned by the owner of the focal field.

To assess spatial heterogeneity, five covariates were included for diversity (one for each annulus) and five were included for cropland extent, with the focal field size remaining unchanged. To assess heterogeneity by crop type, we also evaluated the relationship between diversity (extent and field size) for each of the top six insecticide use crops. We again defined the surrounding area as a circle with a radius of 2,500 m and included year dummy variables. Thus, the individual crop models allow for crop-specific slopes and intercepts while accounting for year shocks shared by all fields of the specific crop type in question.

Repeated observations over time or nearby fields are likely to have correlated disturbance terms. Although estimates from the fixed effects model would remain unbiased and consistent (32), such autocorrelation in the error terms could result in artificially small standard errors (SEs) (33). Here, we use cluster robust SEs clustered at the 93-km^2 region (township) to allow for arbitrary spatial and temporal autocorrelation between fields within the same region (33).

All geospatial data manipulation was done in ArcGIS 10.3, and all data analyses were completed in Stata 12 SE (StataCorp).

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