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Variation in pesticide use across crops in California agriculture: Economic and ecological drivers

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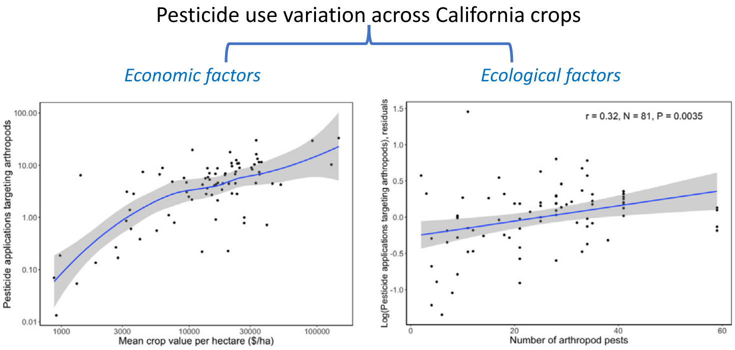
HIGHLIGHTS

- We present the first comparative analysis of pesticide use across California crops.
- Crop value is correlated with use of pesticides targeting arthropods and diseases.
- Crops with a greater number of pest species receive more pesticide applications.
- Perennial crops receive more herbicide applications than do annual crops.

GRAPHICAL ABSTRACT



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ABSTRACT

Pesticide use is a key component of efficient crop production, but is associated with a suite of costs. Understanding the main drivers of pesticide use will help us target research to develop effective alternatives. Although economic models predict, and empirical tests confirm, that the value of the crop being protected is an important determinant of between-crop variation in pesticide use, previous tests of this prediction have examined only modest numbers of crops and have not assessed the relative importance of crop value versus ecological determinants of pesticide use. Here we analyze variation in pesticide use across 93 crops grown in California, USA. We examine the joint roles of crop value and ecological determinants of pesticide use, including (i) the number of pest species associated with each crop; (ii) the distinction between annual vs. perennial crops; and (iii) the distinction between unprocessed vs. processed crops. As predicted, crop value was the dominant driver of the use of pesticides directed at arthropods and at plant pathogens, explaining 52.7% and 54.6% of total deviance, respectively. Ecological determinants of pesticide use were, however, also detected. Pesticide use was greater on crops that hosted a larger number of arthropod pest species ($r = 0.32$) or plant pathogen species ($r = 0.29$); for these pest groups, we saw no differences in pesticide use between annual vs. perennial crops, or processed vs. unprocessed crops. Perhaps surprisingly, crop value failed to explain the substantial between-crop variation in use of pesticides targeting weeds (1.7% of deviance explained, n.s.). Instead, an ecological factor, whether the crop was an annual versus a perennial plant, was the most important predictor of pesticide use against weeds, with more frequent applications on

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perennial crops. We conclude that both economic and ecological drivers influence the magnitude of potential crop losses, thereby shaping farmer pest control practices.

1. Introduction

Pesticide use in modern agriculture can be viewed very differently by different observers. On the one hand, many farmers view prudent use of pesticides as a valuable aid to cost-efficient crop production. Pesticides can shield crops from unpredictable impacts of irruptive pest populations, support yields, and keep food costs down for consumers (Fernandez-Cornejo et al., 1998; Cooper and Dobson, 2007). On the other hand, ecologists have long highlighted potential problems associated with pesticides (van den Bosch, 1980). Pesticide use can threaten environmental quality and human health and can disrupt ecosystem services contributed by beneficial insects (Hoppin and LePrevost, 2017; Larsen et al., 2017; Tsvetkov et al., 2017; Jin et al., 2018). Pesticide use can also result in resistance evolution in pest populations, potentially undermining the long-term sustainability of crop protection (Denison, 2012). Understanding the main drivers of pesticide use is thus important as we seek to target research to develop alternative control methods that can provide the same benefits for farmers while minimizing the problems identified by ecologists.

Studies examining drivers of pesticide use often focus on individual farms or farmers, where decision-making can be observed directly. These studies have revealed a broad array of important influences on pesticide use, including economic factors (e.g., crop value, intended market, labor costs, farm size, credit availability, land ownership, costs of pesticides and non-pesticide alternatives), social factors (e.g., farmer experience and education, sources of pest management advice), biological factors (e.g., weather, landscape context, crop rotation, pest pressure, crop susceptibility), and regulatory risk (Rahman, 2003; Galt, 2008a; Grovermann et al., 2013; Meisner et al., 2017; Rahman and Chima, 2018). Farm-level studies can produce a detailed view of pesticide use in a particular production setting, often involving a single crop or a small set of crops grown by farmers in a particular focal community. Here we seek to complement these studies with a broader investigation of variation in pesticide use across the highly diversified agricultural economy of California, United States. Our comparative analysis of pesticide use across California's main crops creates opportunities to address novel questions tied to the different economies and ecologies of different crops.

A mature theory has been developed in the agricultural economics literature to understand pesticide use by farmers. Economic theory predicts that farmers will apply an additional unit of pesticide if the marginal benefits are greater than or equal to the marginal costs, where benefits and costs are shaped by many factors. Pesticides function not as a productive input, like a fertilizer, but rather as a damage-abating input (Lichtenberg and Zilberman, 1986). This theory generally assumes that farmers act to maximize profits (e.g., Fernandez-Cornejo et al., 1998; Rahman, 2003, 2016; Serra et al., 2005; Sexton et al., 2007; Waterfield and Zilberman, 2012; Grovermann et al., 2013, 2017; Tisdell et al., 2017; Rahman and Chima, 2018), although other objectives are sometimes considered (e.g., cost minimization, risk aversion, and uncertainty in crop and pest development; Horowitz and Lichtenberg, 1994; Fernandez-Cornejo et al., 1998; Sexton et al., 2007; Tisdell et al., 2017). A corollary of the profit maximization objective is the prediction that pesticide use should increase with crop value (Serra et al., 2005, Sexton et al., 2007; Grovermann et al., 2013; Osteen and Fernandez-Cornejo, 2013; see also Schreinemachers and Tipraqsa, 2012; Tisdell et al., 2017), and thus that differences in crop value should be a major determinant of variation in pesticide use across different crops (e.g., Serra et al., 2005). Empirical support for this prediction has been observed, although some of the analyses have been informal, and the numbers of crops considered have been modest (e.g., Fernandez-Cornejo et al., 1998 – 10 crops; Galt, 2008a – 8 crops; Grovermann et al., 2013 – 15 crops, Grovermann et al., 2017 – 7 crops), preventing previous authors from examining multiple determinants, including ecological drivers, of between-crop variation in pesticide use.

The agroecology literature on pesticide use has, instead, emphasized the difficulties experienced by farmers in achieving profit maximization and factors that may lead to the misuse or overuse of pesticides. First, agrochemical marketing may promote overuse (van den Bosch, 1980; Liu and Huang, 2013; Lefebvre et al., 2015). Second, some licensed pest control advisors may have conflicts of interest that could incentivize heavier use of pesticides. For example, in California, USA, most licensed pest control advisors are employed by agrochemical firms (Brodt et al., 2005); they scout farmers' fields, make application recommendations, and are then paid a commission based on pesticide sales. Similar problems have been highlighted in China (Huang et al., 2002; C. Zhang et al., 2015). Third, pesticide use may create positive feedbacks by disrupting the ecological interactions that normally contribute to the regulation of pest populations, including interactions between competitors, predators and prey, and hosts and parasites. This can promote pest population resurgences and secondary pest outbreaks, creating what has been termed a “pesticide treadmill” (van den Bosch, 1980; Sexton et al., 2007; Galt, 2008b). Thus, even if we set aside the external costs of pesticide use that are borne by society rather than the individual farmer, the conventional wisdom in the agroecology literature has been that farmers overuse pesticides (Grovermann et al., 2013).

Neither the agricultural economics literature nor the agroecology literature has asked what factors, other than crop value, might consistently shape variation in pesticide use across crops, even though such variation is observed to be substantial (e.g., Rahman, 2003; Grovermann et al., 2013; Osteen and Fernandez-Cornejo, 2013; Hossard et al., 2017; Larsen et al., 2019). Here, we present what is, to our knowledge, the first analysis of economic and ecological drivers of variation in pesticide use across a diverse array of crops within a broad farming region of the world. California agriculture provides an unusual opportunity to do this, because the exceptionally diverse array of crops grown allows us to assemble a dataset that is large enough (here, $N = 93$ crops) to support comparative tests of a variety of hypotheses.

Because we are interested in exploring ecological drivers of pesticide use, and because different pest groups (arthropods, pathogens, and weeds) are ecologically quite distinct (Raffa et al., 2019), we consider each of these pest groups separately. We test several hypotheses. First, we test the hypothesis that pesticide use will be increased on higher value crops; this hypothesis should be applicable to all pest groups. Second, we test the hypothesis that pesticide use will be increased on crops that harbor a larger number of pest species. While the number of species in the pest community is a highly imperfect measurement of the actual magnitude of potential crop losses due to pest attack – a metric for which field estimates are unavailable for California crops – we judge that it provides an initial opportunity to explore whether or not farmers respond to between-crop variation in pest pressure. Third, we test the hypothesis that pesticide use is reduced for perennial crops, which are disturbed less frequently than annual crops and thus might retain more natural suppression of pest populations by a diverse community of natural antagonists, including competitors, predators, and parasites (Jackson, 1980; Blubaugh and Kaplan, 2015; Lefebvre et al., 2015; Neher et al., 2019; Sarabi, 2019). Fourth, we test the hypothesis that pesticide use is reduced for crops that are processed, and therefore largely freed of consumer demands for cosmetic quality (Yue et al., 2009; De Hooge et al., 2017). This hypothesis is applicable to both arthropod pests and pathogens that can mar the appearance of the harvested crop, but is unlikely to apply to weeds; weeds thus provide a negative control for the effects of crop processing on pesticide use. Finally, it is possible that crops that are planted on fewer hectares, and that therefore may represent a too-small market for agrochemical companies, receive fewer pesticide registrations (Farrar et al., 2018), thereby reducing pesticide use; this hypothesis should be applicable to all pest groups. We therefore include hectares planted as a covariate in our full models.

2. Materials & methods

2.1. Comparative analysis of pesticide use across crops

For each of the 93 crops grown in California in the open field on >600 ha annually, we gathered publicly-available statewide data, averaged across 2011–2015, on pesticide use (https://calpip.cdpr.ca.gov/main.cfm). These data are available because the California Department of Pesticide Regulation (CDPR) mandates reporting of all applied agrochemicals (Pesticide Use Reporting system), providing what CDPR describes as the most comprehensive record of agricultural pesticide use in any region of the world (https://www.cdpr.ca.gov/docs/pur/purmain.htm). Following recommendations from a recent National Academy of Sciences report and other authors for the selection of a metric of pesticide use that is most appropriate for studies whose goal is to quantify the use of pesticides for suppression of target pest populations (NAS, 2016; Kniss, 2017; Letourneau et al., 2017), we used the mean number of pesticide applications per hectare per year, rather than kg of active ingredient per hectare, as our metric of pesticide use. Application rates (kg AI/ha) of different pesticides vary widely, and we were interested in the intensity of control efforts rather than the gram for gram potency of the particular materials applied. We also opted against using an indicator of pesticide use that focused on toxicity to humans or the environment (e.g., Möhring et al., 2019), as our analysis was focused on suppression of the intended target pest populations, rather than non-target impacts.

We analyzed use of pesticides targeting three classes of pests: (1) arthropods, including pesticides categorized as insecticides, miticides, and insect growth regulators; (2) plant pathogens, including pesticides categorized as fungicides, bactericides, antimicrobials, nematicides, and virucides; and (3) weeds, including pesticides categorized as herbicides. Farmers do not report the actual pest target of any pesticide application; thus, in those cases where a particular pesticide (e.g., sulfur) is labeled for use against multiple classes of pests (e.g. fungicide and miticide), the label of the pesticide product was used to identify all potential uses, and the application was included under each use. This injects some inaccuracies into the pesticide use totals that we calculated. Pesticide applications were counted as the number of active ingredients (AI) applied. Thus, a tank-mixture of two pesticides was counted as two applications; we suggest that this is appropriate, given the goals of our study, because tank mixtures are often motivated by the need to control different target pests. Data on crop value per ha per year (gross revenues) were obtained from publicly available data assembled by the California Department of Food and Agriculture (https://www.cdfa.ca.gov/statistics/), again averaged across 2011–2015.

Different crops are likely to vary in the potential for arthropods, diseases, and weeds to impact yield and harvest quality, but data quantifying the potential of pests to produce economic losses in different crops in the absence of control measures are generally unavailable for most crops (Fernandez-Cornejo et al., 1998; Savary et al., 2019). However, as one indicator of variation across crops in the potential for economic impact of arthropod pests and plant pathogens on crop productivity, we collated species lists of crop pests published by the University of California Statewide Integrated Pest Management Program (https://www2.ipm.ucanr.edu/agriculture/) and other UC Cooperative Extension publications. Pests are generally included in these lists because they have the potential to generate meaningful damage to crops. Pest species number is an imperfect measure of the potential for crop losses for several reasons: (i) any given crop field will generally harbor damaging populations of at most a small subset of the full pest community; (ii) certain pest species may produce much more damage than others, and therefore elicit much more pesticide use than others; and (iii) pesticides applied to control one pest may often suppress populations of other, related pest species. Nonetheless, each of the organisms placed on UC Cooperative Extension pest lists are likely to emerge as economic threats, and be the target of control measures, in at least some times and places. Thus, we judge that the number of species included in crop-specific pest lists can function as a rough indicator of the potential for damage posed by each crop's pest community. We found pest lists for 81 of the 93 crops in our pesticide use dataset; thus, our analyses of pesticide use targeting arthropods and pathogens used this reduced dataset (reducing the dataset did not produce any important changes to the main results presented below). Pest lists are not available for weed species, allowing us to analyze pesticide use across the full set of 93 crops.

To accommodate the possibility of non-linear relationships between crop value and pesticide applications, data were analyzed with Generalized Additive Models (GAM) using the *mgcv* package (Wood, 2019) in R. Crop value and the number of pesticide applications were $\log_{10}$ transformed to satisfy the assumption of homoscedasticity. Categorical predictors (processed versus not processed; and perennial versus annual) were included as binary dummy variables. For each class of pesticides, the full model was: *Pesticide applications* ~ s(*crop value*) + *pest species number* + *processed* + *perennial* + *hectares*. To understand the contribution of pest species number to the deviance explained by the full GAM model, the model was fit with versus without *pest species number* as a predictor, while holding the smoothing parameters fixed for the *crop value* predictor. The function *gam.check* was used to assess homoscedasticity and other distributional assumptions as well as other aspects of model fit.

2.2. Analysis of the influence of crop value on pesticide use within single crop plant species

Our comparative analysis of pesticide use across California crops is purely observational. Thus, we need to consider the possibility that there might be one or more unmeasured variables, correlated with a focal predictor variable (e.g., crop value), that are instead driving patterns in the response variable (pesticide use). Our analyses point to a central role for crop value in motivating pesticide use (see below); although we have been unable to identify strong candidates for unmeasured variables that might be correlated with crop value across different crops and also control pesticide use decisions by farmers, we reasoned that if such variables exist, they would most likely be linked to the particular crop plant species being considered. Crop plant species vary in their inherent resistance traits to attack by herbivores and pathogens, in their competitiveness with weeds, and in the composition of their associated pest communities. With this in mind, we decided to complement our broad, comparative analysis of pesticide use with tests that examined single host plant species. We reasoned that by holding host plant species constant, we would control for any host plant specific variables that otherwise might cause spurious correlations in our analysis.

To do this, we capitalized on five crop plant species that are each sold as multiple, distinct crop commodities that differ in value by >2-fold; these are *Allium cepa* (dry onions, green onions); *Brassica oleracea* (broccoli, cabbage, cauliflower, Brussels sprouts, kale); *Solanum lycopersicum* (processing tomatoes, fresh market tomatoes); *Beta vulgaris* (beets, sugarbeets, Swiss chard); and *Zea mays* (grain corn, forage-fodder corn, sweet corn). Within each of these crop plant species, we converted crop value into an ordered, categorical variable (e.g., low, medium, high) and analyzed pesticide use with ANOVA. Because the appropriateness of ANOVA for ordinal predictors is a topic of diverse opinions, we also confirmed all results (data not shown) using the ordAOV function in the R package *ordPens* (Gertheiss, 2015), which is designed expressly for this use.

3. Results

3.1. Pesticides directed against arthropods

There was substantial variation across California crops in use of pesticides directed against arthropods (mean $\pm$ SD $= 6.25 \pm 6.48$ applications per year, range 0.013–33.0). Our full GAM model incorporating five predictors (*crop value*, *pest species number*, *perennial*, *processed*, and *hectares*) explained 59.3% of the total deviance in pesticide use. Crop value was the central driver of pesticide use, explaining 52.7% of the deviance when it was included in a GAM as the sole predictor (Fig. 1). Pest species number, which varied widely across different crops (mean = 25.1, range 2–59), was also a significant predictor of pesticide use targeting arthropods (GAM, *pest species richness* coefficient $= 0.0105 \pm 0.0037$ (SE), $P = 0.006$; Fig. 2). This corresponds to a 2.45% increase in pesticide applications per year for crops with each additional pest species listed in University of California Cooperative Extension publications; pest species number explained approximately 4.6% of total deviance in the number of pesticide applications against arthropods. We found no support for the other ecological predictors; contrasts between perennial and annual crops (GAM, *perennial* coefficient $= -0.112 \pm 0.106$ (SE), $P = 0.29$) and crops that are processed or unprocessed (GAM, *processed* coefficient $= 0.079 \pm 0.210$ (SE), $P = 0.71$) were non-significant. Our covariate of statewide hectares of the crop grown was also non-significant (GAM, *hectares* coefficient $= 7.23 \pm 8.03 \times 10^{-7}$ (SE), $P = 0.37$), suggesting that any possible difficulties with registering pesticides on small-area crops did not translate into reduced application frequencies.

An important influence of crop value on pesticide use against arthropod pests was confirmed by analysis of pesticides applied to five plant species that are grown as different crop commodities and that differed in value by >2-fold (Fig. A1, $P < 0.0001$). In all five cases, pesticide use showed an increasing trend with increasing crop value, with the increases significant ($P \le 0.005$) in 4 of 5 cases. These confirmatory within-crop plant species contrasts reduce the likelihood that the effect of crop value observed in the large, comparative across-crop plant species analysis (Fig. 1) was due to some unmeasured variable linked to crop identity that was correlated with both crop value and pesticide use.

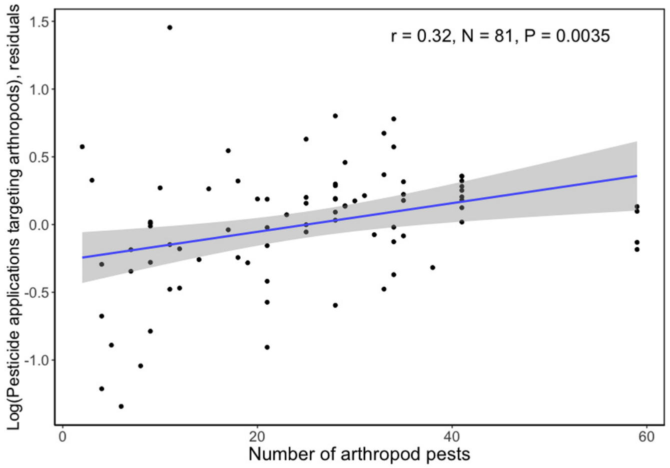

Fig. 2. Linear regression between (i) the number of arthropod pest species listed in University of California Cooperative Extension publications on each of 81 crops grown in California and (ii) the number of pesticide applications targeting arthropods on those crops. Shown are Log_{10} pesticide application number residuals, after correcting for effects of *crop value*; shaded region = 95% confidence interval.

3.2. Pesticides directed against plant pathogens

There was substantial variation across California crops in use of pesticides directed against plant pathogens (mean $\pm$ SD $= 3.52 \pm 4.68$ applications per year, range 0.0004–28.4). Our full GAM model incorporating five predictors (*crop value*, *pest species number*, *perennial*, *processed*, and *hectares*) explained 58.9% of the total deviance in pesticide use. Crop value was, again, the central driver of pesticide use, explaining 54.6% of the deviance when it was included in a GAM as the sole predictor (Fig. 3). Just as was observed for pesticide applications targeting arthropods, only one ecological variable – the number of plant pathogen species associated with the crop – was a significant predictor of pesticide use against pathogens (GAM, *pest species number* coefficient $= 0.0215 \pm 0.0078$ (SE), $P = 0.007$; this corresponds to a 5.08% increase in pesticide applications per year for each additional pathogen

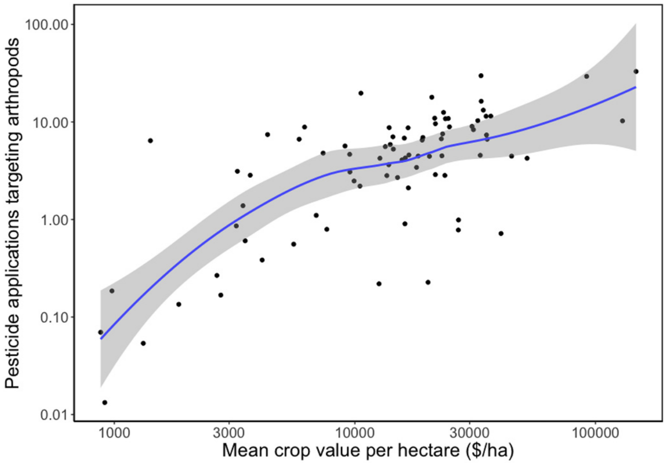

Fig. 1. Crop value (US $/ha) explains 52.7% of the variation in mean number of pesticide applications targeting arthropods per year across each of 81 California crops; log-log scale. Shown is a LOESS (locally estimated scatterplot smoothing) curve with 95% confidence interval; GAM model with *crop value* as the sole predictor, $F = 28.1$, $P < 0.0001$.

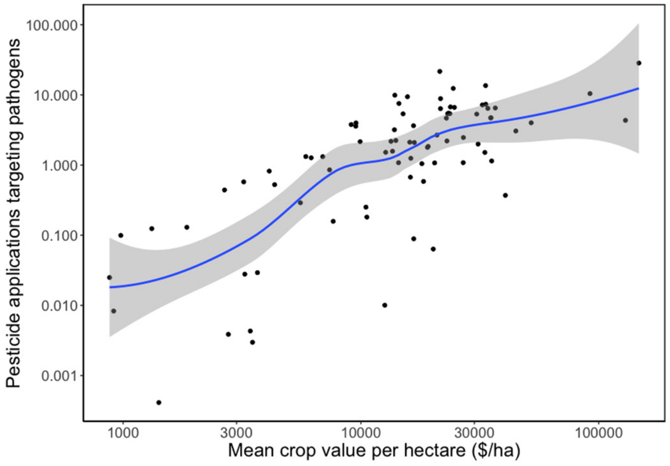

Fig. 3. Crop value (US $/ha) explains 54.6% of the variation in mean number of pesticide applications per year targeting plant pathogens across 81 California crops; log-log scale. Shown is a LOESS (locally estimated scatterplot smoothing) curve with 95% confidence interval; GAM model with Log(*crop value*) as the sole predictor, $F = 34.1$, $P < 0.0001$.

species present). The number of plant pathogen species listed as pests of each crop varied widely (mean = 21.4, range 1–37), and crops with more pathogen species received a greater number of pesticide applications targeting pathogens. The relationship was noisy, however, with pest species number explaining only approximately 2.35% of total deviance in the number of pesticide applications against pathogens (Fig. 4). The contrast between perennial and annual crops did not approach significance (GAM, *perennial* coefficient = 0.116 ± 0.174 (SE), $P = 0.51$), whereas the contrast between crops that are processed or unprocessed was marginally non-significant (GAM, *processed* coefficient = −0.505 ± 0.276 (SE), $P = 0.07$). The covariate of statewide hectares of the crop grown was non-significant (GAM, *hectares* coefficient = $3.89 \pm 11.68 \times 10^{-7}$ (SE), $P = 0.74$).

Our analysis of the influence of crop value on pesticide use against pathogens within single crop plant species confirmed the result of the broad, across-species comparison: with one exception (onions), higher value commodities received more pesticide applications targeting plant pathogens (Fig. A2, $P < 0.0001$). This supports the central role of crop value in motivating pesticide use, while controlling for any unmeasured variables that may vary across crop plant species.

3.3. Pesticides directed against weeds

There was substantial variation across California crops in use of pesticides directed against weeds (mean ± SD = 1.76 ± 1.36 applications per year, range 0.079–6.32). The full GAM model incorporated only four predictors (*crop value*, *perennial*, *processed*, and *hectares*), as weed pest species lists are not available on a crop-by-crop basis; the model explained only 23.3% of the total deviance in pesticide use. Notably, crop value was not a significant predictor of variation in use of pesticides against weeds (GAM, smooth term for *crop value*, $F = 0.60$, $P = 0.44$; Fig. 5); a GAM model with crop value as the sole predictor explained only 1.7% of the observed deviance in pesticide use ($P = 0.61$). Of the remaining predictors, only the contrast between annual and perennial crops was significant, with perennial crops receiving more applications (mean ± SD = 2.37 ± 1.11, $n = 34$) than annual crops (mean ± SD = 1.40 ± 1.37, $n = 59$; Fig. 6). As expected, since weeds do not produce cosmetic damage to crops, the contrast of processed vs. unprocessed crops was not significant (GAM, *processed* coefficient = 0.020 ± 0.140 (SE), $P = 0.89$). Finally, the covariate of crop hectares planted was also non-significant (*hectares* coefficient = $9.84 \pm 5.97 \times 10^{-7}$ (SE), $P = 0.10$).

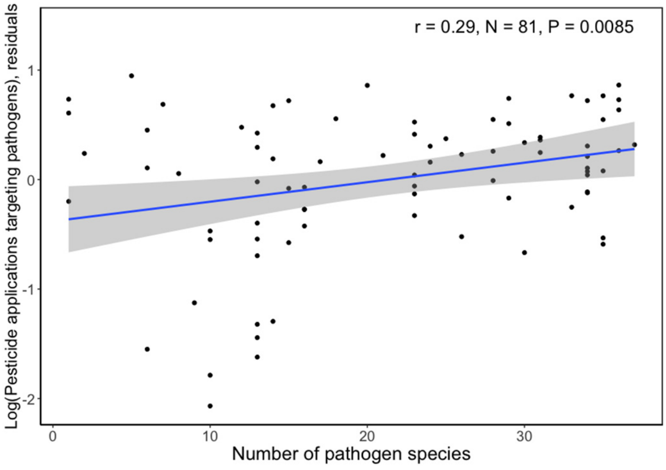

Fig. 4. Linear regression between (i) the number of plant pathogen pest species listed in University of California Cooperative Extension publications on each of 81 crops grown in California and (ii) the number of pesticide applications targeting plant pathogens on those crops. Shown are Log_{10} pesticide application number residuals, after correcting for effects of *crop value*; shaded region = 95% confidence interval.

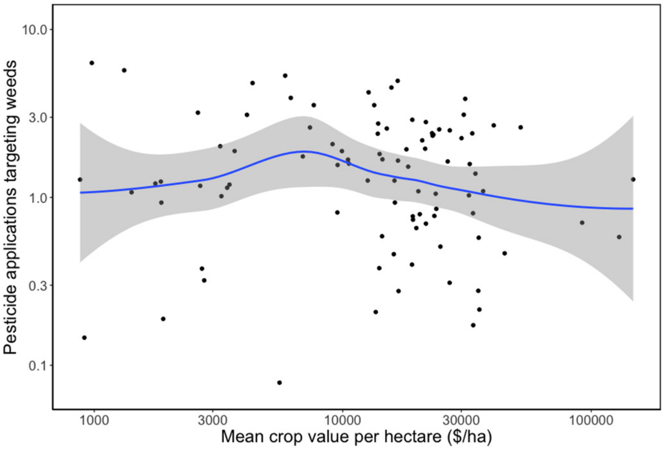

Fig. 5. Crop value (US $/ha) explains only 1.7% (N.S.) of the variation in the mean number of pesticide applications per year targeting weeds across 93 California crops; log-log scale. Shown is a LOESS (locally estimated scatterplot smoothing) curve with 95% confidence interval; GAM model with log(*crop value*) as the sole predictor, $F = 0.35$, $P = 0.61$.

The tests of the effect of crop value on pesticide use targeting weeds conducted within single crop plant species confirmed the lack of a consistently positive influence of crop value; trends were significantly negative for three of the five crop plant species that provided within-species contrasts (Fig. A3). Thus, the within-species contrasts mirrored the larger, across-species comparative analysis.

4. Discussion

Mean annual pesticide use varies dramatically across different California crops, with some crops receiving pesticide applications only very rarely and others receiving large numbers of treatments (>30 applications per year directed at arthropods, >25 directed at plant pathogens, and >6 directed at weeds). Our analysis reveals both economic and ecological determinants of this across-crop variation in pesticide use. Crop value is predicted by economic theory to act as the primary determinant of pesticide use, and we found that differences in crop value explained 52.7% and 54.6% of the variance in the number of pesticide applications targeting arthropods and plant pathogens (Figs. 1 and 3). To address the possibility that these strong effects of crop value,

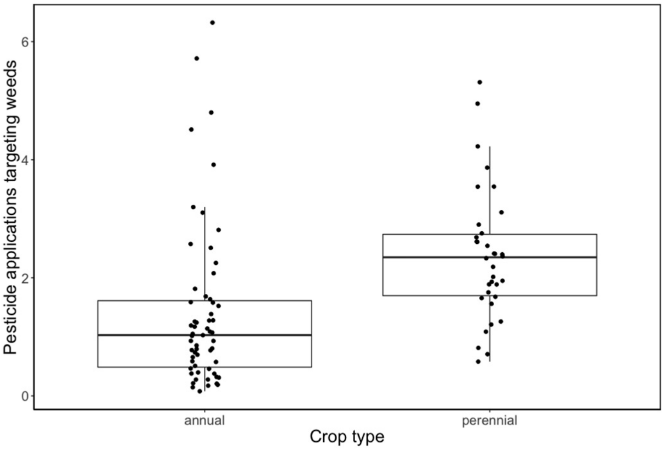

Fig. 6. Annual crops received significantly fewer pesticide applications per year targeting weeds than did perennial crops (GAM, parametric coefficient for *perennial* = 0.402 ± 0.081 (SE), $t = 4.99$, $P < 0.0001$).

observed in our across-crop plant species comparative analysis, might reflect spurious correlations associated with unmeasured variables, we also conducted complementary tests within single crop plant species that are marketed as multiple distinct commodities. These within-species contrasts reinforced the conclusion that higher value crops are associated with more frequent pesticide applications.

Crop value entirely failed, however, to explain between-crop variation in use of pesticides targeting weeds. In that case, an aspect of crop ecology – the distinction between annual and perennial crops – was instead the strongest predictor of variation in pesticide use. For pesticide use targeting arthropods and plant pathogens, another ecological factor, the number of pest species identified in the pest community associated with a given crop, was also a significant predictor of pesticide use. The amount of variation explained by the number of pest species was small; the noisiness of these regressions (see Figs. 2 and 4) is perhaps to be expected, as the number of pest species is likely to be a crude measure of the actual magnitude of crop damage generated by the full pest community in the absence of control measures. Unfortunately, direct estimates of the damage potential of pest communities in California are not available. Our observation that the number of species identified as pests contributes to explaining variation in pesticide use suggests that farmer pest control decisions are influenced by the ecological features of the underlying crop-pest interactions, and not just crop value alone.

Finally, the agroecology literature includes discussions, and some empirical support, for the idea that the highly disturbed nature of annual agroecosystems often precludes the assembly of an effective community of natural pest control agents, which could replace some of the need for chemical pest control (Jackson, 1980; Blubaugh and Kaplan, 2015; Lefebvre et al., 2015; Neher et al., 2019; Sarabi, 2019). Nevertheless, we found no consistent difference in pesticide use between annual crops and the more temporally persistent perennial crops. We also saw no increase in pesticide applications on crops that are not processed, and for which cosmetic damage has been suggested to be an important driver of pesticide use (Bentley, 2009; Yue et al., 2009).

4.1. Effects of crop value

Crop value explained approximately half of the variation in use of pesticides directed at arthropod pests and plant pathogens. As predicted for profit-maximizing farmer decision making, farmers apply more pesticides when the monetary value of the threatened crop loss is greater.

An unanticipated result, however, was the absence of any effect of crop value on the use of pesticides targeting weeds. Why don't California farmers increase their use of pesticides to suppress weeds on higher-value crops? The answer does not seem to be linked to possible differences in mean value per ha between annual crops (18,712 ± 2709 (SE) USD, $n = 59$) versus perennial crops (22,872 ± 4328 USD, $n = 34$), because the mean value of these crops did not differ significantly (ANOVA, $F_{1,91} = 0.74$, $P = 0.39$). We hypothesize that the explanation may involve the greater availability, and broader adoption, of non-chemical methods for weed suppression. Although all pests can be, and are, managed by multiple methods – as promoted by integrated pest management programs – weeds in particular are frequently controlled with cultural methods, including mechanical cultivation, mowing, hand-weeding, use of mulches, weed fabrics, flaming, planting of cover crops, and other practices (https://www2.ipm.ucanr.edu/agriculture/). Some of these cultural methods may be too expensive for farmers producing low-value crops. Price elasticity of demand for herbicides has been found to be higher than for insecticides or fungicides (Böcker and Finger, 2017), which may be consistent with farmers having more readily-available alternatives to herbicide use than they do for other classes of pesticides. Thus, a hypothesis for future testing is that non-chemical methods of weed control become increasingly dominant components of weed management programs on higher-value crops.

4.2. Ecological determinants of pesticide use: annual vs. perennial crops

Farmer use of pesticides targeting arthropods or plant pathogens did not differ consistently between annual and perennial crops. Thus, although the greater spatial and temporal stability of perennial agroecosystems is generally thought to favor communities of organisms that can contribute to the natural control of agricultural pests (e.g., Blubaugh and Kaplan, 2015; Schellhorn et al., 2015; Rusch et al., 2016; Neher et al., 2019; Sarabi, 2019), thereby reducing the need for chemical control, the complete yearly elimination and regeneration of the entire food chain in annual agroecosystems does not appear to promote additional pesticide use for control of arthropods or plant diseases compared to less disturbed, perennial agroecosystems in California.

Instead, perenniality was associated with a substantial increase in the use of pesticides targeting weeds. There are several possible contributors to this result. First, although annual crops generally require some intervention to suppress weeds near the time of planting, when the crop is not very competitive, as the crop grows and shades more of the soil surface its enhanced competitiveness often effectively suppresses weed growth (Evers and Bastiaans, 2016). Perennial crops are nearly all trees or vines; farming these crops requires that space be retained permanently between rows of plants to permit access of machinery. A consequence of this is that the soil surface is rarely fully shaded, and thus that weeds on the orchard or vineyard floor are not effectively suppressed by competition for light imposed by the crop plant canopy.

Second, whereas perennial crops are present for the full calendar year, most annuals are planted during the spring and harvested during the fall. California has a Mediterranean climate in which most rain falls during the winter months, and weeds grow aggressively during the late winter and early spring. Herbicides applied during this time, often before the planting of an annual crop, will generally appear in the CDPR database as fallow ground applications, rather than being tied to a particular crop.

Third, perennial crops are more likely to harbor perennial weeds (Hakansson, 1995; Gaba et al., 2014), which are often more difficult to suppress than annual weeds, and this may promote heavier pesticide use.

Finally, pesticides targeting weeds may be easier and less expensive to use in perennial crops, simply because it is easier to achieve selectivity (i.e., poisoning the weeds but not the crop plant) by directing applications to the orchard or vineyard floor, minimizing contact with the sensitive parts of the crop plant. Because herbicides that achieve selectivity by their physiological mode of action are often more expensive (Peltzer et al., 2009), the ability to use cheaper, non-selective materials in a selective manner may promote pesticide use for weed control in perennial crop settings.

Offsetting some of these factors that might promote increased pesticide use for weed control in perennial crops is the common practice of applying 'strip sprays' of herbicides in the tree or vine rows only, and then using either mowing or cultivation to suppress weeds in the middles (Brunharo and Hanson, 2018). For example, a strip spray application that covers one quarter of the floor of a 100-ha almond orchard would be recorded in the CDPR database as a 25 ha application, thus adding only 0.25 to our tally of applications for that orchard.

In sum, the ecology of weed growth and suppression is quite different in annual versus perennial cropping systems, and thus it should not be surprising that pesticide use for weed control differs considerably in these two settings.

4.3. Ecological determinants of pesticide use: processed vs. unprocessed crops

The risk that pests might generate cosmetic damage to crops has long been hypothesized to be a substantial driver of pesticide use (van den Bosch, 1980; Powers and Heifner, 1993; Bentley, 2009). Consumers are strongly responsive to the cosmetic appearance of produce in the retail market (Yue et al., 2009; De Hooge et al., 2017), and commercial packinghouses in California grade fresh fruits and vegetables, with corresponding price premiums or discounts paid to farmers (Powers and Heifner, 1993).

To test whether the threat of cosmetic damage shapes variation in pesticide use across crops, we compared pesticide use on processed crops, for which cosmetic damage is of little or no economic importance, to pesticide use on unprocessed crops, where cosmetic quality can be assessed by the consumer. Perhaps surprisingly, using a multivariate statistical analysis that accounted for the major explanatory role of crop value, we found no difference in pesticide use between processed and unprocessed crops. Further work is required to understand why the risk of cosmetic damage is not expressed as elevated pesticide use for crops that are sold in a fresh and unprocessed form.

4.4. Pest species number and pesticide use

A direct test of the optimality of farmer decisions to use pesticides requires information about the marginal costs of pesticide applications and the marginal benefits, in terms of reduced losses of harvest value (i.e., damage abatement). How pesticide use contributes to damage abatement depends on pest densities, pest behavior, and the plant's ability to compensate for damage, all of which are likely to vary in time and space. Thus, we lack broad-scale estimates of crop damage for most crop-pest combinations, and even the few studies generating estimates are often based on expert opinion rather than direct measurement (e.g., Savary et al., 2019). Our informal observations, made across years of studying pest-crop interactions in California, suggest to us, however, that there is meaningful variation across crops in the amount of pest damage generated, with some crops being heavily attacked by arthropod pests and diseases, whereas others are rarely subject to meaningful damage. Because University of California Cooperative Extension personnel work to provide farmers with guidelines for managing those pest species that are actually capable, in some times or places, of producing economic damage, we reasoned that pest species lists developed for each crop should provide at least a first, rough estimate of the aggregate damage potential of different pest communities.

Our analyses suggest that the number of pest species listed in University of California Cooperative Extension publications is a meaningful predictor of pesticide application frequency. Thus, farmers appear to recognize and respond to crop-to-crop variation in at least the perceived impact of the pest community. We will present separately an analysis of factors contributing to the strong variation in the size of the pest species community found on different crop plants – i.e., the processes that contribute to the large variation in pest species diversity seen in Figs. 2 and 4. Future research on determinants of pesticide use would, however, be greatly enhanced by having direct measures of the damage potential of unmanaged pest communities and the efficacy of pesticide applications in abating that damage.

5. Conclusions

California farmers generally operate in a highly competitive environment with narrow profit margins (https://coststudies.ucdavis.edu/en/), and may therefore have little choice but to be keenly aware of the costs and benefits of their pest management decisions (Larsen and Noack, 2017). This is in full agreement with studies demonstrating that costs and benefits drive use decisions for other classes of agricultural chemicals, including fertilizers (X. Zhang et al., 2015; Wu et al., 2018). Our analyses suggest that the value of the harvest being protected is a dominant determinant of pesticide use against arthropod pests and plant pathogens, consistent with profit-maximization by farmers. Crop value does not, however, appear to explain any of the substantial variation in use of pesticides against weeds across California crops, where alternatives to chemical control are widely practiced. Instead, an ecological factor – the distinction between annual and perennial crops – appears to be the primary determinant of variation in use of pesticides for weed control. The ecology of crop-pest interactions also seems to shape pesticide use targeting arthropod pests and plant pathogens, for which pesticide use was positively correlated with the number of different pest species associated with each crop. Thus, we see evidence that farmers are not locked into a rigid program of pesticide use, but rather seize opportunities to save on pest control costs by matching pesticide use with the magnitude of the threat posed by each crop's pest community. This should encourage pest management researchers, in that it suggests that what is needed to reduce pesticide use is the development of alternative control methods that are truly effective in reducing the risk of economic damage.

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CRediT authorship contribution statement

Jay A. Rosenheim: Conceptualization, Investigation, Formal analysis, Writing - original draft. **Bodil N. Cass:** Conceptualization, Writing - review & editing. **Hanna Kahl:** Conceptualization, Writing - review & editing. **Kimberly P. Steinmann:** Conceptualization, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The datasets analyzed during the current study are available in the DRYAD repository, doi:10.25338/B8B03Q.

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