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RESEARCH

Conflicts of interest, risk aversion, and pesticide use in California agriculture

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Abstract

Pesticides support crop production, enhancing global food security, but are associated with serious environmental and health risks. Factors that promote overuse of pesticides are therefore of great concern. Pest control advisors (PCAs) are agricultural professionals who scout fields for pests and may recommend pesticide applications. We test two hypotheses regarding the influence of PCAs on pesticide use by California farmers, contrasting four groups: independent PCAs, sales PCAs, farm-staff PCAs, and farmer PCAs. The long-discussed conflict of interest hypothesis posits that sales commissions earned by PCAs who work for agricultural chemical retailers ("sales PCAs") incentivize pesticide use; it predicts elevated use of all pesticides by farmers advised by sales PCAs. The risk aversion hypothesis posits that the risk of damaging pest outbreaks incentivizes pesticide use; it predicts elevated pesticide use when targeting pests that can exhibit outbreaks (arthropods and plant pathogens) but not when targeting non-outbreak pests (weeds). We assembled a dataset of pesticide use on nearly 600,000 crop-years grown in California from 2012 to 2021 by farmers advised by different types of PCAs. Our analysis provides little to no support for the conflict of interest hypothesis; farmers advised by sales PCAs used slightly less pesticides than farmers advised by independent PCAs (who receive no sales commission). Instead, our analysis reveals pesticide use consistent with the risk aversion hypothesis, with elevated use of pesticides by one group of PCAs (farm-staff) when managing arthropods and pathogens, but not when managing weeds. Risk aversion, rather than sales commissions, may be shaping pesticide use in California.

Keywords Pesticide use · Conflict of interest · Risk aversion · Outbreak pests · Pest control advisor

Introduction

Pesticide use in modern production agriculture supports the production of abundant food at lower cost, supporting food security (National Research Council 2000; Cooper and Dobson 2007; Savary et al. 2019). But pesticides also bring myriad risks. These include direct pesticide exposures with ensuing health impacts for farmworkers, farmers, and residents of nearby rural communities; non-target impacts on microbial, plant, and animal communities; pesticide contamination of air, water, and soil; and potentially toxic pesticide residues in the water and food that we consume (Hoppin and LePrevost 2017; Larsen et al. 2017; Tsvetkov et al. 2017). The societal costs of pesticide use have motivated agricultural researchers to develop alternative pest control practices that reduce the reliance on pesticides while retaining the effective pest regulation that is essential for crop productivity. Consequently, there is intense interest in eliminating any influences that might have the opposite result, promoting the overuse of pesticides.

To understand key influences on pesticide use, attention has long focused on the role of professional pest control advisors (PCAs; Woodworth 1912). Farmers hire PCAs for several reasons. First, pest management requires specialized skills to identify pests and estimate their densities. Second, private pesticide applicators generally require a PCA recommendation before they will make an application, for liability reasons. Third, the State of California requires a written

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PCA recommendation before some high-risk pesticides ("restricted use materials") can be applied. Consequently, most farmers secure the services of PCAs to scout their fields, sample populations of potentially damaging arthropods, disease organisms, and weeds, and make recommendations for the use of pesticides (Headrick 2021).

In California, the focus of this study, and in many other regions of the world, PCAs must be licensed by the government to recommend pesticide applications (Hallett 1976). We can recognize four groups of licensed PCAs (National Research Council 2000; Warner 2006). The first and largest group, the "sales PCAs," are sales staff who work for agricultural chemical retailers. Their field scouting services and pest management recommendations are provided to client farmers for free, with their companies generating income through chemical sales. Sales PCAs receive commissions for their pesticide sales, but data on the commission structures of pesticide sales are generally not publicly available. The second group, the "independent PCAs," have a different business model: they charge their client farmers a flat, per-hectare fee for pest scouting services and control recommendations, and they do not sell agricultural chemicals. Like the sales PCAs, independent PCAs typically work with several different client farmers. The third group is the "farm-staff PCAs." These are full-time staff employed by a farming operation to conduct the pest scouting and pest management decision-making. Thus, farm staff PCAs are distinguished by working with only a single farmer. Finally, some farmers undertake the training necessary to pass licensing exams themselves, and subsequently do their own PCA work; these are the "farmer PCAs."

In this study, we address two non-mutually exclusive hypotheses that have been advanced concerning the influences of PCAs on pesticide use in commercial agriculture. The first we call the "conflict of interest hypothesis." This hypothesis posits that sales PCAs are incentivized to promote pesticide use because of the financial benefits that are reaped either by their companies, through sales receipts, or by themselves personally, through commissions (Woodworth 1912; van den Bosch 1980; Coble et al. 1998; National Research Council 2000; Huang et al. 2003; Warner 2006; Harrison 2011; Ehler and Bottrell 2000; Vanzant 2014; Headrick 2021). The conflict of interest hypothesis predicts that sales PCAs will be associated with a blanket increase in the use of any agricultural chemical that is sold, including all pesticides and other types of agricultural chemicals. Sales PCAs can also be predicted to recommend the use of more expensive pesticides, and especially newer pesticides that are still under patent protection, assuming that such sales would produce larger commissions.

From a societal perspective, sales receipts and commissions may create a perverse incentive favoring elevated use of pesticides. From the perspective of the individual PCA, sales commissions may create a conflict of interest, in which the interests of the farmer client are subordinated to the financial interests of the PCA and the PCA's employer. Concern regarding the adverse consequences of these perverse incentives and conflicts of interest is longstanding. Legislation was introduced in California in 1971, when the licensing requirements for PCAs were first established, that sought to separate legally the roles of the PCA and the pesticide salesperson (van den Bosch 1980; Vanzant 2014); this legislation failed, however, and sales PCAs remain the largest group of PCAs in the state. That conflicts of interest promote overuse of pesticides has become conventional wisdom, shaping central policy documents in both California (Sustainable Pest Management Work Group and Urban Subgroup 2023) and globally (UNFAO 2010).

The enshrined stature of the conflict of interest hypothesis has been established, however, without the benefit of much empirical support. Hall et al. (1975) conducted an early questionnaire-based study of pesticide use by citrus and cotton growers in California, showing that farmers advised by sales PCAs spent twice as much on pesticides as farmers advised by independent PCAs. However, Hall et al. (1975) noted that pesticide use practices of the two groups of farmers appeared to be converging over the 5-year period analyzed (1970–1974), which followed the introduction of the PCA licensing requirement in California. Two subsequent questionnaire-based studies of California almond and cotton farmers found no significant differences in pesticide use by farmers advised by sales versus independent PCAs (Brodt et al. 2005, 2007). More recent work conducted in China analyzing pest control recommendations emerging from 'pest clinics' visited by farmers similarly found little to no difference in recommendations coming from sales versus non-sales PCAs (Zhang et al. 2017; Wan et al. 2019). Further analyses have been hampered by the lack of large-scale data on pesticide use and PCA activities in commercial agriculture.

The second hypothesis we address, the "risk aversion hypothesis," focuses on the adverse consequences that PCAs may face for pest outbreaks that cause severe crop damage, including outright crop failure (Warner 2006; Harrison 2011; Vanzant 2014). Heavier pesticide use may reduce the likelihood of such outbreaks or, at least, reduce the likelihood that a PCA would be blamed for not having done enough to forestall such an outbreak. How different groups of PCAs might vary with regard to the consequences of pest outbreaks has received relatively little attention. Farmer-PCAs are unique among PCAs in that they have a direct financial stake in the outcome of each crop, with losses causing reduced income. The remaining groups of PCAs, including sales, independent, and farm-staff PCAs, do not suffer direct economic damage from outbreaks, but each can suffer reputational damage from pest outbreaks that are perceived to have occurred because of mistakes in pest management practices (Warner 2006; Harrison 2011). Warner (2006) suggested that independent PCAs might be exposed to greater adverse consequences from pest outbreaks, because they may lack the legal liability insurance ("errors and omissions") that is provided for sales PCAs by their chemical distributor employers. Informal discussions with PCAs and agricultural chemical distributors revealed two additional scenarios that could strengthen risk aversion in some PCAs. First, sales PCAs and independent PCAs can lose individual farmer clients if they are blamed for damaging pest outbreaks. Second, farm-staff PCAs could lose their entire employment if they are blamed for outbreaks. Finally, farm-staff PCAs might be expected to have greater regard for the financial success of their farmer employer compared to independent or sales PCAs who work for many different farmer clients.

Altogether, these considerations do not create a well-defined prediction for how risk aversion might shape differences in pesticide use across different groups of PCAs. However, we can define a clear expectation for the signature of agricultural chemical use under elevated risk aversion within a given group of PCAs. Arthropods and pathogens can be difficult to detect when present at low densities, but both are highly mobile and have relatively short generation times and thus can exhibit irruptive population dynamics. In contrast, weeds are conspicuous, have generally low mobility and relatively long generation times, and thus lack the potential to generate rapid, uncontrollable outbreaks that could threaten a crop. A more risk averse group of PCAs would therefore be expected to show elevated use of pesticides when targeting outbreak pests (arthropods, pathogens) but not when targeting non-outbreak pests (weeds). The risk aversion hypothesis also predicts no increase in the use of plant growth regulators, which are not pesticides; predictions for the use of adjuvants, compounds that are marketed as reducing pesticide drift or enhancing pesticide coverage of the target crop, are perhaps equivocal. This is a clear contrast to the predictions of the conflict of interest hypothesis, which predicts a blanket rise in the use of all agricultural chemicals by sales PCAs.

Two databases established in California have together created an opportunity to test the conflict of interest and risk aversion hypotheses on a large scale. In 1990, California introduced the *Pesticide Use Reporting* (*PUR*) system, which records all agricultural chemical use in the state (Wilhoit 2018a). In 2011, California introduced the *CalAgPermits* system, which is used in county-based Agricultural Commissioner offices to record data describing the pest management operations in farms that apply for pesticide use permits, including the identity of PCAs making recommendations (Wilhoit 2018a). The completeness of data recording practices varies both within and across counties, and counties also vary in the length of time for which historical records are retained. Nevertheless, *CalAgPermits* data enabled us to link particular PCAs to a large number of farming operations. We used publicly available data to identify the employers of each PCA, allowing us to place PCAs into one of the four groups (independent, sales, farm staff, and farmer). We analyzed the influences of PCAs on pesticide use on crops grown in California agriculture across ten years (2012–2021). Our basic unit of replication was defined within PUR data by identifying a particular crop (e.g., crop code 3001 = almond) grown in a particular field ("SITE_LOCATION_ID") farmed by a particular farmer ("GROWER_ID") in a particular year ("YEAR"); we will call these individual observations "crop-years." Our final dataset included 592,069 crop-years with defined PCAs; descriptive summary statistics are provided in SI Appendix, Table S1.

Materials and methods

Assembling datasets on pesticide use and PCAs

We sought to contrast pesticide use by farmers being advised by different groups of PCAs, while controlling for other key factors, including crop identity, location (county), year, whether the field was being farmed organically vs. conventionally, the size of the field, and the size of the farming operation (total hectares). The unit of replication was a single commercial agricultural crop grown outdoors in a particular field location in California within a single calendar year, 2012–2021. In cases where a single physical field location was cropped sequentially with different crop plants, each crop was considered separately. In cases of winter crops, which may be planted in the fall and harvested the following spring, we analyzed each year's pesticide use separately to retain the California Department of Pesticide Regulation's Pesticide Use Reporting (CDPR PUR) calendar-year based data segmentation. The dataset that we analyzed was created by integrating several different data streams, all of which are publicly available (Fig. 1).

PUR data

We analyzed PUR data that were provided by CDPR for 2012–2021. The PUR database reports actual pesticide applications made in California; it does not report the recommendations made by PCAs, which may differ from the applications performed, because some farmers may reject some PCA recommendations. CDPR processes PUR data through a series of error detection procedures to improve the quality of their data reporting (Wilhoit 2018b; Yanga and Steinmann 2018); underreporting (failure to report

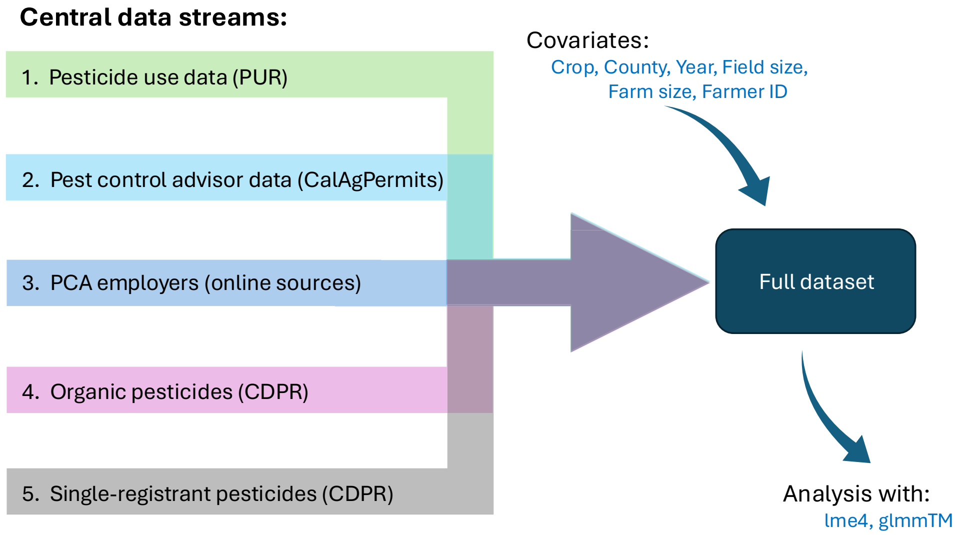

Fig. 1 Sources of information used to assemble our full dataset, and covariates used in our analysis of the influence of pest control advisors (PCAs) on the use of pesticides by California farmers. PUR, Pesticide Use Reporting; CDPR, California Department of Pesticide Regulation

applications) can occur, but appears to be relatively rare (e.g., Rosenheim 2013), and we are unaware of any use of black market pesticides in California that farmers would not report. We analyzed PUR data as provided with one exception. Some farmers, especially those growing in coastal regions, operate "truck farms" that involve a very large number of very small plots, often with multiple cropping cycles per year. To make pesticide use reporting less onerous, these farmers can select a "Complex Rotational Cropping" reporting option, which allows them to report the size of groups of fields, or sometimes their entire farming operation, in the "field size" data cell. Because we use the ratio of hectares treated to the full size of the target field to measure partial-field applications, we could not use these records. Please see the SI Appendix 1 for additional details, including the algorithm that we used to exclude these cases.

CDPR reports the registered target class uses for each pesticide, allowing us to partition total pesticide use into different target classes, as follows: (i) arthropods, including pesticides categorized as insecticides, miticides, and insect growth regulators; (ii) plant pathogens, including pesticides categorized as fungicides, bactericides, antimicrobials, virucides, and nematicides; and (iii) weeds, including pesticides categorized as herbicides. Some pesticides list targets in more than a single category (e.g., insecticide and fungicide); in these cases, we partitioned the pesticide use equally across the multiple target class bins (e.g., an application of a pesticide registered as both an insecticide and a fungicide was allocated half to arthropods and half to pathogens).

PUR data allowed us to calculate three complementary measures of pesticide use: the number of pesticide applications per field (with each registered product counted separately in cases where multiple products were applied together as a 'tank mixture'), the total amount of formulated pesticide product applied (kg/ha), and the total amount of active ingredient (AI) applied (kg AI/ha).

Any crop fields that received zero applications of chemicals that fall under mandatory reporting (pesticides, adjuvants, or plant growth regulators) would not appear in PUR reporting at all; thus, some true zeroes are missing from our data set. We did not make any attempt, however, to impute zeroes. We made this decision because cases of missing PUR records could reflect a field that was fallowed or a field for which pesticide use reporting failed. Missing true zeroes will bias the mean pesticide use figure upwards, but we do not expect this bias to vary across the different groups of PCAs.

CalAgPermits data

California farmers wishing to apply pesticides must receive a pesticide use permit from their County Agricultural Commissioner's office. Beginning in November 2011, county staff statewide began using the CalAgPermits database to record information for permitting; 2012 was thus the first full calendar year of adoption (Wilhoit 2018a; Yanga and Steinmann 2018). CalAgPermits includes 44 supplementary data fields, including a field for the name of any PCA who makes pesticide use recommendations for the permit holder. Despite the use of common software, the completeness of data reporting varies substantially within and between counties. Counties are required to retain CalAgPermits data for the current year plus the four previous years; some counties, however, retained older records. Statewide CalAgPermits data for 2012–2021 were provided to us by the *California Agricultural Commissioners and Sealers Association* (CACASA). CalAgPermits allowed us to associate PCAs with a particular farming operation (permit holder), but for some larger farming operations that employed multiple PCAs we could not associate PCAs with the particular fields they managed. We applied the composition of the full PCA team recorded for a given farmer to each of the fields managed by that farmer. This introduced some imprecision in our analysis for farmers that used PCAs of different types. Because any errors should act to reduce observed differences between PCA groups, thus making our analysis more conservative, we opted to retain all records. We did, however, repeat our central analysis with a reduced dataset that excluded all records associated with mixed-type multi-PCA teams, and obtained results nearly identical to those for the full dataset (Figure S2).

We discovered that CalAgPermits data may contain two kinds of temporal errors in reporting associations of PCAs with farmers. First, such associations may erroneously be propagated forward in time, because when a permit is renewed (generally annually), county staff sometimes carry forward prior-year information rather than making updates. Second, such associations were also sometimes propagated backward in time, because of an error in the software (J. Gless, pers. comm.). We attempted to correct both of these error types, using independent sources of information on PCA employment (see below). Farmer transitions between different groups of PCAs (e.g., changing from an independent PCA to a sales PCA) were quite rare, and the precise timing of such changes, when they did occur, is difficult to pinpoint using CalAgPermits data. This dissuaded us from using panel data models to analyze our data.

PCA employers

CalAgPermits data provided PCA names to assign PCAs to different groups (independent, sales, farm staff, farmer); however, we needed to identify the PCA's employer for each year analyzed (2012–2021). We did this using diverse publicly available online information sources. CalAgPermits itself does include a data field for PCA employer; this was not consistently completed, however. Online searches for PCA name (and name variants) plus key words 'pest control advisor' or 'crop advisor' frequently revealed employer websites with lists of PCA employees. We also searched a variety of business and employment-focused online professional platforms (e.g., LinkedIn), business directories (e.g., Dun & Bradstreet, Open Corporates, All People, Bizarchive, Buzzfile, Radaris, Manta), and business-to-business sales platforms (e.g., Zoominfo). We searched farming service clearinghouses (e.g., farmranch.org) and social media platforms (e.g., Facebook, SnapChat) for additional records. Finally, some employers were identified using more traditional media, including trade journals (e.g., Horti Daily, farmprogress.com, AgAlert.com, vegetablegrowersnews.com), University of California Cooperative Extension publications and blogs (e.g., ucanr.edu/blogs/), or stories in local, regional, statewide, or national newspapers (e.g., dailyrepublic.com, Sonoma County News Initiative, San Francisco Chronicle, Bloomberg), including obituaries (e.g., legacy.com). PCAs who were government employees were identified using an online database (transparentcalifornia.com) and were excluded from our analyses. In all, we were able to identify employers and place PCAs into one of our four groups of interest in 96.6% of all PCA-year combinations, with the remaining cases added to the group of records for which PCA names were unknown.

Organic vs. conventional farming

Pesticide use can vary substantially between fields under conventional vs. organic management (Larsen et al. 2021). To control for this, we used a dataset assembled by CDPR staff in 2020 that attempted to identify all CDPR registered pesticides and adjuvants ("Product numbers" in CDPR data) that were organically approved. Products were considered to be organically approved if they were (i) approved by the Organic Materials Review Institute (OMRI) in 2006, 2008, 2012, or 2019; (ii) certified by the Washington State Department of Agriculture (WSDA) Organic Program; or (iii) had a USDA organic logo on their product labels (either a National Organic Program (NOP) label or a "USDA For Organic Production (FOP)" label). Matching of CDPR product names with the product brand names marketed by different companies followed a fuzzy logic to accommodate the many small variations in product naming conventions. We considered a field to be under organic management if 100% of all pesticides (product numbers) applied were organically-approved.

Single vs. multiple registrant materials

Under the conflict of interest hypothesis we can predict that sales PCAs might be motivated to recommend to their client farmers increased use of more expensive pesticides, if larger sales receipts are associated with larger sales commissions. Data on pesticide costs are, however, very difficult to obtain, and costs vary over time, regionally, and across growers. We can, however, create a proxy for pesticide cost by measuring the use of pesticides that are still patent protected and marketed by a single registrant. Patent protected pesticides are generally much more expensive than generic, non-patent protected materials. We obtained from CDPR a listing of all pesticide products, along with their registrants ("FIRM_NAME"), the beginning and end date for their registration ("REG_DT" and "PROD_INAC_DT," respectively), and the kg of product used each year, statewide, under each registration. This allowed us to categorize, for each pesticide and each year (2012–2021), whether the material was marketed by just 1, or by >1, registrant; single-registrant materials were almost always materials still under patent protection. We used the proportion of the number of all pesticide products applied that were single-registrant materials as a metric of the costliness of the pesticide use program recommended by a PCA. For the details of the rules used to assign a given pesticide to a registrant number category, see the SI Appendix 2.

Crops analyzed

We analyzed pesticide use across a diverse California agriculture, including 223 different crops, each identified by a unique CDPR "site_code" value. PUR data include pesticide use in many different settings; our focus was on outdoor commercial agriculture. We excluded crops grown primarily in greenhouses or other indoor settings. We also excluded site codes linked to residential use or structural pest control; nurseries, landscaping, rights of way, or recreational areas; ornamental plants; ditch banks and water areas; animal agriculture; vertebrate pest control; forestry; preplant soil fumigation that is not linked to a known crop; or uncultivated non-ag settings. See the SI Appendix 3 for a full listing of the included and excluded site codes.

Data analysis

We analyzed the influence of the PCA group on pesticide use by fitting linear mixed-effect models using the R package *lme4* (Bates et al. 2025). Our analyses all used the following model structure:

$$\text{lmer}(\log(\text{pesticide use}) \sim sales\_PCA + independent\_PCA + farm\_staff\_PCA + farmer\_PCA + coname + site\_code + year + area\_planted + farm\_size + is\_organic + (1|permit\_number)$$

All pesticide use metrics (number of applications; kg/ha of formulated pesticide applied; kg/ha of pesticide active ingredient applied) were $\log_{10}$ transformed. This placed the effects of all predictors into a multiplicative framework and allowed us to analyze pesticide use across diverse crops for which pesticide use varies across many orders of magnitude (Rosenheim et al. 2020). In the model description above, the first four predictors describe the proportional group composition of the single or multiple PCAs who were advising a given farmer (permit holder). A farmer advised by only sales PCAs (one sales PCA or multiple sales PCAs) would have a value of 1.0 for the *sales* predictor and 0.0 for other PCA predictors (*independent*, *farm staff*, and *farmer*). A farmer advised by one sales PCA and one independent PCA would have a value of 0.5 for the *sales* predictor, 0.5 for the *independent* predictor and 0.0 for the remaining PCA predictors. The baseline condition is a farmer whose PCAs are unknown; this was not coded to avoid having the different PCA categories sum to 1.0 (i.e., model overspecification). The remaining covariates included the county name (*coname*, fixed effect; 57 included; baseline level = Alameda County); crop type (*site_code*, fixed effect; 223 included; baseline level = small fruits (all or unspecified)); year (*year*, fixed effect; coded as a factor variable with 10 levels included; baseline level = 2012); field size (*area_planted*, fixed effect); farm size (*farm_size*, fixed effect; calculated as the sum of all field sizes that were farmed under a single pesticide use permit); whether the field was farmed conventionally (*is_organic* = 0) or organically (*is_organic* = 1; fixed effect); and a random effect for farmer ID (*permit_number*). Some very large farming operations used > 1 permit number, so this metric of farm size underestimates the size of some of the largest farms. *area_planted* and *farm_size* were scaled (mean subtracted, divided by the standard deviation) to facilitate model convergence. Covariates were included because they each are known to influence pesticide use (Shennan et al. 2001; Larsen and Noack 2017, 2021; Pearse and Rosenheim 2020; Rosenheim et al. 2020, 2022; Larsen et al. 2021).

We analyzed several response variables, including total pesticide use, pesticide use partitioned by class of targets (arthropods; plant pathogens; weeds), and pesticide use for each of California's top ten crops. We also analyzed the use of two non-pesticide classes of agricultural chemicals. First, we analyzed adjuvants, materials intended either to perform a variety of functions related to the actual application of the pesticide (antifoaming agents, antidrift agents), or agents that putatively improve the coverage of the target crop surface (including spreaders or stickers). We analyzed adjuvant use (number of applications; kg formulated adjuvant) per application event, where an application event was defined as one or more registered pesticides applied to the same field area at the same time (day, time of application, which is reported in PUR). Adjuvants are relatively inexpensive additives, but several large agricultural chemical distributors develop and sell proprietary adjuvants. The second class of non-pesticides was plant growth regulators; crops that are never or only very rarely treated with plant growth regulators were excluded before analysis. Finally, we used a zero-inflated generalized linear mixed model, fit with R package *glmmTMB* (Brooks et al. 2025) with a binomial distribution and a logit link to model the proportion of all pesticides used that were single-registrant.

Our dataset included records for pesticide use on 592,068 crop-years grown outdoors in California from 2012 to 2021 for which we could identify associated PCAs and place them into one of our four groups. 381,371 of these had just a single PCA, with the remaining 210,697 having 2–14 PCAs.

The 592,068 records with known PCAs broke down as follows: independent PCAs were associated with 165,577 total records; of these, 102,748 crops had 100% independent PCAs and 62,829 had some independent PCAs as well as other PCA groups ('partial'); sales PCAs were associated with 349,072 total records (276,419 as 100% sales, 72,653 as partial sales); farm staff PCAs were associated with 58,326 records (39,694 as 100% farm staff, 18,632 as partial farm staff); and farmer PCAs were associated with 10,828 records (6,351 as 100% farmers, 4,477 as partial farmers). A larger set of 820,351 records for crop-years where the PCAs were unknown allowed us to estimate a baseline picture of pesticide use across California. Our full dataset included pesticide use for 1,412,419 crop-years. We adopted the conservative approach of considering two PCA groups to differ in associated agricultural chemical use if the 95% confidence intervals for their estimated effects did not overlap.

Our test of the conflict of interest hypothesis posits that farmers advised by sales PCAs will have elevated pesticide use, as evidenced by a positive coefficient for the sales PCA term in our statistical model (SI Appendix 4). This should be true for the analysis of total pesticide use as well as analyses of the use of each of the different classes of agricultural chemicals considered singly (pesticides targeting arthropods; pesticides targeting plant pathogens; pesticides targeting weeds; adjuvants; and plant growth regulators). Our test of the risk aversion hypothesis posits instead that any group of PCAs that experiences elevated risk aversion should display increased use of pesticides (positive model coefficient for that group of PCAs) only when targeting pests that can exhibit outbreaks (arthropods and plant pathogens) but no increase in pesticide use (negative or near-zero model coefficient) when targeting non-outbreak pests (weeds).

Results

We found no support for the hypothesis that conflicts of interest in sales PCAs result in elevated use of pesticides. Farmers advised by sales PCAs did not exhibit elevated total use of pesticides relative to the other groups of PCAs, regardless of which measure of pesticide use was considered (number of applications, kg/ha formulated material, or kg/ha active ingredient; Fig. 2A, SI Appendix 4). If we compare farmers advised by sales PCAs with farmers advised by independent PCAs, which is perhaps the comparison that isolates the conflict of interest effect most directly, we see that sales PCAs are associated with slightly reduced total pesticide use (Fig. 2A); this effect is very small in magnitude, but still statistically supported, and appears to be generated by reduced use of pesticides targeting plant pathogens (Fig. 2C). Pesticide use by sales PCAs that is lower than pesticide use by independent PCAs is the opposite of what is expected under the conflict of interest hypothesis. We also found that farmers advised by sales PCAs use less of the expensive, single-registrant pesticides than do farmers advised by independent PCAs (Fig. 3). This is again the opposite of what is expected under the conflict of interest hypothesis.

Analyses of pesticide use in the top ten best represented crops in our dataset revealed some crop-to-crop variation in patterns, but generally confirmed the lack of support for the conflict of interest hypothesis: across the thirty total contrasts of independent versus sales PCAs (10 crops $\times$ 3 response variables per crop $=$ 30), we observed 11 cases where pesticide use was higher for farmers advised by independent PCAs, 16 cases where pesticide use did not differ (95% confidence intervals overlapped), and only 3 cases where farmers advised by sales PCAs used more pesticides (SI Appendix, Figure S1).

If there is any hint of support for the conflict of interest hypothesis in our analyses, it comes from the use of adjuvants (Fig. 2E). Farmers advised by sales PCAs used an increased number of adjuvants per pesticide application compared with farmers advised by other groups of PCAs. This elevated use was not seen, however, if we consider the total amount of adjuvant applied (kg/ha; Fig. 2E).

Our analyses instead provide some initial support for the predictions of the risk aversion hypothesis. Farm staff PCAs are associated with strongly elevated use of pesticides when targeting pest groups capable of rapid outbreaks (arthropods, plant pathogens; Fig. 2B, C). In contrast, when comparing farm staff PCAs with independent PCAs or sales PCAs, farm staff exhibited lower use of pesticides when targeting the one class of pests that is not capable of rapid outbreak dynamics – weeds (Fig. 2D). Farm staff PCAs were also associated with similar or reduced use of non-pesticide agricultural chemicals – including adjuvants and plant growth regulators – compared to other PCA groups (Fig. 2E, F). Thus, farm staff PCAs do not exhibit globally elevated use of agricultural chemicals; rather, they show elevated use only of those chemical products that are associated with the control of outbreak pests. This is the signature of agricultural chemical use expected under risk aversion.

Finally, farm-staff PCAs also exhibited somewhat elevated use of the more expensive, single-registrant pesticides, higher than that observed for sales PCAs but not significantly higher than that observed for independent PCAs (Fig. 3). This was not a predicted outcome, but we discuss it below.

Discussion

We tested two hypotheses for how different groups of PCAs might influence pesticide use by California farmers. The conflict of interest hypothesis predicts that farmers advised

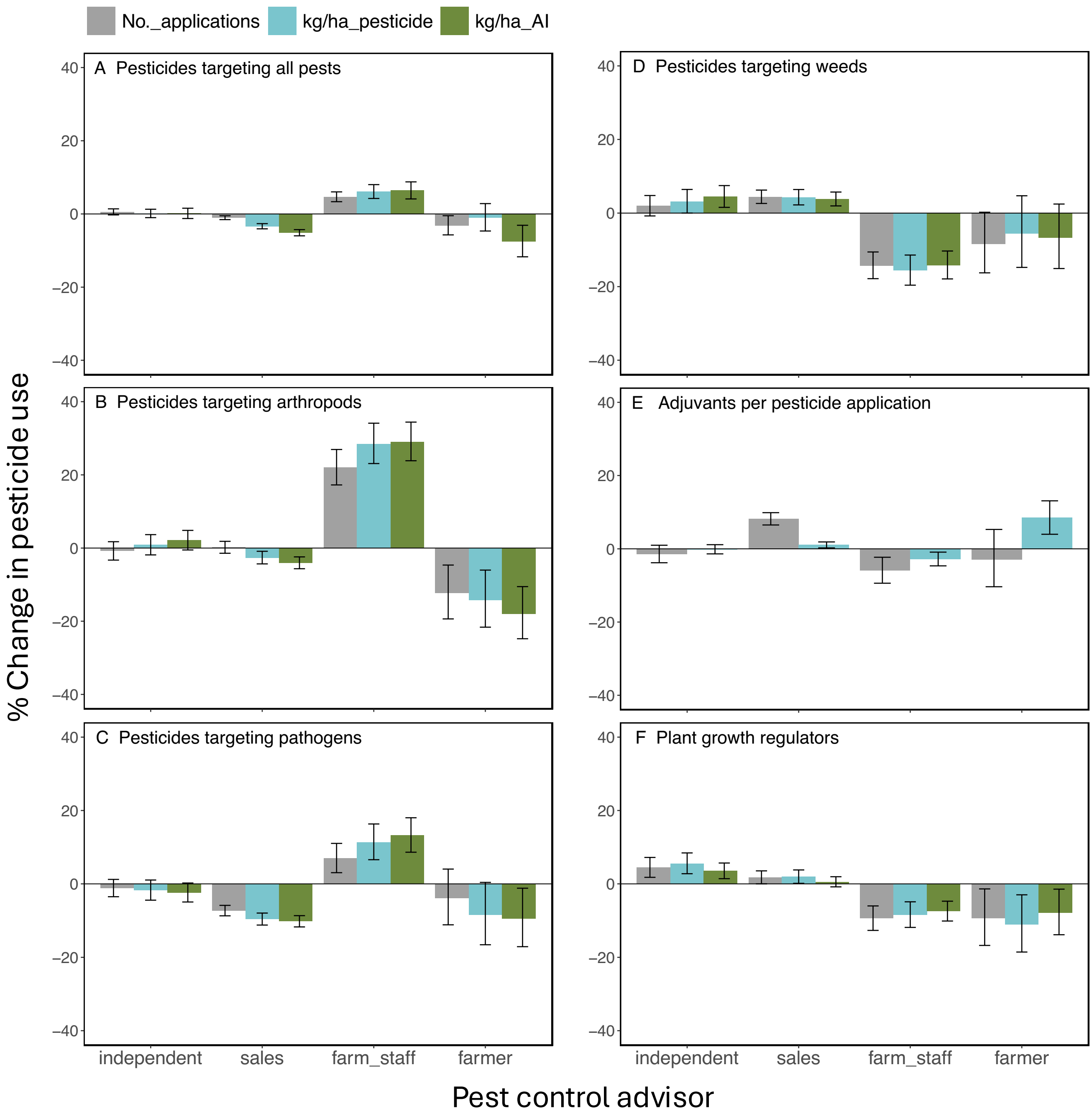

Fig. 2 Percent change in the use of agricultural chemicals by farmers advised by different groups of pest control advisors (PCAs), including independent, sales, farm staff, and farmer PCAs. The baseline case is the mean chemical use observed for the 820,351 records for which PCAs are unknown. Chemical use is measured as the number of applications (gray bars), kg/ha of formulated material applied (blue bars), or kg/ha of active ingredient applied (green bars). Shown are the use of (**A**) pesticides targeting all pest groups; **B** pesticides targeting arthropods; **C** pesticides targeting plant pathogens; **D** pesticides targeting weeds; **E** adjuvants included with each pesticide application; and **F** plant growth regulators

by sales PCAs will show a globally elevated use of all agricultural chemicals. We see no support for the predicted increase in pesticide use by farmers advised by sales PCAs. Only for adjuvants, which are a group of relatively inexpensive compounds that lack pesticidal activity, and which are not associated with the same negative non-target and environmental impacts as pesticides, do we see some elevated use by farmers advised by sales PCAs. The idea that conflicts of interest propel overuse of pesticides, with negative consequences for society as a whole, has been widely

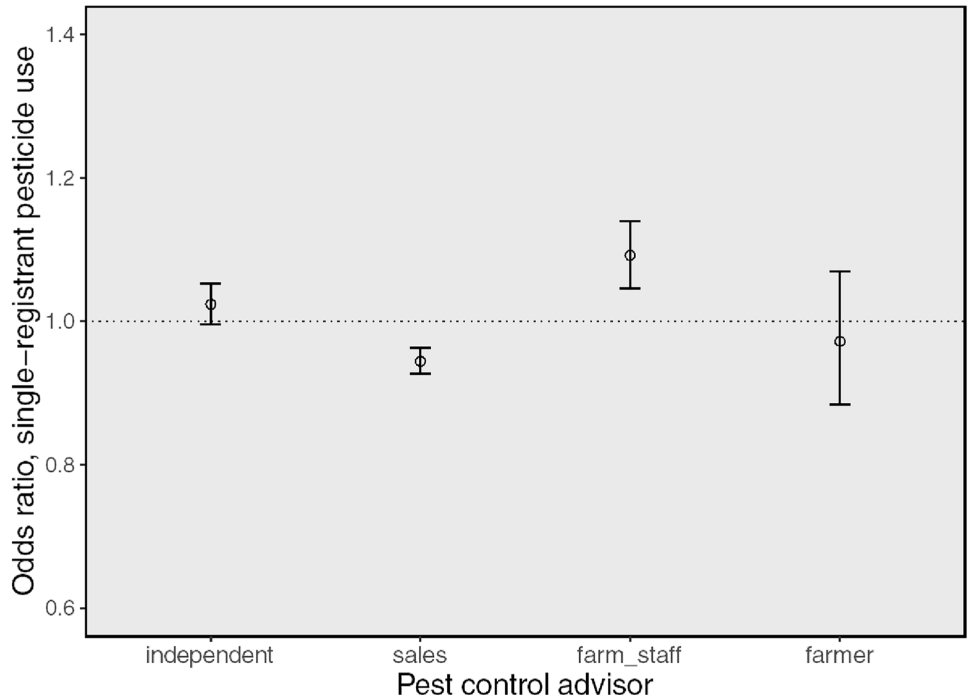

Fig. 3 Odds ratio for use of single-registrant, patent-protected pesticides and adjuvants by different groups of pest control advisors. The baseline case is the use of single-registrant pesticides and adjuvants observed for the 820,351 records for which PCAs are unknown

accepted in California and elsewhere; this idea continues to shape governmental policy documents that guide pest management and pesticide use regulations (UNFAO 2010; Sustainable Pest Management Work Group 2023). Nevertheless, neither the body of previously published studies nor our present results support the assumed underlying connection between sales PCAs and elevated pesticide use.

The application of the risk aversion hypothesis to our analysis was less well defined, because it was unclear which PCA group, if any, would experience stronger risk aversion. The risk aversion hypothesis does, however, predict a particular signature of agricultural chemical use: high risk aversion should be reflected in elevated use of pesticides when targeting outbreak pests (arthropods, pathogens) but not when targeting non-outbreak pests (weeds). Furthermore, the risk aversion hypothesis predicts no increase in the use of plant growth regulators. Exactly this signature emerges for pesticide use by farmers who are advised by farm-staff PCAs (Fig. 2).

Thus, overall, our analyses suggest that it may be fear (of pest outbreaks) rather than greed (the desire to earn greater sales commissions) that drives differences across groups of PCAs in pesticide use.

All of our analyses are based upon an observational dataset rather than an experimental dataset; that is, we have not randomly assigned a PCA 'treatment' to different farmers. We highlight two potential problems in this regard. First, farmers with different philosophies for pest management may choose to employ different types of PCAs to guide their pest management practices. Surveys of California farmers have suggested that farmers who tend to rely more on the use of pesticides to control pests are more likely to be associated with sales PCAs, whereas farmers who use more diverse pest management practices ("integrated pest management") are more likely to be associated with independent PCAs (Shennan et al. 2001; Brodt et al. 2004). These associations could be the result of (a) non-random choice of PCAs by farmers; (b) PCAs shaping the pest management practices of their client farmers; or (c) both a and b. All other things being equal, a preferential association of pesticide-oriented farmers with sales PCAs should tend to inflate the apparent pesticide use exhibited by our class of sales PCAs, for reasons unrelated to any conflicts of interest. This makes it all the more remarkable that our analyses failed to find any support for elevated pesticide use by farmers who employ sales PCAs. Second, farm-staff PCAs are generally found in association with larger farming operations that can afford to hire specialized staff. We include farm size as a covariate in our statistical models to control for any effects of farm size; we note furthermore that although we do find that larger farms are associated with slightly elevated pesticide use, the effect is small (a 1 SD increase in farm size was associated with a 0.63% increase in the total number of pesticide applications (95% CI: 0.05 – 1.20%)). Thus, we think it is unlikely that differences in farm size affect our central inferences. Most importantly, our test of the risk aversion hypothesis relies primarily on within-group contrasts: within the group of farmers who hire farm-staff PCAs, we compare use across different classes of agricultural chemicals (pesticides targeting outbreak pests versus pesticides targeting non-outbreak pests plus non-pesticides), and thus our inferences should not be sensitive to any possible feature of farmers who choose to employ farm-staff PCAs.

Our study cannot evaluate which pest management practices are higher performing for either society as a whole or for the client farmer. It is tempting to say that less pesticide use is always better for society, but this would be an oversimplification, because pesticides are associated with complex direct and indirect societal costs and benefits (National Research Council 2000; Cooper and Dobson 2007; Savary et al. 2019). Moreover, we do not know if the increased use of pesticides against outbreak pests exhibited by farm staff PCAs actually improves pest control by reducing the likelihood of infrequent but perhaps catastrophic crop damage events; data on pest densities and crop yield and quality are needed to address such questions. When such data have been available, analyses have demonstrated cases of both underuse and overuse of pesticides in commercial California agriculture, sometimes within the same system (e.g., Rosenheim and Meisner 2013). Establishing an optimal control program can be surprisingly difficult, and ecological factors associated with mean pest densities can be very different from ecological factors associated with pest population variability and outbreaks (Paredes et al. 2022). Some might suggest that the levels of pesticide use demonstrated by farmers when they themselves execute the pest scouting and decision making (i.e., farmer PCAs) should be considered to be close to the farmer's economic optimum, and that pesticide use exceeding this level is likely to reflect overuse; but this presumes that farmers, who may have little time to devote to pest management given their myriad other responsibilities, are consistently capable of identifying and implementing the optimal management program. Thus, we remain agnostic about which of the four groups of PCAs studied here should be viewed as achieving the more nearly optimal pesticide use practices.

Why do not sales commissions lead to elevated pesticide use?

Discussions with PCAs and agricultural chemical retailers revealed three factors that may weaken or break the expected linkage between sales commissions and pesticide use. The first concerns the details of the sales commission itself. Sales PCAs do receive a supplement to their base salary from sales commissions, but these commissions are based not on gross sales receipts, but rather on the profit generated by a sale. A near-universal observation shared with us is that profit margins associated with pesticide sales are small, significantly smaller than profit margins associated with the sale of other agricultural chemicals, and in particular the sale of proprietary adjuvants and microfertilizers. The larger profit margins associated with adjuvant sales may explain why adjuvants are the sole class of agricultural chemicals for which we see elevated use by farmers advised by sales PCAs.

The second reason that sales commissions do not appear to translate to heavier use of pesticides concerns the nature of the relationship between PCAs and their client farmers. PCAs with whom we spoke emphasized this point above all: PCAs establish long-term relationships with their client farmers that are based on trust (Warner 2006). PCAs are acutely aware of the costs incurred by their clients as they farm their crops, and PCAs must strive to achieve high-quality outcomes (good pest suppression; vigorous crop growth; high quantity and quality yields) with cost efficiency. PCAs who fail to achieve this will lose clients and incur the reputational damage that will prevent them from gaining new clients. Thus, PCAs operate in a highly competitive environment. PCAs reach financial success not by attempting to inflate sales to a particular farmer client, but rather by providing high-quality, cost-efficient service to farmers, building a reputation of success, and then leveraging that reputation to recruit more clients. Total sales commissions rise, therefore, by increasing the number of clients rather than elevating the amount sold to a particular client. In some cases, highly successful PCAs may hire their own staff to assist with the labor-intensive scouting of fields, allowing them to expand the scope of their pest advising services; thus, there are strong opportunities for growing the number of farmer clients.

Finally, sales commissions may not translate to increased pesticide use because, although commissions might motivate sales PCAs to recommend a particular pesticide application, the farmer may choose not to accept the PCA's advice. Although some farmers accept virtually all PCA recommendations, others balance the judgment of the PCA against their own appraisal and may choose to decline making a particular recommended pesticide application. Farmers are fully aware of the commissions earned by their sales PCAs and may provide a balancing counterinfluence.

Pesticide use as a response to risk aversion

Agricultural economists define risk as "variability in crop revenues" (Möhring et al. 2022). Loss of crop revenues can be caused by many factors, including adverse weather. From the perspective of PCAs, a particular subset of risk-generating factors is, however, paramount: rapid outbreaks of pest populations that are capable of producing major crop losses or, in some cases, complete crop failures. Different groups of pests have varying potentials to generate rapid outbreaks. Insects and disease agents are often highly mobile and have rapid generation turnover; incipient populations may be difficult to detect, but still capable of producing rapid population growth (outbreaks), generating major crop damage and irretrievable losses in a short period of time. Weeds, in contrast, are less mobile, more conspicuous, and have longer generation times; thus, population growth is slower, and PCAs can almost always intervene at any time with herbicide applications or tillage to suppress populations that are judged to be approaching damaging levels. Thus, arthropods and pathogens are outbreak pests, producing risk for PCAs, whereas weeds generally are not.

We hypothesized, then, that heightened risk aversion should produce a distinctive signature of pesticide use, including elevated use of pesticides targeting the outbreak-capable pests that threaten the crop, arthropods and pathogens, but no increase in the use of pesticides targeting non-outbreak pests, weeds. We were unable, a priori, to predict clearly which types of PCAs should be candidates for the expression of heightened risk aversion. Thus, although we find the signature of risk-aversive pesticide use displayed specifically by farm-staff PCAs, we must be tentative in interpreting this result as a risk effect. Additional work is needed to test this interpretation.

Why might elevated pesticide use be an expected outcome of heightened risk aversion? Pesticide use has been shown to be positively correlated with risk aversiveness across individual farmers (Liu and Huang 2013; Li et al. 2022). Although pesticides have been criticized as having low efficacy when viewed over the course of a full growing season (Janssen and van Rijn 2021), in many cases season-long control is less important for farmers than the protection of the crop through a narrow window of crop susceptibility, even if repeat applications are sometimes necessary. The short-term field efficacy of pesticide applications appears to be relatively high (Rosenheim 2021). Thus, it is not surprising that risk-averse farmers would resort to increased use of pesticides.

Why might farm-staff PCAs express greater risk aversion? To our knowledge, this question has not previously been considered in the academic literature. One possibility is that farm-staff PCAs, who have a single employer rather than consulting for multiple farmer clients, have a greater sense of shared interests with their sole employer. Another possibility, which was shared with us in conversations with members of the pest control industry, is that farm-staff PCAs have more to fear if they are blamed for adverse pest management outcomes—the loss of their full employment—than do other PCAs. Additional work will be needed to explore these or other possible contributors.

We have also found that farm-staff PCAs are more likely to use newer, still patent-protected pesticides. It is possible that this is another expression of elevated risk aversion. Control failures following pesticide applications can be associated with major crop damage. These failures can occur for several reasons, but one of the most common is resistance evolution in the target pest (Gould et al. 2018). Because resistance evolution is a gradual process, resistance problems are more commonly encountered when applying older pesticides (Timmermann 2015). Newly introduced pesticides may, therefore, be perceived as safer, with lower risk of resistance-based control failures.

Additional research is needed to determine if the elevated use of pesticides targeting pests with outbreak potential and the increased use of newer, patent-protected pesticides are actually effective in strengthening the protection of the crop. If not, it will be important to design prescriptions that moderate these risks to reduce the number and cost of pesticide applications. Could insurance help to reduce risks perceived by PCAs? Crop insurance that covers damage generated by pests has been shown to decrease pesticide use in some cases (Li et al. 2022). In some cases, however, insurance can also influence farmer choice of which crops to grow, which can have unexpected influences on pesticide use (Möhring et al. 2020). We can envision that crop insurance purchased by the farmer, combined with close consultation between the farmer and the PCA, could facilitate using fewer pesticide applications targeting potential outbreak pests. This would require the farmer and PCA to decide together to accept the small risk of a pest outbreak in exchange for a reduction in total crop input costs.

Conclusions

The conflict of interest hypothesis has been accepted largely uncritically because the underlying logic was so simple and compelling: anyone earning commissions on pesticide sales will be motivated to sell more pesticides. It would therefore seem foolhardy to place the often-subjective evaluation of whether or not a pesticide application is needed in the hands of a pesticide salesperson. But empirical support for this hypothesis has been largely absent. California's uniquely comprehensive reporting requirements for pesticide use created an opportunity to test this hypothesis on a large scale. We find that the expected link between sales commissions and elevated pesticide use is absent. Pesticide use by farmers advised by sales PCAs is similar to, or slightly below, that of farmers advised by independent PCAs, who lack the incentives generated by sales commissions. In a highly competitive market, all PCAs strive for cost-efficiency with the goal of maintaining long, trust-based relationships with their farmer clients or employers. We find also that farm-staff PCAs are associated with heavier use of pesticides when managing pests capable of outbreaks, a signature of risk aversion. Further research is needed to test how risk aversion shapes PCA recommendations and pesticide use. Our results suggest that regulatory and policy initiatives devoted to reducing unnecessary pesticide use should be redirected away from interventions focused on pesticide sales and instead towards management of the perceived risks of pest outbreaks, which could be driving increased pesticide use.

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Author contribution JAR and MCM conceived and designed research. JAR and MCM prepared the datasets. JAR analyzed the data and wrote the manuscript.

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Data availability The datasets analyzed during the current study are available in the DRYAD repository for reviewers at this DOI: https://datadryad.org/share/J525DAx2O4dIY9_pe2XHHafS5gmfmnxLbXl_Be1R23c.These data will be made available publicly after publication.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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