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High highs and low lows: Elucidating striking seasonal variability in pesticide use and its environmental implications

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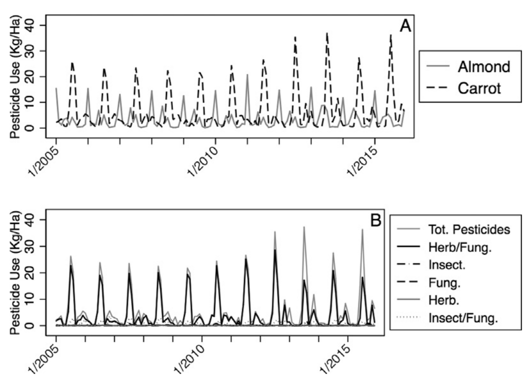
HIGHLIGHTS

- Harm from pesticide use is partially determined by spatiotemporal overlap of use with sensitive populations.
- Data limitations have inhibited understanding where and when high levels of pesticides occur.
- We show monthly pesticide use rates ($kg\ ha^{-1}$) are crop-specific with distinct peaks that are consistent year-to-year.
- Further, regions with very high pesticide use exist throughout the year, yet vary in spatial location across seasons.
- Results suggest opportunities to refine on-farm and policy efforts to reduce the negative consequences of pesticide use.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite substantial public and scientific concern regarding unintended environmental and health consequences of agricultural pesticide use, identifying when and where high levels of use occur is stymied by a dearth of data at biologically relevant spatial or temporal scales. Here we investigate intra-annual patterns in pesticide use by crop and by pesticide type using unique pesticide use data from agriculturally diverse croplands of California, USA. We find that timing and type of pesticide use is strongly crop-dependent, and that for many high pesticide use crops, monthly application rates are highly consistent from year-to-year. Further, while pesticide use hotspots are concentrated in early summer, regions with very high use occur throughout the year with spatial distributions varying therein. The enormity of intra-annual variation in pesticide use, as well as the consistency in those patterns through time, suggests opportunities for crop-specific pest management and region-specific mitigation approaches to limit environmental and human health hazards from agricultural pesticide use.

1. Introduction

In the past half century, agricultural production has increased to meet the demands of an increasingly large and wealthy human population (Foley et al., 2011; Tilman and Clark, 2014). The doubling of agricultural production in this period is attributable to a combination of conversion to agriculture and intensification of existing production lands through the use of input technologies, among other innovations (Tilman et al., 2011). While the increase in available food production led to dramatic reductions in starvation and poverty worldwide, there are numerous negative consequences to agricultural technologies that

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have widespread impacts on human and ecological communities across the globe (Clark and Tilman, 2017; Vandermeer, 2011).

Of particular interest to natural and health scientists, as well as economists and policy makers, is the widespread and increasing use of pesticides. Recent estimates of agricultural pesticide use suggest that around 400 million kg of active ingredients are applied annually to United States (US) farms, at a cost of about 9 billion US dollars to producers in 2012 (Atwood and Paisley-Jones, 2017). However, evidence from ecological and health studies suggests the purchase price of pesticides far underestimates the societal cost of pesticide use (Bourguet and Guillemaud, 2016; Paul et al., 2002; Sexton et al., 2007; Soares and de Souza Porto, 2009). For example, numerous ecological studies have found negative effects of pesticides on a wide range of taxa including beneficial insects, pollinators, amphibians, and birds (Geiger et al., 2010; Mineau and Whiteside, 2006; Woodcock et al., 2016). Further, pesticides can harm human health directly through both occupational (Soares and de Souza Porto, 2009; Stillerman et al., 2008; Weichenthal et al., 2010) and non-occupational exposures (Gemmill et al., 2013; Harley et al., 2016; Larsen et al., 2017), and indirectly through reductions in ecosystem functions and services (Chagnon et al., 2015; Dale and Polasky, 2007).

Understanding when and where high levels of pesticide exposures occur could provide valuable opportunities to mitigate both human and ecological externalities. Such knowledge would be particularly valuable for human fetal and infant health, where certain temporal windows of development are particularly sensitive to environmental contaminants (Perera and Herbstman, 2011) and for which high levels of pesticide use have been shown to have a disproportionately large impact on adverse health outcomes (Larsen et al., 2017). Identifying peaks in pesticide use may also be key to understanding hazards for flora and fauna with sensitive yet seasonal activities such as breeding aggregations and larval development (Du Gas et al., 2017; Moye and Pritsos, 2010; Rohr et al., 2013, 2008). This is especially true in regions with high value and highly diverse croplands since the amount, type, and seasonality of pesticide use may be difficult to disentangle using observations of individual farmer behavior.

Unfortunately, locating or predicting high exposures is often hampered by a surprising dearth of pesticide use data in most agricultural regions. While air pollution and water quality are monitored consistently throughout much of the developed world and have been for decades, pesticide use is often aggregated to county or greater spatial units, estimated annually at best, and rarely available by individual crop type or chemical. Progress has been made by aggregating disparate regional and national datasets to understand long-term time trends in pesticide use (Mall et al., 2018), and how on-farm and landscape features (Gardiner et al., 2009; Larsen, 2013; Larsen et al., 2015; Tscharntke et al., 2005) as well as technological innovations such as the introduction of genetically modified crops (Kniss, 2017) changed pesticide trends. Yet, these studies have generally been limited by the underlying data to coarse spatial scales (e.g. county or country), coarse crop groups (e.g. fruits and vegetables), coarse time scales (e.g. annual) or more often, a combination of the three that limits the scientific questions that can be addressed.

Since the early 1990s, California has required full reporting of pesticide use on agricultural lands. California accounts for about 20% of United States agricultural pesticide use (Atwood and Paisley-Jones, 2017; CDPR, 2014), and like many fruit, vegetable, and nut producing regions around the world, California grows a diversity of high value, high pesticide use crops as well as a range of lower value forage and grain crops (CDFA, 2016). The California Pesticide Use Reports (PUR) database provides unparalleled opportunities to understand the drivers, consequences, and trends in agricultural pesticide use.

Before the unique, statewide application data were available, efforts to synthesize pesticide use in California focused on understanding the amount and diversity of chemicals in production and forecasts of future use trends (Maddy, 1983). Yet, even now that refined spatio-temporal data exist, the focus has primarily been on annual statewide trends in total use or chemicals of regulatory interest. More recent efforts have centered on understanding annual trends in the toxicity of pesticide applications overall and for specific applications such as organophosphate use in dormant season treatments (Epstein and Bassein, 2003; Zhang et al., 2005; Epstein and Zhang, 2014). Annual use trends undoubtedly provide valuable information for how farmers are adapting to policy, education campaigns and new technologies. However, refined spatio-temporal knowledge provides added opportunities to understand and reduce health and environmental hazards stemming from heterogeneous agricultural activities. Further, understanding crop-specific pesticide use and variability over time provides insight into the amount of pesticides that are routine, due to "calendar application" or consistently reoccurring pests, and the amount that is variable and likely to be influenced by Integrated Pest Management (IPM) interventions and monitoring of ecological conditions (Lescourret, 2017; Mall et al., 2018).

Here we investigate the magnitude and consistency of pesticide use within and between years by analyzing detailed pesticide use data from California. Specifically, we address the following questions, (1) What are the intra-annual patterns in pesticide use and how consistent are they year-to-year? (2) Is pesticide use driven by seasonality (i.e. persistent seasonal trends), by annual characteristics or by a combination of the two? (3) Where are the hot spots of pesticide use and how do they vary throughout the year? Based on IPM and agronomic research, we hypothesize that intra-annual pesticide use for any given crop, and the timing of peak use for top pesticide use crops, are heterogeneous due to applications at specific periods of the crop lifecycle. We expect seasonality to be a stronger driver of pesticide use than annual characteristics, but anticipate strong variation by crop. Further, we expect that hotspots of pesticide use will be spatially concentrated in the major agricultural producing valleys (e.g. San Joaquin, Sacramento), and those regions will be pesticide hotspots for most months of the year. Overall, we expect a detailed, spatiotemporal examination of the peaks and troughs of pesticide application in major crops to help identify key areas and crops which would benefit most from the implementation of alternative management practices aimed at reducing pesticide use.

2. Methods

2.1. Kern County data

Kern County is California's second most valuable agricultural county with around 7 billion dollars in sales (~15% of California's sales) (CDFA, 2016). We obtained PUR data from the 2005–2015 Kern County Agricultural Commissioner's (CAC) Office Spatial Data. The Kern CAC data include observations of daily pesticide use including pounds of product used (converted to kg), and area and date treated. Unlike the statewide PUR data, the Kern County data include field-level information. Kg of active ingredients was then calculated using the Product Database from the California Department of Pesticide Regulation (CDPR). The Product Database includes a variety of information on individual pesticide products registered in California including pesticide category, re-entry intervals, percent active ingredients and specific hazards (e.g. freshwater). The Product Database can be matched to the Kern County pesticide use data and the statewide Pesticide Use Reports (PUR) using the product number field. Data on pesticides were matched with field-level data on crop type and area in production from the Kern CAC to calculate kg of active ingredients ha^{-1}. For the purpose of this study, a field is a unique commodity-year-physical location combination. Here and below, dashes indicate a multiplicative ("commodity by year by physical location"). Thus, if a location first produced strawberries then rotated to broccoli on the same site in the same year, pesticide use data and area in production capture each crop individually.

For each individual pesticide application in the pesticide use reports, pesticide use (kg active ingredients) was calculated using total kg of