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Spatial and temporal patterns of pesticide use on California almonds and associated risks to the surrounding environment

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HIGHLIGHTS

- Saptiotemporal patterns of pesticide use/risk in California almonds were studied.
- Use intensities of insecticides/fungicides/herbicides showed latitudinal gradients.
- Overall, herbicide use increased considerably, while fungicide use decreased.
- The risks to surface water, groundwater, and soil decreased in many areas.
- Risk patterns were mainly associated with use patterns of high-risk pesticides.

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ABSTRACT

Various stakeholders of California almonds have been investing efforts into mitigating pesticide impacts on human and ecosystem health. This study is the first comprehensive evaluation that examines the spatial and temporal patterns of pesticide use and associated environmental risks. The pesticide use data from 1996 to 2010 were obtained from the Pesticide Use Reporting database. The Pesticide Use Risk Evaluation indicator was employed to evaluate the pesticide environmental risks based on the pesticide properties and local environmental conditions. Analyses showed that the use intensities (*UI*) of insecticides (oils accounted for 86% of the total insecticide *UI*) and herbicides both increased from north to south; fungicides showed the opposite spatial pattern; and fumigants were used most intensively in the middle region. The *UI* of fungicides and herbicides significantly decreased and increased, respectively, throughout the study area. The insecticide *UI* significantly decreased in the north but increased in many areas in the south. In particular, the organophosphate *UI* significantly decreased across the study area, while the pyrethroid *UI* significantly increased in the south. The fumigant *UI* did not show a trend. The regional risk intensities of surface water (RI_W), soil (RI_S), and air (RI_A) all increased from north to south, while the groundwater regional risk intensity (RI_G) decreased from north to south. The main trends of RI_W, RI_G, and RI_S were decreasing, while the RI_A did not show a trend in any region. It's noticeable that although the herbicide *UI* significantly increased, the *UI* of high-leaching herbicides significantly decreased, which led to the significant decrease of RI_G. In summary, the temporal trends of the pesticide use and risks indicate that the California almond growers are making considerable progress towards sustainable pest management via integrated pest management, but still require more efforts to curb the fast increase of herbicide use.

1. Introduction

Almonds are one of the most important specialty crops in California, USA, which produced about 80% of the global almond supply and generated $3.87 billion in revenue in 2012 (Almond Board of California, 2012). Almost all the California almond orchards (3080 km^2 in 2012) are located in the Central Valley (58,000 km^2), which has a mild climate, fertile soil, and abundant sunshine. The Central Valley is one of the most productive agricultural areas in the world. Key pests in almond are navel orangeworm (*Amyelois transitella*), San Jose scale (*Quadraspidiotus perniciosus*), peach twig borer (*Anarsia lineatella*), web-spinning spider mites, and ants (CEPA, 2011). In the dormant season, oil spray alone can control low to moderate populations of San Jose scale and mites. When populations of peach twig borer (also targeted during bloom) and San Jose scale are high, oils are likely sprayed with other insecticides. In the growing season, insecticide treatments (mainly in July and August) mostly control navel orangeworm. Diseases during winters and early springs, such as anthracnose (pathogen: *Colletotrichum acutatum*), brown rot blossom blight (pathogen: *Monilinia laxa*), and scab (pathogen: *Cladosporium carpophilum*) are controlled by various fungicides, e.g., captan, copper, or ziram (UC IPM, 2012). Weeds, such as bermudagrass (*Cynodon dactylon*), dallisgrass (*Paspalum dilatatum*), and

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hairy fleabane (*Conyza bonariensis*), are treated with pre-emergence or post-emergence herbicides. To minimize the yield loss caused by pests, pathogens, and weeds, California almond growers apply a large amount of pesticides; 9.3 million tons of pesticide active ingredients were applied in 2010 (CEPA, 2012). However, the applied pesticides threaten the environment and human health, as evidenced by pesticide detections in groundwater (Kolpin et al., 2000) and surface water (Guo et al., 2007; Hladik et al., 2009).

Various stakeholders have made efforts to reduce or eliminate their uses of the pesticides that are known to harm human health or degrade environmental quality. The United States Environmental Protection Agency (USEPA) regulates pesticide use under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA). Both of these acts were significantly amended by the Food Quality Protection Act of 1996 (FQPA), which set tougher safety standards, including mandatory pesticide reregistration (USEPA, 2012). In addition, integrated pest management (IPM) practices have been promoted to achieve the goal of sustainable pest management. Growers monitor pest pressure and apply pesticides only when necessary, and high-risk pesticides tend to be replaced with reduced-risk pesticides. For instance, organophosphates that were found to deteriorate surface water quality were partially replaced with oils or *Bacillus thuringiensis* (Bt), and hence the majority of insecticides (in terms of mass) applied on almonds in recent years were oils (Epstein et al., 2001; Zhang et al., 2005). To present an overall and more recent picture of the shift of pest management practices for California almonds, it is important to evaluate all the pesticides that are used, which has not been done in previous studies.

Analyzing the data for pesticide use alone is insufficient for evaluating environmental consequences of pest management practices (Barnard et al., 1997), thus numerous pesticide risk indicators considering pesticide effects and exposure have been developed around the world (Bockstaller et al., 2009), including PRoMPT (Whelan et al., 2007), SPIDER (Renaud et al., 2008; Renaud and Brown, 2008), EPRIP (Trevisan et al., 2009), and I-Phy (Lindahl and Bockstaller, 2012). These indicators vary in methodologies, input data requirements, indicator outputs, and applicable scales. Several indicator comparison studies have been carried out to identify ideal indicators for different purposes (Maud et al., 2001; Reus et al., 2002; Stenrod et al., 2008), but they have failed to reach clear agreements. In recent years, along with the advancement of the Geographic Information System (GIS) software techniques and accumulation of environmental data, pesticide risk indicators have become closely integrated with GIS for preparing site-specific environmental condition data and presenting risk maps (e.g., Centofanti et al., 2008; Sala et al., 2010; Schriever and Liess, 2007; Vaj et al., 2011).

Yet, two obstacles exist in applied pesticide risk evaluation: (1) the shortage of real pesticide application data; and (2) the lack of a suitable pesticide risk indicator equipped with extensive data of pesticide properties and environmental conditions. This study overcame these two obstacles with the Pesticide Use Reporting (PUR) database (CEPA, 2012) and the Pesticide Use Risk Evaluation (PURE) indicator (Zhan and Zhang, 2012). The PUR database has comprehensively recorded temporal and spatial data for agricultural pesticide use in California, USA since 1990. The PURE indicator was specifically developed for California agricultural pesticide use, and evaluates pesticide's risks to surface water, groundwater, soil, and air, by considering pesticide properties and on-site environmental conditions. The PURE indicator was validated against surface water monitoring data (Zhan and Zhang, 2012) and was evaluated with a sensitivity analysis (Zhan and Zhang, 2013).

This study provides the first comprehensive analysis of overall pesticide use for a crop, along with risk evaluation by a pesticide risk indicator. The goal is to evaluate the past performance of pest management in California almonds. The specific objectives are: (1) to characterize the spatial and temporal patterns of pesticide use; and (2) to analyze the spatial and temporal patterns of pesticide environmental risks. The results and conclusions are expected to reflect the outcome of California almond stakeholders' efforts towards sustainable pest management and to provide suggestions for prioritizing pest management practices.

2. Materials and methods

2.1. Study area

The Central Valley, where almost all of the almonds in California were cultivated, was selected as the study area (Fig. 1a). The study

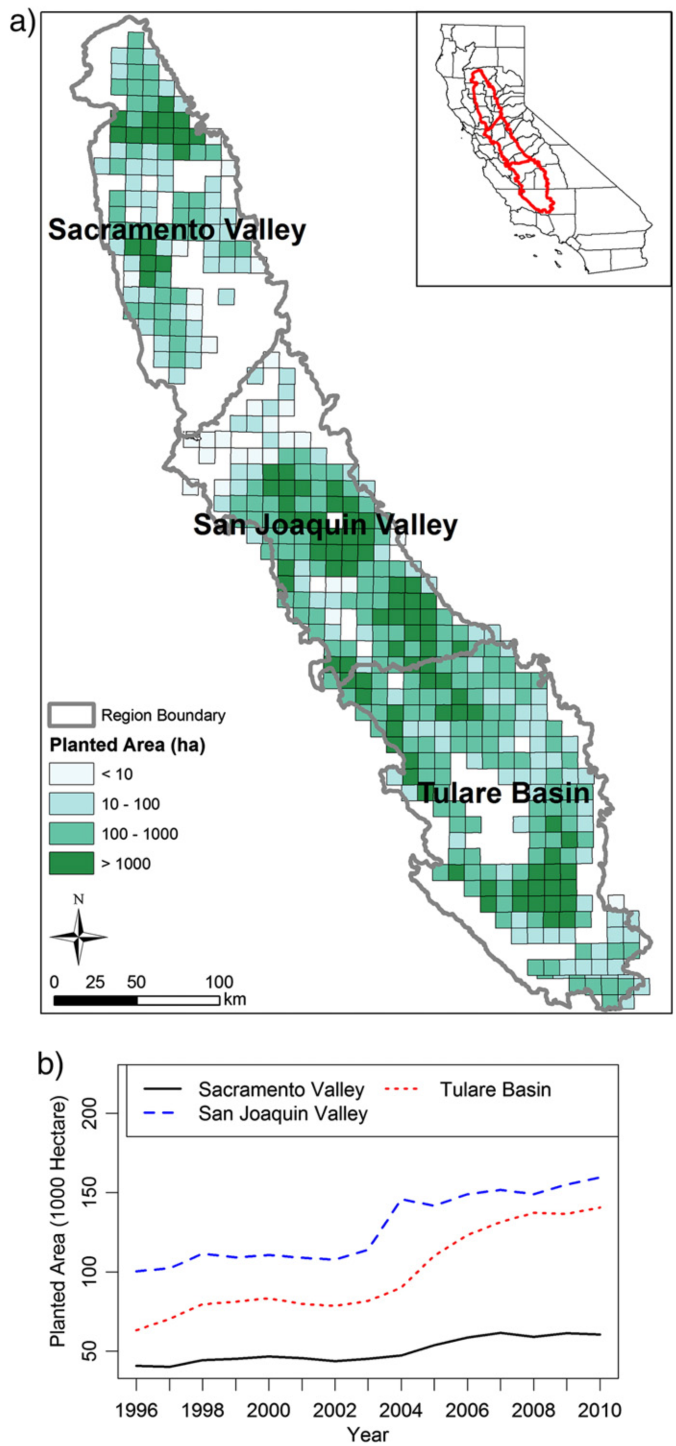

Fig. 1. Spatial and temporal patterns of the almond planted areas from 1996 to 2010 in the Central Valley, California, USA. (a) The average annual planted areas at township (~9.7 × 9.7 km^2) level, and (b) the annual planted areas for each region.