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Response of macroinvertebrate communities to temporal dynamics of pesticide mixtures: A case study from the Sacramento River watershed, California☆

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ABSTRACT

Pesticide pollution from agricultural field run-off or spray drift has been documented to impact river ecosystems worldwide. However, there is limited data on short- and long-term effects of repeated pulses of pesticide mixtures on biotic assemblages in natural systems. We used reported pesticide application data as input to a hydrological fate and transport model (Soil and Water Assessment Tool) to simulate spatiotemporal dynamics of pesticides mixtures in streams on a daily time-step. We then applied regression models to explore the relationship between macroinvertebrate communities and pesticide dynamics in the Sacramento River watershed of California during 2002–2013. We found that both maximum and average pesticide toxic units were important in determining impacts on macroinvertebrates, and that the compositions of macroinvertebrates trended toward taxa having higher resilience and resistance to pesticide exposure, based on the Species at Risk pesticide ($SPEAR_{pesticides}$) index. Results indicate that risk-assessment efforts can be improved by considering both short- and long-term effects of pesticide mixtures on macroinvertebrate community composition.

1. Introduction

Pesticide pollution is one of the major concerns in aquatic ecosystems worldwide because of their widespread presence both in surface water and bed sediments (Anderson et al., 2006; Warren et al., 2003). In addition to having ecological effects, pesticide residues in water, sediments, and fish tissues are of socioeconomic concern, for example in human health risk-assessments that use information on exposure to pesticide residues in rivers subject to intensive agricultural activities (Fianko et al., 2011; Ogbeide et al., 2016). Furthermore, pesticide residues in freshwater environments from agricultural runoffs can give rise to toxic effects on biotic assemblages, and can also result in secondary or indirect effects through ecological interactions that can reverberate through the food web (Hela et al., 2005). Both acute and chronic effects of pesticide contamination can contribute to loss of freshwater biodiversity (e.g., fish, invertebrates, and algae) and ecosystem function (Malaj et al., 2014; Marcel et al., 2013).

Pesticide inputs into lotic ecosystems have been shown to play an important role in the dynamics of macroinvertebrate assemblages (Kattwinkel et al., 2016), and generally have negative effects on macroinvertebrate abundance (Van Dijk et al., 2013). For example, insecticide contamination resulted in reduction or elimination of common species (Schulz and Liess, 1999) and structural, functional, and dynamic changes in macroinvertebrate communities (Beketov et al., 2013; Kattwinkel et al., 2016; Schäfer et al., 2007). Pesticide pollution can pose secondary threats to any ecological processes associated with the community composition of macroinvertebrates in the same or adjacent habitats, e.g., a decline in leaf-litter breakdown in streams (Schäfer et al., 2007). In addition to mortality and other acute toxicity effects, pesticide contamination can cause sublethal responses of macroinvertebrate communities, e.g., short-term mobility loss (Stoughton et al., 2008) and dramatic increases in downstream drift (Beketov and Liess, 2008; Berghahn et al., 2012; Lauridsen and Friberg, 2005). In addition, pesticide pollution can influence macroinvertebrate populations through the alterations of survivorship, growth, and emergence, e.g., as reported for a numerically dominant mayfly in Japanese rivers (Hatakeyama et al., 1997).

Recent applications using biological traits of macroinvertebrates have revealed a mechanistic framework linking ecological

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responses of invertebrate communities to anthropogenic stressors or natural disturbances (Menezes et al., 2010). The Species at Risk pesticide ($SPEAR_{pesticides}$) index is a trait-based approach to evaluating responses of macroinvertebrate communities to pesticides that has been developed and successfully applied in Europe (Orlinskiy et al., 2015; Schäfer et al., 2007, 2012). The $SPEAR_{pesticides}$ index classifies each taxon as either "species at risk" or "species not at risk" based on four biological traits: (1) physiological sensitivity to organic compounds (2) generation time; (3) pesticide exposure potential; and (4) migration ability (Liess and von der Ohe, 2005). The relationship between pesticide toxicity and abundance of sensitive macroinvertebrates, derived from the $SPEAR_{pesticides}$ index, also has been documented in studies from Australia and Siberia (Schäfer et al., 2012). The $SPEAR_{pesticides}$ index has been shown to respond to pesticide stressors, and to be less sensitive to many other stressors (e.g., Liess and von der Ohe, 2005; Rasmussen et al., 2011). However, additional efforts are needed to assess the general application of the $SPEAR_{pesticides}$ index through its development in other areas with different climate, biogeography, and/or agricultural practices.

It is a challenge to determine how to best characterize pesticide exposure in predicting ecologic effects on aquatic communities (Schäfer et al., 2013). Both peak and average pesticide levels are expected to be important in determining impacts on macroinvertebrate communities, but with differing temporal effects based on acute and/or chronic toxicity. Most studies consider either maximum exposure (e.g., Beketov et al., 2009; Rasmussen et al., 2012b; Schäfer et al., 2007) or average exposure (e.g., Schäfer et al., 2011), but not both. A comparison of results using average vs maximum values is more useful for evaluating the total toxicity of pesticide mixtures on macroinvertebrate communities, and for selecting the best exposure metrics in ecological risk assessments.

In this study, our objectives were to test the hypotheses that: (1) both average and maximum pesticide toxic unit (TU) values can have significant effects on macroinvertebrate communities; and (2) average and maximum pesticide TU values have different but complementary ways of explaining variations in macroinvertebrate communities. To test these hypotheses, we used reported pesticide-application data as input to a hydrological fate and transport model to simulate spatiotemporal dynamics of pesticides mixtures in streams on a daily time step. Then, using a regression model selection process, we explored the relationship between macroinvertebrate communities and pesticide dynamics in the Sacramento River watershed of California during 2002–2013.

2. Materials and methods

2.1. Study area

We conducted this study in the Sacramento River watershed of California (Fig. 1) because of the extensive agricultural land-use in the basin (Carter and Resh, 2005), and the relatively large amount of existing invertebrate bioassessment data in streams within the watershed. The Sacramento River is 644-km long and is the largest river in California, draining an area of 72,132 km^2 (Carter and Resh, 2005).

In the Sacramento River watershed, agricultural land-use covers 15.1% of the basin, and the limited urban areas (1.7%) are concentrated around the cities of Sacramento and the San Francisco Bay area (Carter and Resh, 2005). Almost all farming activities in the Sacramento River watershed happen in the Sacramento Valley rather than the upper watershed.

The Sacramento River watershed has a varied landscape and is located in a Mediterranean climate, with hot dry summers and wet cool winters (Bonada and Resh, 2013). The mountain tributaries in the upper watershed drain into the Sacramento main stem, which then flows through the Sacramento Valley and into the Sacramento-San Joaquin Delta. The watershed has an elevation ranging from 4000 m in the Sierra Nevada to sea level at it mouth (Carter and Resh, 2005). Temperature varies with altitude and the watershed has monthly averages ranging from 4.5 to 22.4 °C; mean annual precipitation ranges from 100 to 2000 mm across the Sacramento River watershed, with most rainfall occurring during November to March (Carter and Resh, 2005). Mediterranean-climate streams such as those in the Sacramento River watershed are characterized by highly seasonal streamflow (Carter and Resh, 2005). Low flow or drought occurs in dry summers, and high flow or flooding results from rainfall and snowmelt during winter and spring. In addition to providing drinking water, the Sacramento River watershed provides irrigation water for agriculture, and the natural flow regime is greatly altered by dam and reservoirs operations as well as downstream diversions (Carter and Resh, 2005).

2.2. Invertebrate samples

The benthic invertebrate bioassessment samples used in our analysis were collected under the California Surface Water Ambient Monitoring Program (SWAMP; http://www.waterboards.ca.gov/water_issues/programs/swamp/bioassessment/), and data from 2000 to 2013 were downloaded from the California Environmental Data Exchange Network (CEDEN) database (http://www.ceden.org/). Invertebrate samples were available for 376 sites in the Sacramento River watershed, and we selected 33 sites that had little or no urban influence but had extensive agricultural land-use. At each of the 33 sites, invertebrate samples were collected at least once between May and August during the period from 2002 to 2013. For two sampling locations, two samples were collected at the same site, and in these cases we randomly selected one sample to include in our analysis.

Sample collection followed standard operating procedures, but these were modified and calibrated several times during the sampling period. The SWAMP bioassessment monitoring procedures were modified over time, and three different methods (Margin-Center-Margin, Reach Wide Benthos, and California Stream Bioassessment Procedure Transects) were used at the various sites included in our study. All three methods collected benthic macroinvertebrate at three locations along the transect by placing the D-shaped net on the substrate and disturbing an area as wide as the net and 1 ft upstream. At most sites, only one method was used, but at two sites, two or three different sampling methods were used on the same dates, and in these cases we combined all samples for data analysis. All macroinvertebrates in each sample were identified, usually to genus or family level.

2.3. SWAT model and input data

We selected the Soil and Water Assessment Tool (SWAT) as the watershed model we used to predict daily streamflow, sediment transport, and pesticide fate and transport (Arnold et al., 1998). In SWAT, hydrologic response units (HRUs) are the basic calculation elements within sub-basins in the watershed system, representing the heterogeneity of the biogeochemical properties and processes. The HRU is a basic computational unit assumed to be homogeneous in hydrologic response to land cover, weather, and other environmental changes. We used ArcSWAT for initial parameterization of the model. In our model, daily amounts of reported pesticide applications were distributed into each HRU. Irrigation for each of the HRUs was simulated during the growing season based on plant demand. The SWAT model has previously been validated in the Sacramento watershed, where its application for insecticide fate