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Climate-change influences on the response of macroinvertebrate communities to pesticide contamination in the Sacramento River, California watershed

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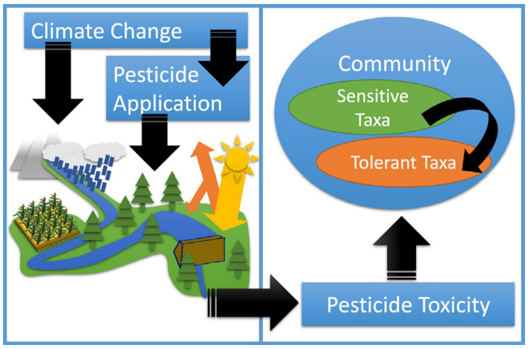
HIGHLIGHTS

- There will likely be increased pesticide application with increasing temperature.
- Increased ecological impacts of pesticides were predicted in most of the watershed.
- More increases in impacts were predicted in areas with less intensive agriculture.

GRAPHICAL ABSTRACT



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ABSTRACT

Limited studies have addressed how future climate-change scenarios may alter the effects of pesticides on biotic assemblages or the effects of exposures to repeated pulses of pesticide mixtures. We used reported pesticide-use data as input to a hydrological fate and transport model (Soil and Water Assessment Tool) under multiple climate-change scenarios to simulate spatiotemporal dynamics of pesticides mixtures in streams on a daily time-step in the Sacramento River watershed of California. We predicted that there will be increased pesticide application with warming across the watershed, especially in upstream areas. Using a statistical model describing the relationship between macroinvertebrate communities and pesticide dynamics, we found that compared to the baseline period of 1970–1999: (1) most climate-change scenarios predicted increased rainfall and warming across the watershed during 2070–2099; and (2) increasing pesticide contamination and increased impact on macroinvertebrates will likely occur in most areas of the watershed by 2070–2099; and (3) lower increases in effects of pesticides on macroinvertebrates were predicted for the downstream areas with intensive agriculture compared to some upstream areas with less-intensive agriculture. Future efforts on practical adaptation and mitigation strategies can be improved by awareness of altered threats of pesticide mixtures under future climate-change conditions.

1. Introduction

Pesticide pollution is one of the major concerns in river ecosystems worldwide (Ippolito et al., 2015; Malaj et al., 2014). Acute and chronic

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effects of pesticides have been reported to affect macroinvertebrates, and both are considered to be important (Kuzmanović et al., 2016). For example, pesticide contamination can cause acute responses in macroinvertebrate communities (Neumann and Dudgeon, 2002), e.g., short-term motility 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). In riverine environments, toxicant effects of pesticides on macroinvertebrate community dynamics can be associated with reduced biodiversity (Beketov et al., 2013; Thiere and Schulz, 2004) and altered ecosystem functions, e.g., leaf litter decomposition (Rasmussen et al., 2012; Rasmussen et al., 2013).

The global climate is projected to warm, leading to increases in frequency and severity of extreme weather in the future (IPCC, 2013). Climate change can directly influence pesticide contamination of aquatic ecosystems, e.g., effects of warming on degradation of pesticide residuals (Kookana et al., 2010) and pesticide transport by altered patterns of precipitation (Noyes et al., 2009; Steffens et al., 2013; Steffens et al., 2014). In addition, climate change is projected to result in increased pesticide applications (Delcour et al., 2015) as a result of higher temperature leading to more pressure to control increased number of pests. However, limited quantitative predictions have been made regarding alteration of pesticide runoff into lotic ecosystems under future climate change, and the subsequent changes in the impacts on biodiversity and community structure of macroinvertebrates. For example, precipitation was predicted to have higher influence than warming on pesticide runoff in the San Joaquin Valley watershed of California (Ficklin et al., 2010). A strong increase in insecticide application and risk of insecticide exposure was predicted for freshwater communities under future climate change in Europe (Kattwinkel et al., 2011).

A mechanistic understanding of the combined and interactive effects of climate change and other anthropogenic threats (e.g., enhanced loading of nutrients and sediments to river ecosystems from agriculture areas) is important to enable efficient ecosystem management. When relationships among abiotic/biotic variables were characterized by complex mechanisms, modeling helped understand and predict the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish (Mantyka-Pringle et al., 2014). In addition, this modeling process identified the restoration of riparian habitats as an important mitigation management (Mantyka-Pringle et al., 2014). Various ecological mechanisms and species trait-based frameworks can be considered for effectively predicting the joint effects of global climate change and pesticide toxicants on individuals, populations, and communities (Moe et al., 2013). Under scenarios of both climate change and pesticide application, it is necessary to take spatiotemporal information (e.g., across watersheds and over periods) into account to predict how impacts of pesticide contamination are likely to change in the future. This can also enable the planning of adaptation and mitigation strategies for basins with an increased risk in the future (Kattwinkel et al., 2011).

The purpose of this study is to examine how future climate change can influence input of pesticides into, and subsequent impacts on, river ecosystems. To do this, (1) we considered multiple, future climate-change and pesticide-application scenarios for warming in California, and predicted future pesticide toxicity and the consequent responses of macroinvertebrate communities; (2) we then simulated spatiotemporal dynamics of pesticide mixtures in streams on a daily time-step in the Sacramento River watershed of California during 1970–1999 and 2070–2099 using reported pesticide use data as input to a hydrological fate and transport model (Soil and Water Assessment Tool); and (3) we developed a framework that described the relationship between macroinvertebrate communities and pesticide dynamics, and tested the hypothesis that future climate-change will directly (through watershed-based processes of pesticide transport) and indirectly (through adaptations in pesticide application amounts) change pesticide toxicity-levels in rivers and alter responses of macroinvertebrate communities.

2. Materials and methods

We predicted pesticide impacts on macroinvertebrates in the Sacramento River watershed of California (Fig.1; Section 2.1) by examining how spatial and/or temporal variations of land-use and weather can influence pesticide contamination. In order to predict future pesticide impacts, we first used the Soil and Water Assessment Tool (SWAT; Section 2.2) to determine pesticide runoff under future climate change predictions (IPCC, 2013; Section 2.3) and future pesticide application amounts (Section 2.4) for the period 2070–2099 compared with that the baseline period of 1970–1999. Then a model describing the relationship between macroinvertebrate and pesticide toxicity (Section 2.5) was used to estimate the risk to stream invertebrate communities during the two periods. We simulated dynamics of pesticide mixtures and the impacts on macroinvertebrate based on each climate prediction. Under each climate prediction, future pesticide applications were estimated based on future temperatures.

2.1. Study area

This watershed has extensive agricultural land-use (15.1%) and limited urban areas (1.7%), and almost all farming activities in the watershed occur in the Sacramento Valley. Little or no agriculture occurs along the mountain tributaries in the upper watershed. The watershed is in a Mediterranean-climate region, with hot, dry summers and wet, cool winters (Bonada and Resh, 2013). The watershed has monthly temperature averages ranging from 4.5 to 22.4 °C, and mean annual precipitation ranges from 100 to 2000 mm (Carter and Resh, 2005).

2.2. SWAT model

We selected the Soil and Water Assessment Tool (SWAT) as the watershed model to predict daily, pesticide fate and transport (Arnold et al., 1998). The SWAT model uses hydrologic response units (HRUs) as the basic calculation-elements within sub-basins in a watershed system, and HRUs represent the heterogeneity of biogeochemical and hydrological properties and processes within each sub-basin. The pesticide module in the SWAT model simulates pesticide transport in dissolved and particulate phases through surface and subsurface hydrologic pathways (Neitsch et al., 2002). The fate and transport of pesticides are determined by their solubility, degradation half-life, and partitioning coefficients in the SWAT model (Neitsch et al., 2002). The SWAT model has previously been validated in the Sacramento watershed, where its application for insecticide fate and transport was successfully demonstrated (Ficklin et al., 2013). To build the SWAT model, we used soil-type data from the Soil Survey Geographic (SSURGO) database (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627), land-use data from the 2011 National Land Cover Database (http://www.mrlc.gov/nlcd2011.php), and reservoir operations from the California Data Exchange Center (CDEC) (http://cdec.water.ca.gov/). Pesticide fate and transport parameter values used as input to the SWAT model are shown in Table A1. With the exception of temperature and rainfall, which came from downscaled data under climate change scenarios (Section 2.3), weather parameters (wind, relative humidity, and solar radiation) for both the baseline and future periods were produced by the weather generator of the SWAT model based on the period of 1980–2010 (the available period that most closely matches our baseline period).

We used parameter values from our previous research calibrating the SWAT model for the Sacramento watershed (Chiu et al., 2016). In the calibration (Fig. A1), the NSE (Nash-Sutcliffe Model Efficiency

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