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Modeling spray drift and runoff-related inputs of pesticides to receiving water☆

Xuyang Zhang*, Yuzhou Luo, Kean S. Goh

California Department of Pesticide Regulation, Sacramento, CA, 95814, United States

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ABSTRACT

Pesticides move to surface water via various pathways including surface runoff, spray drift and subsurface flow. Little is known about the relative contributions of surface runoff and spray drift in agricultural watersheds. This study develops a modeling framework to address the contribution of spray drift to the total loadings of pesticides in receiving water bodies. The modeling framework consists of a GIS module for identifying drift potential, the AgDRIFT model for simulating spray drift, and the Soil and Water Assessment Tool (SWAT) for simulating various hydrological and landscape processes including surface runoff and transport of pesticides. The modeling framework was applied on the Orestimba Creek Watershed, California. Monitoring data collected from daily samples were used for model evaluation. Pesticide mass deposition on the Orestimba Creek ranged from 0.08 to 6.09% of applied mass. Monitoring data suggests that surface runoff was the major pathway for pesticide entering water bodies, accounting for 76% of the annual loading; the rest 24% from spray drift. The results from the modeling framework showed 81 and 19%, respectively, for runoff and spray drift. Spray drift contributed over half of the mass loading during summer months. The slightly lower spray drift contribution as predicted by the modeling framework was mainly due to SWAT's under-prediction of pesticide mass loading during summer and over-prediction of the loading during winter. Although model simulations were associated with various sources of uncertainties, the overall performance of the modeling framework was satisfactory as evaluated by multiple statistics: for simulation of daily flow, the Nash-Sutcliffe Efficiency Coefficient (NSE) ranged from 0.61 to 0.74 and the percent bias (PBIAS) $< 28\%$; for daily pesticide loading, NSE $= 0.18$ and PBIAS $= -1.6\%$. This modeling framework will be useful for assessing the relative exposure from pesticides related to spray drift and runoff in receiving waters and the design of management practices for mitigating pesticide exposure within a watershed.

1. Introduction

Pesticides have been widely detected worldwide in the surface water and have been determined as one of the major pollutants attributed to degradation of the aquatic ecosystems (Stehle and Schulz, 2015). In agricultural areas, the major pathways for pesticides to move from treated fields to the surface waters include surface and subsurface runoff, spray drift, dust and vapor transport. Surface runoff has been recognized as the most prevalent pathway (Reichenberger et al., 2007; Schulz and Matthies, 2007). However, many studies have suggested that spray drift could also be significant (Cryer et al., 2001; Raupach et al., 2001b). Wauchope et al. (2004) estimated that 40–55% of the amount of pesticides applied could move offsite via spray drift. Such values were confirmed by other studies with values ranging from 20 to 50% of the applied dose (Maybank et al., 1978; Ravier et al., 2005).

Understanding the pathways of pesticide transport is essential to the mitigation of the negative impacts of pesticides on aquatic ecosystems (Reichenberger et al., 2007). Resources should be allocated to the right type of management practices targeting different pathways of pesticide transport. For example, in areas where spray drift is significant, windbreaks and buffers could be installed to prevent spray drift for pesticide applications when wind is blowing toward surface waters. In contrast, if surface runoff is the major pathway, a different set of management practices aiming to reduce tailwater runoff such as sediment pond, recycling tailwater, and vegetated ditches could be implemented.

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* Corresponding author.
E-mail address: xuyang.zhang@cdpr.ca.gov (X. Zhang).

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Studies dedicated to the understanding of pesticide transport pathways and their relative significance are very limited. Schulz (2001) compared spray drift and runoff-related inputs of azinphose-methyl (AZP) (organic carbon normalized soil adsorption coefficient (Koc) = 1112) and endosulfan (END) (Koc = 11500) from fruit orchards into the Lourens River, South Africa. Water samples were collected at sites located at tributary and downstream receiving water. They compared concentration and mass loadings of AZP and END from runoff and spray drift. Both concentration and loadings were higher in runoff samples than in spray drift samples taken at the receiving water site. In terms of loadings, values following runoff were higher than following spray drift by factors of 41–860 for AZP. For END, the factors were between 14 and 2100. Assuming an average year with 12 spray drift, 1.7 large runoff events, and 3.4 small runoff events, they calculated that the load contribution from spray drift is 0.7 and 0.3% for AZP and END, respectively, with the largest contribution from surface runoff.

Another study compared the relative contribution of waterborne (mainly runoff) and airborne (spray drift, vapor, and dust) pathways for END in cotton growing regions in Nanoi River catchment, Australia (Raupach et al., 2001a, 2001b). Their results showed that END concentration from runoff events ranged from 0.6 to 0.23 ppb, spray drift from 0.02 to 0.09 ppb and vapor from 0.01 to 0.05 ppb. Assuming an average year with 26 spray drift, and 11 runoff events, the load contribution from spray drift for END was calculated as 9.9–59%. They concluded that runoff was the dominant pathway when it occurs; however, runoff did not occur frequently, and most of the time, the END detections were due to airborne transport (spray drift and vapor). They also found that dust transport was not significant.

Besides the differences in concentration and loadings, runoff and spray drift events also showed different toxicity effects on aquatic organisms. Dabrowski et al. (2005) conducted microcosm experiments to compare the toxicity of cypermethrin to mayfly from spray drift and runoff events. They found that spray-drift related inputs result in increased dissolved phase pesticide levels, which is readily bioavailable. On contrast, runoff-related inputs result in both dissolved and adsorbed phase as well as increased velocity and turbidity. The adsorption to suspended sediment may reduce the bioavailability of the chemical, while increased velocity may enhance toxicity. They concluded that for cypermethrin, a hydrophobic pesticide, spray drift inputs were more toxic compared to those related to runoff. The relative toxicity of spray-drift vs. runoff inputs depends on the chemical and pesticides with high solubility may show a higher significance of runoff regarding its contribution to aquatic toxicity.

In the above-mentioned studies, the concentration of pesticides resulting from runoff is much higher than those from spray drift or vapor transport. For END (a highly sorbed pesticide), The factor ranged from 2 to 42 (Schulz, 2001) and 2.6–12 (Raupach et al., 2001a). In terms of mass loading, the factor may even be higher (14–2100, Schulz, 2001). The relative contribution of the spray drift and runoff varies significantly depending on the study area and chemical.

Models have been increasingly used to simulate fate and transport of pesticides within a watershed. Most of the watershed models focus on the pathways of runoff (surface and subsurface) and leaching. Spray drift is largely ignored or over-simplified. Mottes et al. (2014) reviewed 16 watershed and field models for pesticide transfer. They found that for most of the models, drifted pesticides may be represented as leaving the system (pure loss of mass) or simply not considered. Only two of the 16 models simulate spray drift as a function of distance from the field. Mottes et al. (2014) highlighted the importance of spray drift as one of the major processes and they recommend that future development of catchment models should consider the integration of landscape drift models.

A couple of studies have been devoted to the modeling of the relative contribution of runoff and spray drift within watersheds. Dabrowski and Balderacchi (2013) developed an indicator to assess the relative mobility and risk of pesticides in the Lourens River catchment, South Africa. Their indicators were able to provide relative exposure and risk rating among pesticides but did not represent absolute exposure. In addition, their method does not consider routing of pesticides within watershed or movement of pesticides attached to sediment.

Cryer et al. (2001) developed a modeling system incorporating the AgDRIFT®, the Pesticide Root Zone Model version 3 (PRZM3) and the Hydrological Simulation Program-FORTRAN (HSPF) models for simulating spray drift and runoff of chlorpyrifos in the Orestimba Creek Watershed of California, USA. The paper highlighted the importance of identifying the relative contribution of different transport processes for pesticide movement such as spray drift and runoff. Daily runoff from agricultural fields was simulated using the PRZM3 and then downscaled to a sub-daily timescale for input to the HSPF model, which simulated instream hydrology. The results on flow and chlorpyrifos loadings were not calibrated. The model over-estimated chlorpyrifos loading and spray drift contribution. According to the paper, "simulated peaks not seen experimentally are probably due to the resolution of the spray drift event since spray drift is the largest predicted contributor to Orestimba Creek loadings". . The hour at which a pesticide application was unknown and the wind direct/speed data was at daily resolution. Additional uncertainties were introduced by using the PRZM3 for simulating pesticide runoff as generated by over-irrigation. The irrigation routines in PRZM3 do not allow runoff resulting from over-irrigation. As a result, a modified RPZM3 algorithm was used for generating tail-water runoff. Yet this algorithm was not validated.

The above mentioned studies represented useful initial steps towards modeling the pesticide inputs via spray drift and runoff in a watershed. The objective of this study is to extend the efforts of simulating watershed behavior by developing a modeling system for evaluating the significance of pesticide spray drift and runoff within watersheds.

2. Methods

2.1. The modeling framework

The modeling framework presented here is an integrated system containing models that simulate fate and transport of pesticides within agricultural watersheds. The core components of the modeling framework include a GIS procedure for identifying agricultural fields with drift potential, the AgDRIFT® model (Teske et al., 2002), and the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) (Fig. 1). The three components are interconnected in the following manner: (1) the GIS procedure identified target fields and spray events with potential to drift pesticides to the receiving water, using the location of the applied field, their distance to the receiving water, and the wind directions during the day of application; (2) the outputs of the GIS procedure serve as the starting point for the AgDRIFT modeling. For each drift event, AgDRIFT model predicts the fraction of mass that moves offsite via spray drift according to pesticide application method and downwind distance from the applied field; (3) finally, the amount of pesticides that deposit on the receiving water during each drift events were added to the corresponding SWAT modeling units as point source inputs. This fraction of pesticides together with pesticide runoff from treated fields will be routed throughout the