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Distinct influence of filter strips on acute and chronic pesticide aquatic environmental exposure assessments across U.S. EPA scenarios

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HIGHLIGHTS

- ▶ A pesticide exposure assessment framework can inform targeted filter strip design.
- ▶ Pesticide application timing is an important input factor in exposure assessments.
- ▶ Pesticide mass reduction is not equivalent to an exposure concentration reduction.
- ▶ Acute and chronic exposure concentration buffer reductions are not equivalent.
- ▶ Generic filter strip design consistent across EPA scenarios should be avoided.

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ABSTRACT

Vegetative filter strips (VFS) are proposed for protection of receiving water bodies and aquatic organisms from pesticides in runoff, but there is debate regarding the efficiency and filter size requirements. This debate is largely due to the belief that no quantitative methodology exists for predicting runoff buffer efficiency when conducting acute and/or chronic environmental exposure assessments. Previous research has proposed a modeling approach that links the U.S. Environmental Protection Agency's (EPA's) PRZM/EXAMS with a well-tested process-based model for VFS (VFSMOD). In this research, we apply the modeling framework to determine (1) the most important input factors for quantifying mass reductions of pesticides by VFS in aquatic exposure assessments relative to three distinct U.S. EPA scenarios encompassing a wide range of conditions; (2) the expected range in percent reductions in acute and chronic estimated environmental concentrations (EECs); and (3) the differential influence of VFS when conducting acute versus chronic exposure assessments. This research utilized three, 30-yr U.S. EPA scenarios: Illinois corn, California tomato, and Oregon wheat. A global sensitivity analysis (GSA) method identified the most important input factors based on discrete uniform probability distributions for five input factors: VFS length (VL), organic-carbon sorption coefficient (K_{oc}), half-lives in both water and soil phases, and application timing. For percent reductions in acute and chronic EECs, VL and application timing were consistently the most important input factors independent of EPA scenario. The potential ranges in acute and chronic EECs varied as a function of EPA scenario and application timing. Reductions in acute EECs were typically less than percent reductions in chronic EECs because acute exposure was driven primarily by large individual rainfall and runon events. Importantly, generic specification of VFS design characteristics equal across scenarios should be avoided. The revised pesticide assessment modeling framework offers the ability to elucidate the complex and non-linear relationships that can inform targeted VFS design specifications.

1. Introduction

Vegetative filter strips (VFSs) reduce sediment and pesticide movement to receiving water bodies through infiltration and reduction of runoff flow volumes, by contact between the sediment and pesticide with vegetation and soil in the VFS, and by increasing hydraulic roughness to reduce the flow velocity and allow sediment-bound pesticide to settle out of the runoff (Muñoz-Carpena et al., 1999, 2010; Sabbagh et al., 2009; Fox et al., 2010). VFS pesticide trapping efficiency depends on their spatially and temporally dynamic hydrological and sedimentological conditions that result

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from unique combinations of climate, soil, vegetation and land uses. Because of this, generic and simple regression equations that attempt to relate reduction efficiency with VFS length, slope, and/or physical characteristics are limited in applicability (Fox and Sabbagh, 2009). Two VFS with equivalent lengths, slopes, and vegetation may provide different sediment and pesticide trapping efficiencies, especially when comparing the responses under diffuse versus concentrated flow (Fox et al., 2010). This was demonstrated explicitly by Sabbagh et al. (2010) (additional details provided in the Supplementary information, see Fig. S-1), and is supported by extensive field data on pesticide reduction by VFS (see Poletika et al., 2009 and Sabbagh et al., 2009 for a summary of several field studies and Reichenberger et al., 2007 for a review on pesticide trapping efficiency).

VFS are currently proposed for protection of threatened and endangered biological organisms from pesticide in runoff (National Marine Fisheries Service (NMFS) Biological Opinion (BiOp) issued November 18, 2008), but there is debate regarding the efficiency and filter size requirements. For example, in their response letter to the 2008 NMFS BiOp, EPA (2010) indicated that to date no quantitative methodology existed for predicting runoff buffer efficiency. The debate is created by the common intent to relate VFS efficiency to simple characteristics like their size or slope.

The complex VFS time-variant behavior suggests the need for simulation models capable of accounting for hydrologic and sedimentological variability. Numerical models have been available for predicting runoff and sediment reductions by VFS such as the Vegetative Filter Strip Modeling System (VFSMOD), developed and evaluated by Muñoz-Carpena et al. (1999), Muñoz-Carpena and Parsons (2004), and tested by others (e.g., Abu-Zreig, 2001). VFSMOD is a finite-element, field-scale, storm-based model that routes an incoming surface flow hydrograph and sedigraph from an adjacent source area through a VFS and simulates the infiltration in the VFS using the Green-Ampt equation, sediment trapping based on GRASSF, and the resulting outflow. Sabbagh et al. (2009) proposed an empirical pesticide trapping function that was integrated with VFSMOD that considers sorption, pesticide reduction by infiltration of the dissolved phase, and sedimentation of the sorbed pesticide. The empirical function also depends on the percent clay content of the incoming sediment into the VFS and a phase distribution factor which represents the ratio between the mass of pesticide in the dissolved phase and the mass of pesticide sorbed to sediment. Degradation processes during runoff transport were not considered in the empirical component because of the small residence time during typical runoff events (min to h). Sabbagh et al. (2009) and Poletika et al. (2009) tested and evaluated the VFSMOD simulation tool linked with the pesticide trapping component. Muñoz-Carpena et al. (2010) and Fox et al. (2010) investigated the importance of various input factors on predicted sediment and pesticide reductions using this linked model.

The EPA uses computer simulation models (PRZM/EXAMS) to evaluate pesticide estimated environmental concentrations (EECs) in surface water. The simulated exposure concentrations are then compared to toxicological endpoints for assessing potential risks to aquatic organisms. The simulation models are typically applied to benchmark scenarios for various crops (Lin et al., 2007; Lin, 2009). These conservative scenarios establish specific field, soil, and receiving water body (static pond) characteristics (additional details provided in the Supplementary information, see Fig. S-2), but do consider variations in weather and management practices through 30-yr simulations (1961–1990) that are conducted using daily weather data and maximum use rates and patterns. The current EPA PRZM/EXAMS assessment approach models pesticide transport from a 10 ha circular field flowing into a 1 ha, 2-m deep circular pond located in the center of the field. The volume of water and mass of sediment in the pond is assumed constant by EXAMS. Risk is then quantified based on the upper 90th-percentile annual peak (acute risk) or the 60-d mean concentrations (chronic risk). Sabbagh et al. (2010) proposed a revised PRZM, VFSMOD, and EXAMS modeling framework that considers the presence of a VFS. Prior to this revised modeling framework, specification of the required VFS characteristics for reducing pesticide risk was largely subjective. The revised framework was applied to a single EPA scenario for four hypothetical pesticides. However, the importance of soil, hydrologic, pesticide and land use factors and their interactions need to be elucidated to advance their application in environmental exposure assessments for pesticides.

Therefore, this research utilized the previously revised modeling framework (PRZM, VFSMOD, and EXAMS) to address three objectives: (1) to determine the most important input factors for quantifying mass reductions of pesticides by VFS in aquatic exposure assessments relative to EPA scenario, and in particular assess the relative importance of pesticide application timing among other variable factors; (2) to quantify the range in percent reductions in acute and chronic EECs for three prescribed EPA scenarios representing a wide range of conditions; and (3) to determine differences in the influence of VFS on aquatic exposure assessments when conducting acute versus chronic exposure assessments. The effect of the local environment (soil, precipitation, and runoff) was captured in three scenarios analyzed in this research, while application timing was considered a characteristic of the pesticide.

2. Materials and methods

This research used the procedures developed by Sabbagh et al. (2010) for conducting aquatic exposure assessments with VFS based on PRZM, VFSMOD, and EXAMS simulation models. Three EPA scenarios were considered: Illinois corn, Oregon wheat, and California tomato. These scenarios were selected to provide a wide range of hydrological and sedimentological conditions (Table 1): Midwestern continental row-crop agriculture (Illinois Corn), wet maritime extensive agriculture (Oregon wheat), and dry Mediterranean irrigated horticulture (California tomato). It should be realized that results presented in this research are limited to the scenarios that the EPA developed for regulatory aquatic exposure assessments. In fact, the tools that are used in this research are applicable to other more realistic field and VFS conditions.

Soils data as specified by the EPA scenario were used explicitly in the aquatic exposure assessments. Climate data from meteorological stations specified in the EPA scenarios were used for conducting 30-yr simulations. Pesticide application was assumed to occur at pre-emergence (10 d prior to emergence date), in-season (30 d after the emergence date), or post-harvest (10 d after the harvest date). The effect of the environment (location, rainfall, soil) was captured in three scenarios analyzed in this research, while application timing was considered a characteristic of the pesticide. Field and VFS slopes were assumed uniform as prescribed in the U.S. EPA scenario. Vegetation type in the VFS was assumed to be bluegrass and default parameters for VFS vegetation characteristics were used. A source of uncertainty when simulating actual VFS performance is the condition of the VFS relative to upkeep and maintenance (regular mowing to maintain design height and vegetation uniformity, resetting by leveling and reseeding every 5-yr). This research assumed a well-maintained VFS with shallow overland flow across the entire VFS width rather than concentrated flow (Fox et al., 2010; Muñoz-Carpena et al., 2010).

Percent reduction in acute exposure was determined from the upper 90th-percentile of the annual peak concentrations during each year of the 30-yr simulations; percent reduction in chronic exposure was determined from the upper 90th-percentile of the