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Predicting pesticide removal efficacy of vegetated filter strips: A meta-regression analysis

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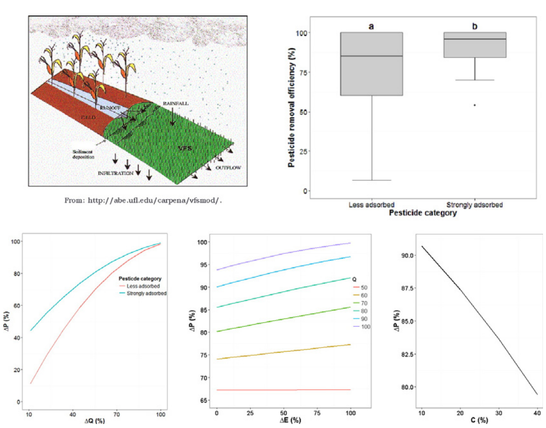
HIGHLIGHTS

- A meta-regression model for predicting VFS pesticide removal efficacy was built.
- The model was developed and tested by a set of statistical metrics.
- Pesticide adsorption property was significant in explaining VFS efficacy.
- Interactions among hydrological and pesticide adsorption processes were significant.

GRAPHICAL ABSTRACT



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ABSTRACT

Vegetated Filter Strips (VFS's) are widely used for alleviating agricultural pesticide loadings to surface water bodies. However, effective tools are lacking to quantify the performance of VFS's in reducing off-site pesticide transport. In this study, we applied meta-regression to develop a model for predicting VFS pesticide retention efficiency based on hydrologic responses of VFS's, incoming pollutant characteristics and the interaction within and between these two factor groups ($R^2 = 0.83$). In cross-validation analysis, our model ($Q^2 = 0.81$) outperformed the existing pesticide retention module of VFSMOD ($Q^2 = 0.72$) by explicitly accounting for interaction effect and the categorical effect of pesticide adsorption properties. Based on the 181 data points studied, infiltration had a leading, positive influence on pesticide retention, followed by sedimentation and interaction between the two. Interaction between infiltration and pesticide adsorption properties was also prominent, as the influence of infiltration was significantly lower for strongly adsorbed pesticides. In addition, the clay content of incoming sediment was negatively associated with pesticide retention. Our model is not only valuable in predicting VFS performance, but also provides a quantitative characterization of the interacting VFS processes, thereby facilitating a deeper understanding of the underlying mechanisms.

1. Introduction

The use of pesticides to manage pest infestation has been a common agricultural practice worldwide for decades. From 2005 to 2009, over

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6.5 billion kg of pesticides were applied annually on global agricultural lands (FAO, 2015). Off-site movement of pesticides into surface water bodies was observed, and in many cases, pesticides were detected at concentrations exceeding water-quality criteria, thus posing severe threats to aquatic organisms and human health (Reichenberger et al., 2007; Zhang and Goodhue, 2010). In California's Central Valley, for instance, pesticides residues are routinely detected in surface water at concentrations exceeding US EPA Aquatic Life Benchmarks (Starner and Zhang, 2011). Surface runoff is one of the primary pathways by which pesticides are transported. Edge-of-field losses of pesticides carried by surface runoff can be more than 10% of the amount of pesticides applied when severe rainfall occurs soon after pesticide application (Schulz, 2004). In order to ensure surface water quality, growers and regulators need to develop effective mitigation plans to reduce off-site transport of pesticides from croplands.

Vegetated filter strips (VFS's) are a best management practice for alleviating agricultural pesticide loadings to surface water bodies (FOCUS, 2007; USDA-NRCS, 2013; USDA-NRCS, 2015; USEPA, 2002). They are strip(s) of vegetation typically placed at the lower edge of a field to intercept surface runoff. As runoff passes through a VFS system, the erect vegetation stems pose an abrupt increase in hydraulic resistance to surface flows. Consequently, the runoff flow velocity is reduced which promotes infiltration and decreases the sediment transport capacity of flow. Sediment deposition occurs when the reduced transport capacity is less than the inflow sediment loads (Barfield et al., 1979). Pesticides transported in the dissolved phase are removed from surface runoff through infiltration into the soil matrix while sediment-bound pesticides settle out of the flowing water through sedimentation. Sorption to the soil surface, vegetation leaves, stems and residues are also important mechanisms for pesticide retention. Pesticides trapped within a VFS are subject to subsequent degradation, which is enhanced by higher microbial activities occurring in the presence of perennial vegetation (Krutz et al., 2005).

VFS's have been implemented across the world for decades, demonstrating their effectiveness in water quality improvement (Arora et al., 2010; Krutz et al., 2005; Norris, 1993). However, considerable variation in VFS pesticide removal efficacy was observed in experimental studies. In herbicide runoff studies, pesticide removal efficiency of VFS's of two drainage to buffer area ratio treatments of 15:1 and 30:1 ranged from 8 to 100% under natural rainfall (Arora et al., 1996) and from 47 to 83% in simulated runoff (Arora et al., 2003). For different filter lengths (the dimension parallel to runoff flow), inflow rates and herbicide concentration, herbicide reduction varied between 46 and 92% (Klöppel et al., 1997). VFS's built with varying vegetation species and lengths removed herbicides and insecticides by 32 to 96% (Schmitt et al., 1999). As VFS length increased, VFS atrazine removal efficiency increased from 44 to 100% (Patty et al., 1997) and from 31 to 80% (Mickelson et al., 2003), whereas short VFS's with lengths of 0.5 to 4 m (Tingle et al., 1998) and 3 m (Otto et al., 2012) were effective in removing herbicides by at least 80%. Trapping percentages of herbicides were above 90% for VFS's located in a karst watershed with high infiltration capacity (Barfield et al., 1998), and ranged from 40 to 85% for VFS's constructed on cracking vertisol soils (Popov et al., 2006). Flow concentration reduced VFS's removal efficacy of chlorpyrifos and atrazine from 85% to 21%, and from 62% to 12%, respectively (Poletika et al., 2009).

Such large variation in VFS performance is mainly attributed to the multiplicity of processes and factors involved in VFS pesticide removal (Lacas et al., 2005). The major processes that contribute to VFS pesticide removal have been identified as infiltration, deposition, sorption and degradation (Krutz et al., 2005; Zhang et al., 2010). The key factors that influence these processes can be divided into two categories: (1) properties of a VFS system, such as filter length, slope, soil texture, structure and antecedent moisture, and vegetation height, density and species; and (2) properties of pollutant inflow, such as rate and amount of rainfall and surface runoff, sediment particle size distribution, and the solubility, hydrophobicity and degradation rate of the pesticides.

Empirical equations have been developed to estimate VFS efficacy based on filter properties such as length and slope (Neitsch et al., 2005; Zhang et al., 2010). However, these equations can only include a limited number of factors and therefore often fail to adequately characterize VFS performance. This limitation has been partially addressed through an effort to incorporate VFS hydrological responses as explanatory variables in calculating the VFS pesticide retention efficiency (%), ΔP (Sabbagh et al., 2009):

$$\Delta P = 24.79 + 0.54(\Delta Q) + 0.52(\Delta E) - 2.42\ \ln\left(F_{ph} + 1\right) - 0.89(C)$$

where ΔQ, ΔE, F_{ph} and C represent runoff volume reduction (%), sediment mass reduction (%), pesticide phase distribution factor (fraction of dissolved over sediment-bound pesticide mass in inflow) and clay content of incoming sediment (%), respectively. Recently, this equation has been integrated into the Vegetated Filter Strips Modeling System (VFSMOD), a 1-D, field-scale model that routes the incoming runoff through a VFS and predicts its pollutant trapping efficiency (Muñoz-Carpena et al., 1999; Muñoz-Carpena and Parsons, 2014). The hydrologic responses of a VFS system (ΔQ and ΔE) are simulated by the hydrology and sediment filtration modules of VFSMOD and then fed into the pesticide retention equation for calculating the final ΔP.

The pesticide module of VFSMOD has shown its potential in predicting VFS pesticide removal efficacy (Poletika et al., 2009; Sabbagh et al., 2009; Winchell et al., 2011). However, it has been found that for strongly adsorbed pesticides, only F_{ph} and ΔE remained significant whereas for weakly to moderately adsorbed pesticides, ΔQ was the only significant predictor (Sabbagh et al., 2009). Nevertheless, the model development team proposed the single empirical equation as robust for all pesticides. One modification which may improve predictive accuracy is to replace the continuous variable (F_{ph}) with a categorical variable to specify the impact of pesticide adsorption properties, as observed in the literature (Arora et al., 2010; Krutz et al., 2005; Reichenberger et al., 2007). The original model also excludes interaction between explanatory variables, which has been widely recognized as critical in determining VFS performance. Arora et al. (2010) concluded from their literature review that the relationships between ΔQ and ΔE with ΔP were largely dependent on pesticide adsorption properties. For strongly adsorbed pesticides, ΔP has a relatively strong association with ΔE while for moderately to weakly adsorbed pesticides, ΔP is mainly dependent on ΔQ (Krutz et al., 2005). Infiltration also interacts with adsorption/sedimentation processes. Popov et al. (2006) observed that adsorption/sedimentation played a more important role in trapping herbicides at low flow depth. Therefore, by reducing flow depth, higher ΔQ is likely to lead to stronger associations between ΔE and ΔP.

Meta-analysis is a powerful statistical method of research synthesis for creating generalizations from the results of many separate experiments (Koricheva et al., 2013). The goal of this study is to develop a model to predict VFS pesticide removal efficacy using a meta-regression approach. Specifically, the objectives include: (1) extracting and aggregating data from the literature for model development and validation; (2) testing the significance of pesticide adsorption properties in explaining variation in VFS pesticide retention; and (3) exploring interaction among hydrologic processes occurring in VFS and incoming pollutant characteristics. A set of statistical metrics (adjusted R^2, Mallow's C_p, $AICc$, BIC, F statistic of general linear test and Q^2 of cross validation) were applied to ensure the robustness of the proposed regression model. This study is the first modeling effort which explicitly and quantitatively accounts for the impacts of (1) pesticide adsorption categories, and (2) interactions among VFS hydrologic processes and incoming pollutant properties on VFS pesticide removal efficacy. The developed model not only serves as a valuable tool for predicting VFS performance, but also contributes to a deeper understanding of the complex, interacting VFS processes and factors responsible for pesticide retention.