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Workshop Synthesis

Incorporating the benefits of vegetative filter strips into risk assessment and risk management of pesticides

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Abstract

The pesticide registration process in North America, including the USA and Canada, involves conducting a risk assessment based on relatively conservative modeling to predict pesticide concentrations in receiving waterbodies. The modeling framework does not consider some commonly adopted best management practices that can reduce the amount of pesticide that may reach a waterbody, such as vegetative filter strips (VFS). Currently, VFS are being used by growers as an effective way to reduce off-site movement of pesticides, and they are being required or recommended on pesticide labels as a mitigation measure. Given the regulatory need, a pair of multistakeholder workshops were held in Raleigh, North Carolina, to discuss how to incorporate VFS into pesticide risk assessment and risk management procedures within the North American regulatory framework. Because the risk assessment process depends heavily on modeling, one key question was how to quantitatively incorporate VFS into the existing modeling approach. Key outcomes from the workshops include the following: VFS have proven effective in reducing pesticide runoff to surface waterbodies when properly located, designed, implemented, and maintained; Vegetative Filter Strip Modeling System (VFSMOD), a science-based and widely validated mechanistic model, is suitable for further vetting as a quantitative simulation approach to pesticide mitigation with VFS in current regulatory settings; and VFSMOD parametrization rules need to be developed for the North American aquatic exposure assessment. *Integr Environ Assess Manag* 2024;20:454–464. © 2023 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Agricultural runoff; Ecological risk assessment; Pesticide mitigation; Risk management; Vegetative filter strip

BACKGROUND

Agricultural runoff is one of the primary mechanisms contributing to pesticide contamination of surface water, in particular by inducing peaks in concentrations (Rabiet et al., 2010). Vegetative filter strips (VFS) are a best management practice (BMP) recommended by the US Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) for reducing nonpoint source pollution (US Department of Agriculture, Natural Resources Conservation Service [USDA-NRCS], 2016b), and are commonly used by producers to mitigate nutrient runoff and soil erosion from production areas. Although the scientific evidence of VFS effectiveness for mitigating runoff and erosion is well established (Dillaha et al., 1989), a growing body of literature

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has demonstrated that VFS are also effective at mitigating pesticide runoff (Arora et al., 2010; Prosser et al., 2020; Reichenberger et al., 2007; Sabbagh et al., 2009) and therefore capable of reducing the amount and concentrations of pesticides that may reach surface waterbodies and/or nontarget terrestrial habitats. Pesticide removal is primarily the result of the vegetation's ability to slow surface runoff, thereby promoting sedimentation, infiltration, and sorption of pesticides (Chen et al., 2016). Despite these published studies of VFS effectiveness and the current use of VFS by growers as a mitigation measure, the contributions of VFS in pesticide mitigation are not currently considered in the standard pesticide exposure risk assessment approach used by the US Environmental Protection Agency (USEPA) and Health Canada's Pest Management Regulatory Agency (PMRA).

Workshops were held in 2018 (Raleigh, NC) and 2020 (virtual) by North Carolina State University's Center of Excellence for Regulatory Science in Agriculture (CERSA) to bring together scientists from academia, government, and industry along with conservation experts and producers to explore the state-of-the-knowledge with respect to VFS function, implementation, benefits, and modeling. In addition to exploring data on the use and management of VFS in conservation programs, information on the economic and agronomic realities of using VFS under different cropping practices was examined, along with ways to quantitatively incorporate VFS mitigation into the risk assessment process (CERSA, 2018).

PURPOSE AND OBJECTIVES

The overall objectives of the 2020 workshop were to identify how to incorporate VFS in risk assessment and risk management of pesticides in North America; improve cooperation and collaboration among stakeholders to leverage available data and information regarding the design, effectiveness, and implementation of VFS for various crops and regions; and support the development of strategies to increase producer engagement and adoption of VFS and other runoff mitigation measures to protect soil and water resources.

This article aims to summarize the state-of-the-knowledge with respect to VFS effectiveness, implementation, regulatory approaches, modeling, and obstacles to grower adoption. It also highlights the main outcomes from the workshop, the importance of harmonizing approaches to VFS evaluation in pesticide risk assessment in North America, and paths forward to promoting science-based consideration and broader use of VFS.

VEGETATIVE FILTER STRIPS AS A PESTICIDE MITIGATION MEASURE

There are several ways to reduce pesticide losses in agricultural runoff. Actions should aim first at controlling pest pressure by using cultural methods (e.g., crop rotation and selection of pest-resistant varieties) and modifying pesticide use (e.g., use rate and application method). Further reduction in pesticide runoff can be achieved by managing hydrologic processes. Runoff can be reduced by managing fields in a way that increases the infiltration rate of the pesticide into soil. This can be achieved through implementation of conservation and/or BMPs such as USDA-NRCS residue and tillage management, no till (USDA-NRCS, 2016c), residue and tillage management, reduced till (USDA-NRCS, 2016d), cover crop (USDA-NRCS, 2014), and contour farming (USDA-NRCS, 2017a). If these practices do not sufficiently reduce the volume of runoff leaving a field, runoff can be further reduced by implementation of peripheral vegetation buffer practices such as filter strip (VFS; USDA-NRCS, 2016b), field border (USDA-NRCS, 2016a), and riparian forest buffer (USDA-NRCS, 2016e). For a given application rate, the loss of pesticides from fields and transport to surface waters depend on soil properties, field management, pesticide properties, and precipitation and/or irrigation characteristics and the subsequent runoff generated. It is always preferable to manage the field so that runoff is minimized. This is not always possible, however, due to factors such as cropping system limitations, equipment, and logistics, among other reasons. Thus, runoff mitigation with VFS is an important additional way of mitigating pesticide losses. It is key to find the right balance when deciding on runoff-limiting practices in the field and the acceptable size of a VFS.

The USDA-NRCS defines a filter strip as “a strip or area of herbaceous vegetation that removes contaminants from overland flow” (USDA-NRCS, 2016b). It is among the most rigorous buffer practices for the purposes of protecting surface waters because the guidelines specify design criteria depending on the purpose for implementing the practice. This definition is also well within the 2018 CERSA workshop-adopted definition of a VFS: a strip of vegetation that removes contaminants from overland flow located at the lower edge(s) of a field. Two important criteria for effective VFS performance are proper ratio of buffer area to contributing area and maintenance of sheet flow through the VFS. In addition, VFS should be established appropriate to local conditions (e.g., climate) with stiff-stemmed, high stem density, and permanent grassed vegetation that is tolerant of herbicides and able to withstand partial burial from sediment. Other crucial design criteria include the proper location of VFS in the watershed considering surface water pathways such as talwegs and avoiding hydraulic bypasses.

Previous studies have demonstrated VFS effectiveness in mitigating pesticide runoff but with considerable variation in pesticide removal efficacy (Chen et al., 2016; Reichenberger et al., 2007, 2019; Sabbagh et al., 2009). Chen et al. (2016) evaluated 16 experimental studies in their meta-analysis. They found that VFS pesticide mass reduction ranged from 6.7% to 100% for VFS widths (the dimension parallel with runoff flow) ranging from 0.3 to 20.1 m. The distribution of pesticide mass reduction was substantially negatively skewed, and VFS were able to achieve considerable pesticide reduction in many cases. Reichenberger et al. (2007) reported pesticide trapping efficiencies for individual events

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between 0% and 99% with long-term efficiencies greater than 50%. Prosser et al. (2020) reported a positive relationship between VFS width and VFS pesticide removal efficacy, whereas relatively great variability in VFS efficacy (10%–100%) was observed at VFS widths around or less than 10 m. This finding suggests that other variables, along with VFS width, are important factors in determining VFS efficacy (Prosser et al., 2020). Concentrated flow can reduce the performance of VFS. Fox et al. (2010) found a significant decrease in pesticide trapping of both atrazine and chlorpyrifos in concentrated flow (7% and 24%, respectively) versus sheet flow (70% and 78%, respectively) through 4.6-m VFS. Stehle et al. (2016) found that VFS installed close to water bodies tend to have lower pesticide retention efficacies due to concentrated runoff entries via erosion rills. Therefore, it is advisable to install VFS higher on the slopes and as close as possible to the source of runoff (Carluer et al., 2011). Sabbagh et al. (2009) noted that pesticide properties can have a significant impact on VFS effectiveness. For example, pesticides with relatively high organic carbon–water partition coefficient (K_{OC}) and relatively low solubility are associated mostly with the sediment in the runoff; pesticides with relatively low K_{OC} and relatively high solubility are associated mainly with the aqueous phase of the runoff. This information helps us better understand VFS effectiveness and allows the use of sediment to serve as a surrogate to represent the transport of sorbed pesticides and runoff to serve as a surrogate for dissolved pesticides.

The composition and condition of vegetation are important factors in determining VFS pesticide trapping efficiency. The USDA-NRCS conservation practice standard indicates that the plant species should be stiff stemmed with a high stem density near the ground surface and appropriate to local conditions (USDA-NRCS, 2016b). Studies have revealed that VFS with greater density of vegetation tend to have higher pesticide removal efficacy (Prosser et al., 2020; Wang et al., 2018), particularly for strongly sorbed pesticides (Muñoz-Carpena et al., 2010). The density of vegetation can be controlled through rates of seeding and regular mowing. Other factors affecting the density and its change over time are plant growth and morphology. Lambrechts et al. (2014) studied the effect of alternative creeping shoot (*Trifolium repens*) and tillering stiff (*Lolium perenne*) plant architectures on VFS trapping efficiency and found that *L. perenne* trapping efficiency increased by 15% between the second and fourth months after planting, whereas the trapping efficiency of *T. repens* decreased by 9% in the same period. This finding highlights the possible change of VFS trapping efficiency with time, due to modifications of plant characteristics with growth stage (Lambrechts et al., 2014).

Overall, critical factors that must be ensured to achieve an effective VFS include sheet flow into and through the VFS, proper area ratio of VFS to the contributing area, the location of VFS in a watershed, and VFS vegetation type and density. Width alone, without reference to the contributing area, soil property, hydrological and pesticide characteristics, location, or vegetation type and density, is not a good predictor of VFS effectiveness (Carluer et al., 2011; Chen et al., 2016; Fox et al., 2021; Prosser et al., 2020; Sabbagh et al., 2009).

COMPARISON OF NORTH AMERICAN REGULATORY APPROACHES REGARDING VFS

In the USA, the Office of Pesticide Programs (OPP) at the USEPA is responsible for pesticide registration and regulation under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA; USEPA, 2022b). For pesticides prone to transport via surface runoff, the OPP *Label review manual* (USEPA, 2021) suggests that labels include advisory language on the use of a VFS. In some cases, such as the pyrethroid registration review case (USEPA, 2020), VFS are considered mandatory as a condition of registration. The USEPA recognizes that a VFS can be an effective tool to reduce soil erosion and enhance infiltration, and therefore by extension, potentially reduce pesticide loading into aquatic systems when used and maintained properly. Therefore, the USEPA considers information on VFS efficacy as a line of evidence when considering potential mitigations for reducing pesticide exposure in aquatic ecosystems. Under FIFRA, in deciding whether to require a VFS, the USEPA considers the cost of constructing and maintaining a VFS and the likelihood of adoption by growers when evaluating potential mitigation measures. Additionally, VFS can also be a potential mitigation measure for providing protections to federally threatened and endangered species under the Endangered Species Act (ESA). Although ESA obligations cannot include a risk–benefit analysis, it is the intention to identify the mitigation that is less burdensome to users while still providing the necessary protections (USEPA, 2022a).

In Canada, the PMRA is responsible for pesticide regulation under the authority of the Pest Control Products Act (PCPA; Minister of Justice, 2002). General guidance to mitigate pesticide runoff from treated areas into aquatic habitats appears in the form of recommendations. For example, a VFS between the treated area and the edge of a waterbody is recommended on Canadian product labels with outdoor uses except for products registered for uses where exposure from runoff is not expected (e.g., insect baits and greenhouse use). The PMRA recognizes the potential for a VFS to help protect aquatic organisms in surface waterbodies from exposure to certain pesticides through runoff. For certain pesticides, commercial class product labels include the requirement for a mandatory VFS of at least 10 m width that must be constructed between the field edge and adjacent, downhill aquatic habitats to protect aquatic organisms from pesticides in runoff. Currently, the decision to require a VFS on a product label is made on a case-by-case basis and includes consideration of the physicochemical properties of the pesticide (i.e., sorption to soil, solubility, and persistence) and toxicity to aquatic organisms. According to the PCPA, all regulatory decisions must be science-based. As such, consideration of the cost associated with the construction and maintenance of a VFS, as

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well as the removal of land from production, does not factor into the PMRA decision-making process.

APPROACHES TO QUANTITATIVELY INCORPORATE VFS MITIGATION INTO RISK ASSESSMENT

The pesticide removal efficacy of VFS is site- and chemical-specific (Fox et al., 2021). These factors hindered the past adoption of quantitative VFS mitigation within pesticide environmental exposure assessment frameworks in North America. Simplified VFS mitigation approaches are available in other jurisdictions like the European Union (EU) Landscape Mitigation (LM) guidelines (Brown et al., 2017; FOCUS, 2007a, 2007b). The EU LM approach is based on fixed reduction factors for a VFS of a given width and depends on the chemical's K_{OC}. In the workshops, the participants largely felt that field data generated in the EU may not sufficiently represent North American conditions. Thus, a mechanistic (process-based) model would be more suitable to realistically quantify VFS mitigation efficiency under a comprehensive range of site or scenario-specific conditions. This led to the consideration of the Vegetative Filter Strip Modeling System (VFSMOD), a computer simulation model developed to study hydrology, sediment, and pollutant transport through VFS (Muñoz-Carpena, 2021).

The VFSMOD is a field scale, mechanistic, storm-based model designed to route dynamically the incoming runoff hydrograph and sedigraph from an adjacent field through a VFS, and to calculate the outflow, infiltration, and sediment trapping efficiency (Figure 1). The VFSMOD comprises four modules: (1) an overland flow module based on the kinematic wave equations, (2) an infiltration module based on the extended Green-Ampt infiltration method (GAMPT) for unsteady rainfall, (3) a sediment filtration module based on the University of Kentucky grass sediment deposition dynamic algorithm, and (4) a water quality and/or pollutant module capable of simulating pesticide trapping (Muñoz-Carpena & Parsons, 2020). In VFSMOD, vegetation is described based on density (average separation of stems [S_s]), roughness of the vegetation based on the shape of stems and leaves next to the soil surface (modified Manning's coefficient [n_m]), and maximum height of the stiff part of the vegetation before mowing (H). These characteristics dynamically control the surface flow velocity, water and dissolved pesticide infiltration time, as well as the transport capacity and deposition of sediment and sediment-sorbed pesticide on the VFS surface. Haan et al. (1994) compiled a list of plant species recommended for VFS and default data on their characteristics that serve as inputs for VFSMOD.

The use of VFSMOD as an appropriate, scientifically defensible simulation tool for VFS quantitative mitigation for risk assessment and management has been supported by numerous studies (see compilation in Muñoz-Carpena, 2021). For example, Winchell et al. (2011) evaluated four simulation models including VFSMOD regarding their ability to predict pesticide trapping for alachlor, pendimethalin, atrazine, and chlorpyrifos. They used uncalibrated versions of each model with best estimates of model parameters. Although all the models predicted reductions that were consistent with the

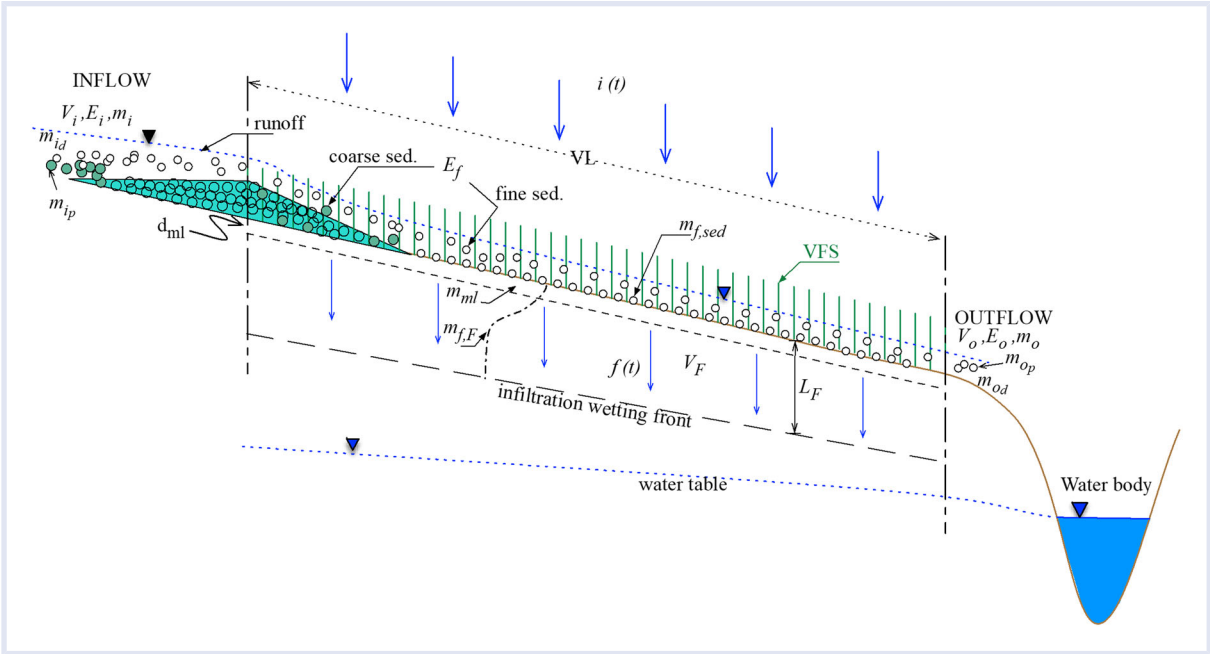


FIGURE 1 Conceptual pesticide mass balance in a vegetative filter strip (VFS) as simulated by the Vegetative Filter Strip Modeling System (VFSMOD). *m*, pesticide mass (g); *E*, sediment mass (g); *V*, runoff volume (m^3); V_F, infiltration volume (m^3); i, f, F, sed, ml, o, *d*, *p* (subscripts), inflow, filter-trapped, infiltrated in the soil, adsorbed onto the sediment, in the soil mixing layer, or outflow, dissolved or particulate (sediment-bound) pesticide fractions; *i(t)*, rainfall hyetograph for event (m/s); *f(t)*, infiltration rate for event (m/s); L_F, infiltration wetting front depth (m); *VL*, effective filter length (m); d_{ml}, mixing layer depth (m); coarse sediment, particle diameter >0.037 mm (bed load transport); fine sediment: particle diameter <0.037 mm (suspended load transport). Modified from Muñoz-Carpena et al. (2018a)

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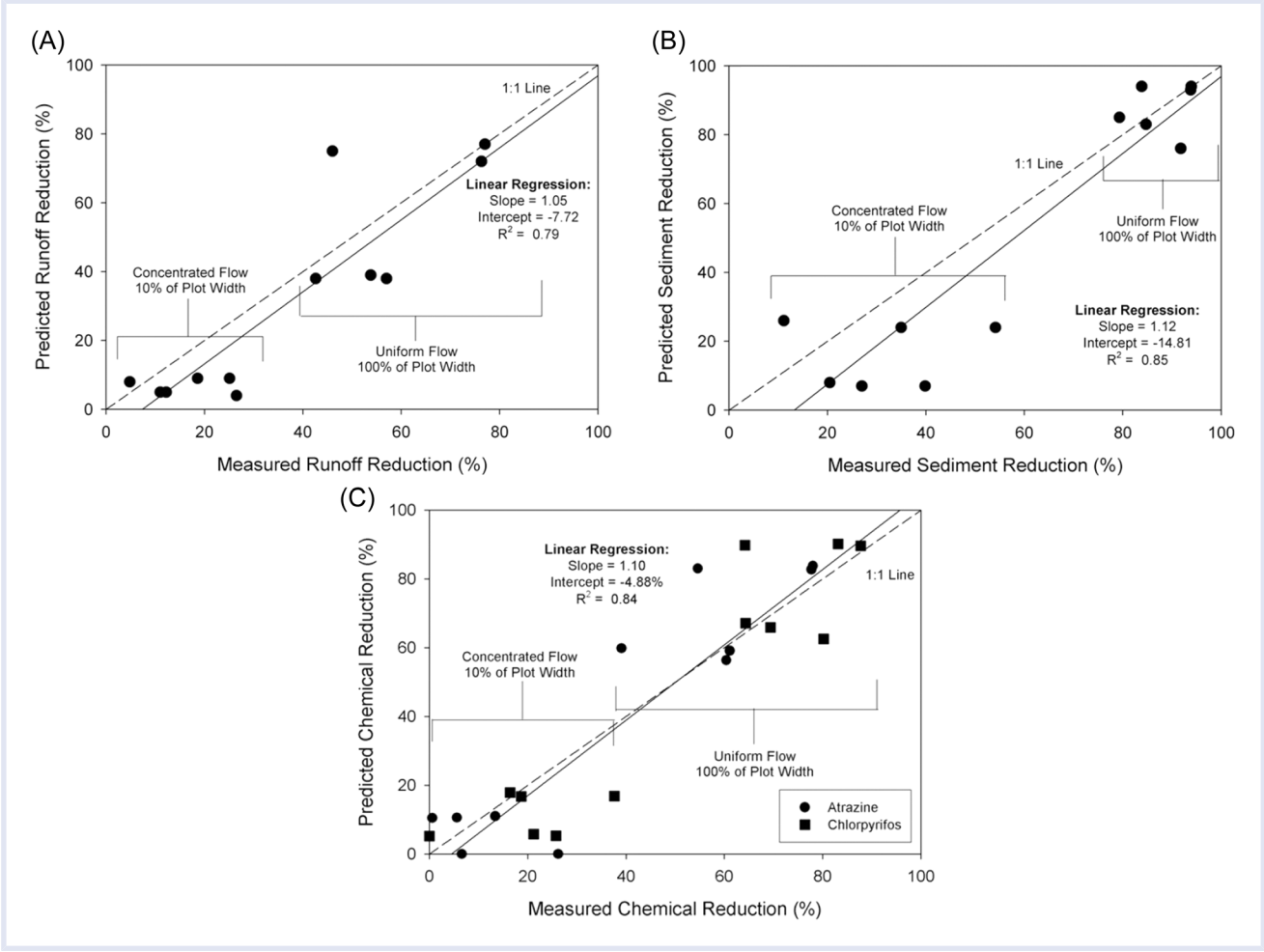


FIGURE 2 Linear regression between observed and Vegetative Filter Strip Modeling System (VFSMOD) predicted (A) runoff reduction, (B) sediment reduction, and (C) atrazine and chlorpyrifos reduction for 4.6 m vegetative filter strips (VFS) with uniform or concentrated flow. Modified from Poletika et al. (2009)

observed reductions, VFSMOD was closest in agreement with the observed data with a mean absolute error (absolute difference between model predictions and observations) of 9% for pesticide reduction prediction, whereas for other models it ranged between 16% and 31%. Poletika et al. (2009) was able to predict atrazine and chlorpyrifos removal efficiency of VFS under uniform and concentrated flow conditions based on uncalibrated VFSMOD. The R^2 values (coefficients of determination) were 0.79, 0.85, and 0.84 for the reduction in runoff, sediment, and pesticide (atrazine and chlorpyrifos), respectively (Figure 2). Recently, Arpino et al. (2023) compared observed acetochlor runoff reductions in side-inlet VFS with uncalibrated VFSMOD predictions. They concluded that VFSMOD captured the variability in VFS effectiveness based on several factors including source to buffer area ratios and recommended its use to design and evaluate these field practices. The advantage of VFSMOD over empirical approaches used to predict VFS pesticide trapping efficiency is the inclusion of a state-of-the-art description of VFS hydrology allowing realistic representation of complex sets of inputs similar to those found in natural runoff events in the field.

Recent developments in VFSMOD include improved approaches to quantify VFS pesticide trapping efficiency (Chen et al., 2016; Reichenberger et al., 2019; Sabbagh et al., 2009). In particular, Reichenberger et al. (2019) developed a new mechanistic mass-balance approach based on a large, single-event field dataset (244 calibration datapoints with a range of K_{OC} of 7.4–73 000 L/kg), which is a reasonable option due to its important advantage of not requiring calibration and its overall good predictive performance of VFS trapping efficiency (Nash–Sutcliffe efficiency [NSE] = 0.74). Other VFSMOD advances available in the latest model v. 4.5.2 (released February 2023) include dynamic calculation of the incoming sediment properties (median particle size and density) based on the event characteristics (Reichenberger et al., 2023) and capability of considering shallow water table conditions, which can affect VFS efficacy in reducing pesticide runoff (Fox et al., 2018; Lauvernet & Muñoz-Carpena, 2018; Muñoz-Carpena et al., 2018b). Another new option is the partial remobilization of pesticide residues in VFS, where dissolved pesticide in the pore water is added to the incoming pesticide mass for the next runoff event, whereas the sorbed fraction stays on the soil and contributes

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to the equilibrium distribution at the mixing layer (Muñoz-Carpena et al., 2015, 2018a; Ritter et al., 2023). These new processes have been validated using empirical datasets and result in more realistic and mechanistic estimation of pesticide trapping.

An area of concern that is frequently presented is whether the quantitative-based approaches can handle less than ideal VFS conditions. Muñoz-Carpena et al. (2019) studied systematically the mitigation prediction of acute and chronic aquatic exposure for a wide range of long-term USEPA scenarios. They found that the mechanistic mass-balance pesticide trapping approach is able to capture the observed variability in VFS trapping efficiency, including lower efficiency with larger events. Therefore, VFSMOD provides a realistic quantification of the VFS mitigation efficiency suitable under current and future climate change conditions with expected rainfall intensity increases in some areas. In addition to large rainfall-runoff events, concentrated flow can also reduce the pesticide removal efficiency of VFS. Previous studies have demonstrated that VFSMOD can predict pesticide trapping efficiency in cases when water flow begins to converge into concentrated flow paths (caused by vegetation aging or poor maintenance), rather than remaining as shallow sheet flow (Fox et al., 2010; Muñoz-Carpena et al., 2010; Poletika et al., 2009).

The establishment of VFSMOD as a state-of-the-art model for accurate prediction of VFS mitigation efficiency has led to its integration into the higher-tier pesticide regulatory tools in the EU, and it is under consideration for integration with the North American ones (Fox et al., 2021; Sabbagh et al., 2010). These activities have demonstrated that VFSMOD can be integrated into the exposure modeling frameworks used in North America. Examples of tools for coupling VFSMOD with regulatory models are the Surface Water Assessment eNabler (SWAN) tool (EC-ESDAC, 2022), using the EU FOCUS (FOrum for the Co-ordination of pesticide fate models and their USe) framework, and in North America, tools under development around the EPA Pesticide in Water Calculator (PWC) framework such as Canada's PMRA VFSPipe, California Department of Pesticide Regulation's (CDPR) Pesticide Registration Evaluation Model, and others. In the standard pesticide exposure modeling frameworks, the USEPA field model provides daily estimates of edge-of-the-field runoff, sediment, and pesticide loads. The field runoff enters a waterbody downslope (pond, stream, channel) where a second modeling component provides daily estimates of pesticide water concentrations. The representative Estimated Environmental Concentration (EEC; US terminology) or Predicted Environmental Concentrations in surface water (PEC_{sw}; EU terminology) is obtained from the calculated concentrations in the waterbody and compared with ecotoxicological thresholds for risk assessment purposes. Quantitative pesticide mitigation with VFS is achieved in these frameworks by coupling VFSMOD between the field and the aquatic model (Figure 3), where daily reductions in field runoff volume (ΔQ), sediment (ΔE), and pesticide (ΔP) are calculated by VFSMOD and applied before material enters the waterbody. More details about coupling VFSMOD with North American regulatory models can be found in Ritter et al. (2023). As a conservative assumption, mitigation of pesticide spray drift by VFS is not considered in the current modeling approach. The USEPA has developed representative field scenarios for a variety of crops across the major growing regions in the USA as inputs to the aquatic exposure model PWC. These scenarios can also provide site-specific characteristics (e.g., soil texture, slope, rainfall data) for use as VFSMOD inputs. Simulations can be performed to calculate the necessary VFS width to achieve a required exposure endpoint, or to calculate reductions for a set of standard buffer widths.

The Surface Water Protection Program (SWPP) at CDPR began model development for VFS mitigation of pesticides in 2017. Two major model components were considered: hydrological simulation (for runoff and sediment removal, ΔQ and ΔE, respectively) and pesticide simulation (pesticide removal, ΔP). The VFSMOD was adopted by SWPP for hydrological simulation, and in-house model developments were conducted for estimating pesticide removal through a VFS. As a part of the modeling efforts for conservation practices in agricultural areas of California, a semimechanistic method was first implemented with bifenthrin as a test agent (Luo, 2019). In a recent study, SWPP developed a mechanistic approach with physically based modeling on the runoff-soil exchange of

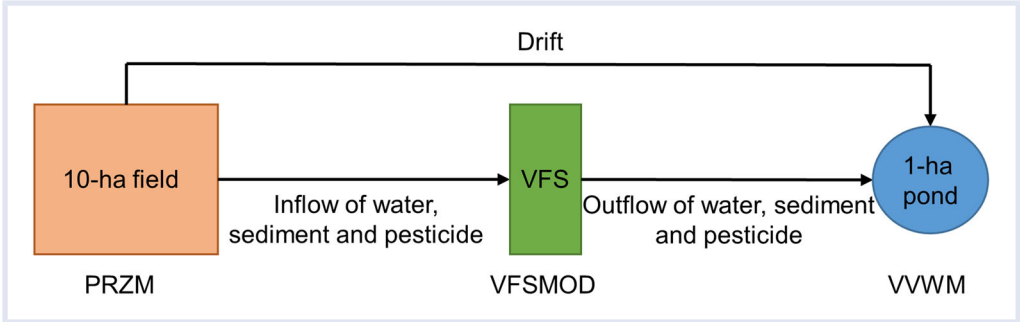


FIGURE 3 Conceptual model for integration of vegetative filter strips (VFS) into pesticide aquatic ecological risk assessment in North America (a 10-h treated agricultural field draining into a 1-ha pond). The regulatory model Pesticide in Water Calculator (PWC) consists of two models (Young, 2020): Pesticide Root Zone Model (PRZM) and Variable Volume Water Model (VVWM). The PRZM simulates pesticide fate and transport in the agricultural field and VVWM simulates subsequent transport to and fate in the receiving waterbody. VFSMOD, Vegetative Filter Strip Modeling System

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pesticide in a VFS (Luo, 2020). This approach allows simultaneous simulation of individual processes and incorporates the concept of lateral flow interacting with the mixing layer from PWC (Young, 2016; Young & Fry, 2019). For PWC scenarios in California, the results of model validation recommended a runoff interaction fraction of 0.4 (i.e., 40% runoff will interact with and extract pesticide from the soil mixing layer), which generated the best modeling performance (NSE = 0.89). The proposed approach extends the previous semimechanistic method to more general field conditions and does not prescribe a certain amount of pesticide mass transport between soil and the overlying runoff. As an alternative, the improved VFSMOD mechanistic mass-balance (Muñoz-Carpena et al., 2015; Reichenberger et al., 2019) and surface residue remobilization approach described earlier can provide similar benefits without the need for SWPP's calibrated (empirical) runoff interaction fraction that can vary across agro-ecological settings, but future research should be conducted to investigate this issue.

Regulatory status of VFSMOD in the EU

In the EU, VFSMOD has been integrated with the highest-tier EU Step 4 SWAN continuous simulation tool to aid in the EU FOCUS pesticide environmental assessment framework. A recent German Environmental Protection Agency (UBA) report on runoff mitigation practices concluded that among different practices, VFS should be included in regulatory frameworks and that these should be simulated mechanistically using VFSMOD (Klein et al., 2022). However, adoption of these and other advanced technologies by risk assessors and regulators remains a barrier at the global level (Topping et al., 2020). In response to these challenges, two workshops were convened in the EU in 2020 on the issue of quantitative mitigation of pesticides in surface runoff with VFS. A first industry-targeted workshop was attended by 80 industry representatives of 27 different entities, followed by a second EU regulators and agencies workshop attended by 50 representatives from seven EU Southern Region countries (Fox et al., 2021). These workshops aimed at shifting the paradigm from qualitative, empirical approaches (i.e., fixed reduction coefficients) to the adoption of process-based models for quantitative estimates of VFS mitigation effectiveness within EU FOCUS STEP 4 pesticide risk assessment regulatory framework. Consensus drawn during the workshops led to the EU Southern Member States Steering Committee (SMS SC) agreement on the use of the SWAN-VFSMOD package for the calculation of PEC_{sw} at EU SMS and zonal level for the authorization of plant protection products (EU SMS SC, 2021).

Recently, the "FOCUS surface water repair action" has sought to address important limitations raised by regulatory authorities and users about the EU FOCUS pesticide environmental exposure framework (EFSA et al., 2020). As a result, an update of accepted higher-tier tools like SWAN is under way. Developers of SWAN and VFSMOD have joined forces to integrate the new version of VFSMOD into the next release of SWAN. This effort provides updated recommendations for regulatory application and incorporates new VFSMOD features to account more realistically for additional field characteristics where needed.

IMPLEMENTATION OF VFS IN THE FIELD

As part of risk management, successful implementation of VFS at the field scale relies on strong relationships with farmers and landowners. Because adoption is voluntary (unless using a pesticide for which its use involves having a mandatory VFS), it is critical to understand common barriers to adoption. Engagement with farmers and technical service providers through focus group meetings and workshops has demonstrated the importance of maintenance and design concerns in buffers. For example, farmers in the northeastern USA generally seem to prefer adoption of grass filter strips rather than forested buffers, as significant concerns exist related to management of invasive species and tree survival. Although the degree of beneficial ecosystem services such as increased biodiversity provided by a VFS varies widely depending on design and landscape features (Southeastern Wisconsin Regional Planning Commission [SEWRPC], 2010), grassed VFS provide comprehensive, closely spaced, vegetative ground covers more rapidly than forested buffers can. This cover helps VFS slow runoff and reduce concentrated flow pathways. As a result, VFS have proven beneficial in increasing infiltration of waterborne contaminants, reducing erosion, and trapping sediment-borne contaminants (Haddaway et al., 2018; Reichenberger et al., 2007).

Challenges in VFS implementation (when not mandatory per pesticide labels) include difficulties communicating expected benefits from adoption to landowners and VFS vulnerabilities to extreme events and erosion. Farm-level factors known to affect VFS performance include factors that cannot be controlled, such as hydrologic soil group and topography and extreme rainfall events, as well as land management decisions on the farm that affect water and pollutant transport into the buffer. In particular, VFS integrity is undermined when incoming runoff converges into concentrated flow pathways that allow surface runoff to bypass the buffer and enter the stream untreated (Dosskey et al., 2002; Piechnik et al., 2012; Wallace et al., 2018). Formation of concentrated flow pathways (e.g., micro-ditches, rills, or gullies) and associated increases in pollutant transport from fields can be minimized in agricultural landscapes by implementing conservation tillage practices, using cover crops, being mindful to use heavy farm machinery when soil is less prone to compaction, and mitigating repetitive livestock movement to and from streams. It is also important to install VFS upslope and as close as possible to the source of runoff (Carluer et al., 2011). Best practices to control ephemeral gully erosion in cropland and guidance on design, management, and maintenance of VFS are available to growers along with potential resources to implement conservation practices (USDA-NRCS, 2017b, 2021).

Farmer decision-making is complex and may vary at both the farm- and field-level scales. A national farmer survey

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indicated that farmers understood water quality problems as readily as agency personnel, but often they focus on visual cues such as sediment loss rather than pesticide or nutrient losses (Woods et al., 2014). Buffers were the most disliked conservation practice as they took land out of production. In a piedmont watershed in North Carolina, VFS were frequently implemented when exclusion fencing was installed to keep cattle out of streams (O'Connell & Osmond, 2018). After more than 20 years of the local Soil and Water Conservation District working with producers, farmers had a positive view of exclusion fencing and VFS. Both studies found that, regardless of the conservation practice, trusted local advisers were the most important ingredient in practice adoption, and the conservation practice had to be cost-effective and convenient because "conservation competes with the time the farmer could be using to make money" (O'Connell & Osmond, 2018; Woods et al., 2014). Additional factors that were important for adoption were the belief system of the farmer, age of the producer, family dynamics, and land ownership. Using VFS to support several ecosystem services and increase their value not only for pollutant reduction but for other uses as well could increase their acceptability, especially if there is support from the entire agricultural community to overcome adoption barriers (such as higher cost, increased maintenance, etc.) from the farmer through the supply chain. Pennsylvania Department of Conservation and Natural Resources and the USDA National Agroforestry Center encourage variable-width, multifunctional buffers and allow harvesting options for willows, wildflowers, nuts, and berries. When VFS are designed for ecological functions as well as pollutant mitigation, function trade-offs must be carefully considered. For example, VFS planted with meadow grasses and wildflowers, as opposed to frequently maintained grass strips, can increase pollinator habitat and encourage bird nesting but will need to be managed to limit adverse impacts of insecticide runoff mitigation to pollinators. Additionally, thinner stands or inconsistent ground cover may reduce trapping and filtering performance, as compared with frequently maintained grass strips.

In addition to their use for risk assessment in regulatory settings, computational models such as VFSMOD are also used to inform field-level risk management decisions to support BMP programs for reducing nonpoint source pollution. For example, VFSMOD has been used to optimize VFS design for mitigation of pesticide transport to surface waterbodies based on local conditions in France in the BUVARD tool (Carluer et al., 2017). A spatially explicit Gaussian process metamodel of BUVARD was then developed for quick estimation of VFS characteristics across France (Lauvernet & Helbert, 2020). Expanding such efforts to other regions of the world would facilitate the design of more effective VFS based on local conditions without consuming unnecessarily large amounts of agricultural land.

OUTCOMES FROM WORKSHOP

Key outcomes from the workshops include: VFS have been proven effective in reducing runoff pollution to surface waterbodies when properly located, designed, implemented, and maintained; VFSMOD, a science-based and widely validated mechanistic model, is suitable for further vetting as a quantitative simulation approach to pesticide mitigation with VFS in current regulatory settings; and VFSMOD parameterization rules need to be developed for the North American aquatic exposure assessment.

DISCUSSION AND PATH FORWARD

The current aquatic exposure modeling approaches in North America are similar between the USEPA, PMRA, and CDPR. Ideally, the use of VFSMOD would also be similar among the agencies. To that end, multistakeholder discussions have continued after the 2020 CERSA VFS workshop to explore and harmonize approaches to evaluating VFS in pesticide risk assessment. Although discussions are still ongoing regarding potential software interfaces between the regulatory models and VFSMOD, a document has been developed to help facilitate future harmonization of VFS modeling approaches (Ritter et al., 2023). The document includes a detailed assessment of VFSMOD inputs, their sensitivity and parameter selection, and methods for integration and harmonization of the model use in the regulatory process. The document does not represent formal guidance approved by the agencies; rather, it is the best effort at a science-based input parameter document to support the agencies' eventual review of VFSMOD-based regulatory modeling approaches.

The technical tools for quantitative implementation of VFS in the pesticide risk assessment process are within reach. This publication, an outcome from the multistakeholder workshops, can provide scientific support for the use of these tools in regulatory risk assessment to inform the development of label mitigations for protection of nontarget species and their habitats. It is also important to provide growers with the resources they need to effectively implement VFS on their farmlands. Future effort is needed to disseminate training materials through NRCS, university cooperative extension programs, company grower meetings, and other venues. In addition, more research is needed to explore the use of VFSMOD as an advisory tool to inform pesticide risk management decisions at the field level. International, interagency, and stakeholder collaboration and information exchange are essential to facilitate adoption of VFS as part of a comprehensive approach to encourage sustainable practices for protection of water resources and enhanced ecosystem services as well as for economic and social benefits for growers.

AUTHOR CONTRIBUTION

Huajin Chen: Conceptualization; project administration; visualization; writing—original draft; writing—review and editing. **Danesha Seth Carley**: Conceptualization; writing—original draft; writing—review and editing. **Rafael Muñoz-Carpena**: Conceptualization; visualization; writing—original draft; writing—review and editing. **Giulio Ferruzzi**: Conceptualization; writing—original draft; writing—review and editing. **Yongping Yuan**: Conceptualization; writing—original

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draft; writing—review and editing. **Eric Henry**: Conceptualization; writing—review and editing. **Amy Blankinship**: Conceptualization; writing—original draft; writing—review and editing. **Tamie L. Veith**: Conceptualization; writing—original draft; writing—review and editing. **Ross Breckels**: Conceptualization; writing—original draft; writing—review and editing. **Garey Fox**: Conceptualization; writing—original draft. **Yuzhou Luo**: Conceptualization; writing—original draft; writing—review and editing. **Deanna Osmond**: Conceptualization; writing—original draft; writing—review and editing. **Heather E. Preisendanz**: Conceptualization; writing—original draft; writing—review and editing. **Zhenxu Tang**: Conceptualization; writing—review and editing. **Kevin Armbrust**: Conceptualization; writing—original draft. **Kevin Costello**: Conceptualization; writing—review and editing. **Laura L. McConnell**: Conceptualization; supervision; writing—review and editing. **Patricia Rice**: Conceptualization; writing—review and editing. **Johnny Westgate**: Conceptualization; writing—review and editing. **Mélanie Whiteside**: Conceptualization.

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DISCLAIMER

The views expressed in this article are those of the authors and do not necessarily reflect the views of Pennsylvania State University, North Carolina State University, USEPA, USDA, or Health Canada.

DATA AVAILABILITY STATEMENT

No data were generated for this article.

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SUPPORTING INFORMATION

Table S1. Acronyms and nomenclature.

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