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Effectiveness of Vegetative Filter Strips in Reducing Pesticide Loading: Quantifying Pesticide Trapping Efficiency

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Pesticide trapping efficiency of vegetated filter strips (VFS) is commonly predicted with low success using empirical equations based solely on physical characteristics such as width and slope. The objective of this research was to develop and evaluate an empirical model with a foundation of VFS hydrological, sedimentological, and chemical specific parameters. The literature was reviewed to pool data from five studies with hypothesized significant parameters: pesticide and soil properties, percent reduction in runoff volume (i.e., infiltration) and sedimentation, and filter strip width. The empirical model was constructed using a phase distribution parameter, defined as the ratio of pesticide mass in dissolved form to pesticide mass sorbed to sediment, along with the percent infiltration, percent sedimentation, and the percent clay content (R^2 = 0.86 and standard deviation of differences [STDD] of 7.8%). Filter strip width was not a statistically significant parameter in the empirical model. For low to moderately sorbing pesticides, the phase distribution factor became statistically insignificant; for highly sorbing pesticides, the phase distribution factor became the most statistically significant parameter. For independent model evaluation datasets, the empirical model based on infiltration and sediment reduction, the phase distribution factor, and the percent clay content (STDD of 14.5%) outperformed existing filter strip width equations (STDD of 38.7%). This research proposed a procedure linking a VFS hydrologic simulation model with the proposed empirical trapping efficiency equation. For datasets with sufficient information for the VFS modeling, the linked numerical and empirical models significantly (R^2 = 0.74) improved predictions of pesticide trapping over empirical equations based solely on physical VFS characteristics.

A common method for alleviating pesticide loading to nearby surface water bodies is the use of edge-of-field riparian buffers or VFS (Popov et al., 2005; Reichenberger et al., 2007). These VFS reduce pesticide movement to streams by reducing runoff volumes through infiltration in the filter strip's soil profile, through contact between dissolved phase pesticide with soil and vegetation in the filter strip, and/or by reducing flow velocities to the point where eroded sediment particles, with sorbed pesticide, can settle out of the water. The mechanism of pesticide trapping has historically been assumed to be a function of the organic carbon sorption coefficient, K_{oc}. Most researchers agree that filter strips trap highly sorbing pesticides in the same manner that they trap sediment. Spatz (1999) suggests that pesticide attached to eroded sediment becomes the dominant transport mechanism only for strongly sorbing (i.e., K_{oc} > 1000 L kg^{-1}) pesticides (Reichenberger et al., 2007). For low to moderately sorbed pesticides, runoff must infiltrate while in the filter strip or pesticide can be removed from solution through contact with the soil or vegetation in the filter strip (USDA, 2000). Leonard (1990) suggests that for most pesticides with relatively low K_{oc}, the most important transport mechanism is runoff as opposed to eroded sediment due to the difference in magnitude between runoff volume and sediment yield from most fields.

Field studies do not always support such correlations between pesticide trapping and K_{oc}. For example, some studies report small reductions in low to moderately sorbed pesticides by filter strips (e.g., Yonts et al., 1996); other researchers report significant reductions in similarly sorbed pesticides by filter strips (e.g., Tingle et al., 1998). In general, numerous studies have investigated the effectiveness of VFS on pesticide trapping for a range of pesticides with varying K_{oc}.

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Abbreviations: *CF,* compaction factor; d_{50}, diameter of soil particle in which 50% is finer (mm); Δ*E,* sediment mass reduction (%); F_{ph}, phase distribution factor (-); K_d, linear sorption coefficient (L kg^{-1}); K_{oc}, organic carbon sorption coefficient (L kg^{-1}); K_{sat}, saturated hydraulic conductivity (cm h^{-1}); Δ*Q*, runoff volume reduction (%); Δ*P*, pesticide mass reduction (%); *SAV*, suction depth (m); W_B, filter strip width (m); θ_o, initial soil water content (-); θ_s, saturated soil water content (-); %*C*, percent clay content (%); %*OM,* percent organic matter content (%); %*S*, percent sand content (%); %*Si*, percent silt content (%).

Reichenberger et al. (2007) provides a detailed summary of several review papers on this topic (i.e., in particular, see Norris, 1993; USDA, 2000; Lacas et al., 2005; and Krutz et al., 2005). Norris (1993) notes that pesticide trapping depends on the physical characteristics of the VFS (i.e., location, vegetation type, and soil properties) along with characteristics of the pollutant being trapped. United States Department of Agriculture (2000) notes that VFS widths less than 0.5 m can be effective in pesticide trapping and that increasing VFS width does not always improve trapping efficiency. This is a result of the site characteristics and nature of the runoff event. In fact, USDA (2000) describes techniques to promote shallow sheet flow across VFS, noting that concentrated flow through a VFS is one of the primary factors limiting trapping efficiency. This document also suggests, based on reviews of literature studies, an exponential relationship between K_{oc} and the potential range in percent of pesticide trapped (i.e., 62 to 100% reduction for highly sorbed pesticides and 8 to 100% reduction for moderately sorbed pesticides).

Numerous studies evaluate the relationship between pesticide trapping and VFS width (e.g., Webster and Shaw, 1996; Cole et al., 1997). Lacas et al. (2005) support previous findings suggesting that a simple model for pesticide trapping based solely on VFS width is not appropriate due to the large number of interacting processes and VFS/pesticide properties. They suggest the development of physically based models for predicting the effectiveness of VFS. Krutz et al. (2005) suggested that VFS width does influence pesticide trapping efficiency for moderately sorbing pesticides, with strongly sorbing pesticides largely removed by sediment deposition at the beginning of the VFS. Reichenberger et al. (2007) concluded from their review of literature that a significant effect of VFS width on pesticide trapping was not uniformly observed across studies, primarily due to the fact that the removal depends largely on the pesticide properties, nature of the runoff event, and antecedent moisture content. Therefore, prediction based on buffer width may provide a broad-level estimate of reduction by the VFS, but cannot provide site and/or event specific estimates of pesticide trapping efficiency.

Even with these rather uniform study conclusions that have demonstrated little predictive power when attempting to correlate pesticide trapping efficiency with physical characteristics (width, slope, area ratios, and vegetation type) of the VFS, watershed-scale models, such as the Soil and Water Assessment Tool (SWAT), commonly correlate removal efficiency to VFS width. In fact, SWAT uses the following equation for VFS trapping efficiency (ΔC) for sediment, nutrients, and pesticides:

$$\Delta C = 0.367\left(W_B\right)^{0.2967} \qquad [1]$$

where W_B is the width of the VFS in meters (Neitsch et al., 2005). The question that remains is whether a better empirical model, based on physical parameters related to both the pesticide and the VFS, can be developed for estimating riparian VFS effectiveness and/or riparian targeting in watershed scale models such as SWAT.

As discussed by Gharabaghi et al. (2000), more specific models for VFS reductions in runoff and sediment do exist, such as the model GRASSF developed by Barfield et al. (1979). This model is physically based and accounts for sediment type and concentration, vegetation type, slope, and length of the filter to predict sediment deposition. Munoz-Carpena et al. (1999) improved on GRASSF by including improved routines for flow through the filter, time-dependent infiltration, and spatial variability in surface conditions (Gharabaghi et al., 2000; Munoz-Carpena and Parsons, 2004). They referred to their model as the Vegetative Filter Strip Modeling System, VFSMOD (Munoz-Carpena et al., 1999; Munoz-Carpena and Parsons, 2004). The VFSMOD is a finite-element, field-scale, storm-based model developed to route the incoming hydrograph and sedigraph from an adjacent field through a VFS and to calculate the resulting outflow, infiltration (based on the Green-Ampt equation for unsteady rainfall), and sediment trapping (based on GRASSF). Researchers (Abu-Zreig, 2001; Abu-Zreig et al., 2001; Gharabaghi et al., 2000) have demonstrated the model's ability to predict reductions in runoff volume and sediment concentration moving through the filter. Even with these VFS hydrologic and sediment prediction advancements, the research community still lacks an effective model or procedure capable of predicting VFS pesticide reduction.

The objective of this research was to develop and evaluate an innovative empirical model for estimating trapping efficiency of total pesticide mass (dissolved and sorbed). The innovative part of this research is that other studies attempting to predict VFS effect of pesticide loading have attempted to correlate VFS trapping efficiency with various VFS physical characteristics (such as width, slope, area ratios, and vegetative types). In most of these studies, the models introduced are not adequate. This research hypothesized that parameters related to the hydrologic response of the VFS to runoff events and the distribution of pesticide between dissolved and sorbed phases are better suited for predicting pesticide trapping than equations based solely on the physical dimensions of the VFS (i.e., width, slope, area ratios and vegetation) and/or pesticide properties. This research also proposed and evaluated procedures linking a VFS hydrologic simulation model, which currently does not possess process based modeling for pesticide trapping, with the proposed empirical pesticide trapping efficiency equation.

Materials and Methods

Initial Data Survey from Literature

Data on effectiveness of VFS were compiled from 127 published journal articles. Five publications reported values for the parameters identified as initially essential for the analysis: (1) water volume (Q, L) and sediment mass (E, kg) in and out of the VFS; (2) dissolved pesticide mass in and out of the VFS; (3) sediment bound pesticide mass in and out of the VFS; (4) size of VFS; and (5) soil characteristics. In terms of soils data, the primary parameters of interest were the percent clay (%C) and organic matter content (%OM). Reported values were used when provided by the source. If only the soil series was documented, then the values of percent clay and organic matter were obtained from the soil survey using the Map Unit Use File (MUUF) and the average values for top layer were considered (Rawls et al., 2001; Fox et al., 2004). A summary of these five

Table 1. Characteristics of the field studies utilized in this research for development of an empirical model for pesticide trapping efficiency.

Study		Arora et al. (2003) IA 1995	Krutz et al. (2003) TX 2001	Hall et al. (1983) PA 1972	Barfield et al. (1998) KY 1991	Schmitt et al. (1999) NE 1996
Event description	Type	Single event	Single event	Total for 11 events	Single event data (2 Events)	Single event
	Rainfall	–	–	Natural	Simulated	–
	Runoff	Simulated	Simulated	Natural	Natural	Simulated
Soil description	Soil Name	Clarion	Houston Black	Hagerstown	Maury	Sharpsburg
	Type	Loam	Clay	Silty Clay Loam	Silt Loam	Silty Clay Loam
	Hydrologic Soil Group	B	D	B	B†	B‡
VFS description	Type	Brome Grass	Buffalograss	Oats	Bluegrass	Switch grass and Tall Fesque
	Length in direction of flow (m)	20.1	3.0	6.0	4.6–13.7	7.5, 15.0
	Area (m^2)	30.2	3.0	10.8	20.9–62.7	22.5, 45.0

† Soil type behaves like Hydrologic Soil Group A (well-drained) due to karst topography.

‡ Soil type behaves like Hydrologic Soil Group A because it is well-drained.

Table 2. Data used in the development of the empirical model for pesticide trapping efficiency.

Study†	Chemical (n)	Parameters‡ ΔQ	Q_i	E_i	ΔE	K_{oc}	%C	%OM	ΔP	F_{ph} (–)
		%	L	kg	%	L kg^{-1}	%	%	%	
1	Atrazine (2)	30–39	4896–9791	20–40	87–90	147	21	4	47–53	71
	Metolachlor (2)					70			48–55	150
	Chlorpyrifos (2)					9930			77–83	1
2	Atrazine (1)	92	750	0	0	147	48	4.2	22	0
3	Atrazine (4)	22–80	547–2304	8–91	54–98	147	25	3	52–87	10–80
4	Atrazine (12)	88–100	473–11,634	1–258	93–100	147	20	3.1	92–100	8–238
5	Atrazine (6)	36–82	1887	19	84–99	147	30	3	32–90	39
	Alachlor (6)					124			41–92	46
	Permethrin (6)					160,000			53–96	0.04
	Bromide (6)					9			44–88	636

† 1: Arora et al., 2003; 2: Krutz et al., 2003; 3: Hall et al., 1983; 4: Barfield et al., 1998; 5: Schmitt et al. (1999).

‡ ΔQ, percent reduction of water volume (infiltration); Q_i, water volume entering VFS; E_i, mass of sediment entering VFS; ΔE, percent reduction of sediment mass; K_{oc}, adsorption coefficient; %C, percent clay content; %OM, percent soil organic matter; ΔP, percent trapping efficiency of pesticide mass; F_{ph}, phase distribution factor.

studies is outlined in Table 1, and the data used in the model development are provided in Table 2.

These five studies included 47 observations which included pesticide/tracer reductions (ΔP) ranging from 22 to 100% for alachlor (K_{oc} = 124 L kg^{-1}), atrazine (K_{oc} = 147 L kg^{-1}), bromide (K_{oc} = 9 L kg^{-1}), chlorpyrifos (K_{oc} = 9930 L kg^{-1}), metolachlor (K_{oc} = 70 L kg^{-1}), and permethrin (K_{oc} = 160,000 L kg^{-1}). Chemical properties for the pesticides/tracer investigated in each field study were amassed from the USDA database on chemical properties (Wauchope et al., 1992; ARS-PPDB, 2006). Widths of the VFS ranged from 3.0 to 20.1 m. Also, only those studies reporting VFS width in the primary direction of flow were considered. The studies included data from both natural and simulated rainfall and runoff events. Most of the data were limited to studies on soils with %C values of 21 to 30%, with only a single observation from the Krutz et al. (2003) study on a soil with 48% clay.

Empirical Model Development and Evaluation

The foundation of the proposed empirical equation is a physically based parameter for the potential for a pesticide to partition between the soil and water phases as quantified through the linear sorption coefficient, K_d:

$$K_d = \frac{K_{oc}(\%OC)}{100} \quad [2]$$

where %OC is the percentage organic carbon in the soil. A phase distribution parameter, F_{ph}, defined as the ratio between the mass of pesticide in the dissolved phase relative to the mass of the pesticide sorbed to sediment, was determined using the data from each study and the following equation:

$$F_{ph} = \frac{Q_i}{K_d E_i} \quad [3]$$

where Q_i and E_i are the volume of water (L) and mass of sediment (kg), respectively, entering the VFS.

Within the initial empirical model, several other parameters were also deemed influential considering their interacting effect with the F_{ph}, including percent runoff volume reduction (i.e., infiltration) by the VFS (ΔQ, %), percent reduction in eroded sediment mass or sedimentation (ΔE, %), VFS width (W_B), and the percent clay content (%C). A number of functions were evaluated using data from these five studies based on multiple linear regressions; however, the following function was statistically the most appropriate, as will be discussed later:

Table 3. Characteristics of field studies utilized for evaluation of the empirical model developed in this research and the empirical equation utilized by SWAT.

Study		Tingle et. al. (1998) MS 1994	Arora et al. (1996) IA 1993–1994	Popov (2005) Australia 2003	Patty et al. (1997) France 1993–1995	Patzold et al. (2007) Germany 1997–1999
Event description	Type	Single event	Six separate events	Single event	Multiple events	Multiple events
	Rainfall	Simulated	Natural	–	Natural	Natural
	Runoff	Natural	Natural	Simulated	Natural	Natural
Soil description	Soil Name	Brooksville	Canisteo	Black Earth (Vertisol)	–	Eutric, Stagnic, Cambisol
	Type	Silty Clay	Silty Clay, Loam	Clay	Silt Loam	Silt Loam
	Hydrologic Soil Group	D	C	D	B	B
VFS description	Type	Tall Fescue	Smooth Bromegrass	Wallaby Grass	Rye Grass	Maize and Pasture
	Length in direction of flow (m)	0.5– 4.0	20.1	1.3	6.0, 12.0, 18.0	6.0, 12.0
	Area (m^2)	2.0– 16.0	30.6	5.0	30.0, 60.0, 90.0	18.0, 36.0

Table 4. Data used in the evaluation of the empirical model for pesticide trapping efficiency.

Study†	Parameters‡									
	Chemical (n)	ΔQ	Q_i	E_i	ΔE	K_{oc}	%C	%OM	ΔP	F_{ph} (–)
		%	L	kg	%	L kg^{-1}	—%—			
1	Metolachlor (5)	83–93	137,000	90	88–98	70	45	3.2	92–98	1169
	Metribuzin (5)					52			93–98	1573
2	Atrazine (12)	4–100	381–19,506	1–80	41–100	147	31	6.0	11–100	23–98
	Metolachlor (12)					70			16–100	49–205
	Cyanazine (12)					217			8–100	16–66
3	Atrazine (7)	39–73	100–1600	0–3	56–93	147	40	6.0	41–85	0–109
	Metolachlor (7)					70			45–85	0–230
4	Atrazine (6)	43–100	457–480	0	87–100	147	16–20	2.0, 7.0	44–100	542,094–3,933,002
	Lindane (6)					1355			72–100	58,810–426,680
	Isoproturon (3)	85–93	535	0	91–98	53	12	3	100	1,873,032
	Didlufenican (3)					2000			97–100	49,635
5	Metolachlor (14)	85–100	16–124	0–1	88–100	70	25	2.9	95–100	39–233
	Pendimethalin (14)					13400			95–100	0–1
	Terbuthylazine (14)					220			94–100	12–74

† 1: Tingle et. al. (1998); 2: Arora et al. (1996); 3: Popov (2005); 4: Patty et al. (1997); 5: Patzold et al. (2007).

‡ ΔQ, percent reduction of water volume (infiltration); Q_i, water volume entering VFS; E_i, mass of sediment entering VFS; ΔE, percent reduction of sediment mass; K_{oc}, adsorption coefficient; %C, percent clay content; %OM, percent soil organic matter; ΔP, percent trapping efficiency of pesticide mass; F_{ph}, phase distribution factor.

$$\Delta P = f\left(\Delta Q, \Delta E, \ln\left(F_{ph}+1\right), W_B, \%C\right) \qquad [4]$$

The natural logarithm term includes the term F_{ph}+1 to ensure that in cases where there is no ΔQ the equation predicts no pesticide trapping. Statistical analysis was performed to evaluate the importance of each variable within this multiple linear regression equation for cases with all pesticides and then also by dividing the compounds into two classes: high mobility ($K_{oc} \leq 147$ L kg^{-1}) and low mobility ($K_{oc} \geq 9930$ L kg^{-1}). Also, the empirical model was evaluated against measured ΔP using linear regression and also based on the STDD:

$$STDD = \sqrt{\frac{\sum_{i=1}^{n}\left(x_m - x_p\right)^2}{n}} \qquad [5]$$

where x_m and x_p are the i^{th} observed and predicted values of n observations, respectively. This function has been used in the past for quantitative evaluation of pesticide fate and transport models (Pennell et al., 1990; Fox et al., 2004; Fox et al., 2006; Fox et al., 2007). This research used a criterion that the STDD between measured and predicted ΔP should be less than 15%.

Five additional publications, summarized in Table 3 with the data provided in Table 4, which initially did not possess all hypothesized variables of significance, included data that can be used to evaluate the final empirical model. The additional studies provided 120 measured ΔP ranging from 8.0 to 100% for atrazine (K_{oc} = 147 L kg^{-1}), cyanazine (K_{oc} = 217 L kg^{-1}), didlufenican (K_{oc} = 2000 L kg^{-1}), isoproturon (K_{oc} = 53 L kg^{-1}), lindane (K_{oc} = 1355 L kg^{-1}), metolachlor (K_{oc} = 70 L kg^{-1}), metribuzin (K_{oc} = 52 L kg^{-1}), pendimethalin (K_{oc} = 13,400 L kg^{-1}), and terbuthylazine (K_{oc} = 220 L kg^{-1}). Widths of the VFS ranged from 0.5 to 20.1 m. The data included studies on soils with %C ranging from 12 to 45%.

Comparison of Proposed Trapping Efficiency Equations

Based on the studies identified for model evaluation, the predicted ΔP using the empirical models developed in this research and the equation utilized in SWAT (based solely on VFS width) were compared with measured ΔP. Linear regression was performed between the measured and predicted ΔP, and the STDD was calculated for both predictive equations. Also, the proposed exponential relationship between ΔP and K_{oc}, reported by the USDA Natural Resource Conservation Service (NRCS; USDA, 2000), was evaluated using the model evaluation dataset. The pesticide's K_{oc} was plotted against the measured ΔP, and visual inspection was used to document any resulting mathematical relationships.

Derivation of Hydrological/Sediment Input Parameters to Estimate Trapping Efficiency

Many of the parameters that are influential for estimating pesticide trapping efficiency, such as ΔQ and ΔE, are not easily predicted. Therefore, techniques must be developed for users to effectively use regression equations of the form of Eq. [4] for predicting pesticide trapping. This research hypothesized that an uncalibrated VFS model that, based on physical characteristics of the VFS such as W_B, predicts ΔQ and ΔE but does not predict pesticide processes, could be used in conjunction with the empirical equations developed in this research. As introduced earlier, one such model is VFSMOD (Munoz-Carpena et al., 1999; Munoz-Carpena and Parsons, 2004).

Many of the critical parameters required by VFSMOD can be estimated from readily available sources. Users must provide estimates of the hydraulic characteristics of the soil in the VFS. Based on sensitivity analyses, the critical parameters for VFSMOD for predicting runoff volume are the saturated hydraulic conductivity (K_{sat}), suction depth (*SAV*), initial water content (θ_o), and saturated water content (θ_s; Fox et al., 2005; Gharabaghi et al., 2000). Previous studies have demonstrated that Manning's *n* value for the VFS only impacted the timing of the peak and not the total runoff volume (Gharabaghi et al., 2000). Since the proposed procedure was based on total runoff volume reduction (i.e., infiltration), default values in VFSMOD were used for Manning's *n*. The main parameters predicting sediment trapping included the slope length, slope, soil erodibility, vegetation cover factor, and practice factor (Gharabaghi et al., 2000).

The following steps were proposed for estimating the critical parameters required for estimating ΔQ and ΔE as part of an uncalibrated simulation. First, K_{sat}, θ_o, and θ_s were calculated with a tool published by the USDA called the Soil Water Characteristics or SWC (Version 6.1.52; http://hydrolab.arsusda.gov/soilwater/Index.htm, December 2008). This tool required inputs of percent clay (*%C*), percent sand (*%S*), and percent organic matter (*%OM*), as well as a compaction factor (*CF*) with values from 0.9 (loose) to 1.3. Except for *CF*, the input data can be obtained from the study site. In this research, *CF* was set at 1 for normal soils and at 0.9 for clay soils with severe cracks during dry periods (if the runoff study was initiated when the soil was dry) and for soil classified as well drained. Next, *SAV* was calculated with the equation reported by Fox et al. (2005) based on the pedo-transfer function of Rawls et al. (1993). This equation required *%C*, *%S*, and the soil porosity, which was calculated from the bulk density value estimated by SWC, assuming a particle density of 2.65 g cm^{-3}.

Other parameters required to run VFSMOD were the hydrographs for rainfall and entering runoff, concentration of sediment in the entering runoff (C_s), the characteristics of the sediment, and the characteristics of the VFS (size and vegetation). Rainfall volume and duration and entering runoff volume and duration were required inputs for the procedure and were obtained from the model evaluation datasets. For simplicity and demonstration purposes, storms were assumed to be uniformly distributed, since not all studies provided the rainfall and runoff hydrographs. For studies where a hydrograph is known, users can input the actual hydrograph.

The C_s was obtained from the studies. For the sediment characteristics, the two critical parameters were the portion of sediment particles from incoming sediment with diameters greater than 0.037 mm and the median particle size, d_{50}. The first value was assumed to be the %*S*. The d_{50} was assigned based on *%C*, *%S*, and percent silt (*%Si*). This information will be readily available to users with soil sampling. For this research, since sampling was not feasible, the d_{50} was assumed as the average diameter for the range of sizes for %*S*, %*Si*, and %*C*.

For characteristics of the vegetation in the VFS, the values recommended by VFSMOD based on the vegetation type were used. If the specific vegetation was not listed, data for a similar vegetation type to that in the study were used. Finally, the slope length, slope, soil erodibility, vegetation cover factor, and practice factor were estimated from observable data on the VFS from the model evaluation datasets.

To demonstrate and evaluate the procedure's usefulness, the technique was applied to several of the field datasets that contained appropriate data to develop estimates for critical parameters (Table 5). The primary criterion for selecting studies to test the combined VFSMOD and empirical pesticide trapping efficiency equation was whether the dataset listed information on entering runoff volume and duration. Only datasets for individual events were used. First, an attempt was made to only utilize those studies in the model evaluation group. Three of the studies provided adequate data: Arora et al. (1996), Popov (2005), and Patzold et al. (2007). Although the Arora et al. (1996) study included six events, the storm hydrograph for only one event was reported. The Popov (2005) study was on clay soil and the authors reported severe cracking; therefore, infiltration parameters for this study were based on a *CF* of 0.9 (Table 5).

Because of the limited number of studies with adequate data, the procedure was also applied to the appropriate model development studies: Arora et al. (2003), Krutz et al. (2003), Hall et al. (1983), Barfield et al. (1998), and Schmitt et al. (1999). In the Barfield et al. (1998) study, the soil was very well drained due to karst geology; therefore, a *CF* of 0.9 was used. Although there were four different vegetated treatments in the Schmitt et al. (1999) study, the entering runoff volumes and sediment concentrations in the runoff were the same; therefore, the variability due to vegetation was not captured in the simplified modeling procedure because equivalent infiltration values were used for all treatments (Table 5).

Table 5. Parameter values used in hydrologic simulation modeling of the vegetated filter strip with VFSMOD for the selected model development and evaluation datasets. Note that *CF* is the compaction factor, K_{sat} is the saturated hydraulic conductivity, *SAV* is the suction head, %*S* is the percent sand (assumed to be the percentage of sediment greater than 0.037 mm), and d_{50} is the average particle size.

Study	*CF* (–)	K_{sat}	*SAV*	%*S*	d_{50}
		cm h^{-1}	m	%	mm
Arora et al. (1996)	1.0	12.2	0.30	20	0.003
Popov (2005)	0.9 (cracked soil)	19.2	0.18	30	0.005
Patzold et al. (2007)	1.0	6.8	0.46	10	0.002
Arora et al. (2003)	1.0	8.2	0.13	47	0.010
Barfield et al. (1998)	0.9	16.2	0.10	50	0.027
Schmitt et al. (1999)	1.0	4.6	0.51	27	0.005

Table 6. Statistical summary of empirical model performance in predicting pesticide removal or trapping efficiency (ΔP) for two empirical equations as functions of runoff volume reduction (Δ*Q*; i.e., infiltration), sediment reduction (Δ*E*), phase distribution factor (F_{ph}), percent clay content (%*C*), and filter strip width (W_B) for model development studies (Table 1).

	Coefficient value	SE	*t*-statistic	*P*-value
Equation: $\Delta P = f\left(\Delta Q, \Delta E, \ln\left(F_{ph}+1\right), W_B, \%C\right)$				
Number of Observations, *n* = 47				
$R^2 = 0.86$	Adjusted $R^2 = 0.84$			
Standard Error of Estimate = 8.41				
Constant	21.9	13.1	1.67	0.10
Δ*Q*	0.56	0.06	9.87	<0.001
Δ*E*	0.49	0.09	5.39	<0.001
$\ln(F_{ph} + 1)$	–2.41	0.65	–3.70	<0.001
%*C*	–0.86	0.26	–3.31	0.002
W_B	0.31	0.27	1.11	0.27
Equation: $\Delta P = f\left(\Delta Q, \Delta E, \ln\left(F_{ph}+1\right), \%C\right)$				
Number of Observations, *n* = 47				
$R^2 = 0.86$	Adjusted $R^2 = 0.84$			
Standard Error of Estimate = 8.43				
Constant	24.8	12.9	1.92	0.06
Δ*Q*	0.54	0.05	10.11	< 0.001
Δ*E*	0.53	0.09	6.01	< 0.001
$\ln(F_{ph} + 1)$	–2.42	0.66	–3.69	< 0.001
%*C*	–0.89	0.26	–3.44	0.001

Results and Discussion

Empirical Model Development and Evaluation

The first analysis involved a multiple linear regression utilizing all of the variables introduced in Eq. [4]:

$$\Delta P = 21.9 + 0.56\left(\Delta Q\right) + 0.49\left(\Delta E\right) - 2.41\ln\left(F_{ph}+1\right) - 0.86\left(\%C\right) + 0.31\left(W_B\right) \quad [6]$$

This equation resulted in an R^2 of 0.86, with an adjusted R^2 of 0.84, a standard error of estimate of 8.41, and *P*-value less than 0.001 (Table 6). Each of the terms in Eq. [6] was assessed statistically regarding their importance, and it was discovered that all parameters, except W_B, had a *P*-value less than or equal to 0.002. These results indicated that W_B was not a statistically significant factor for predicting Δ*P*.

Table 7. Relative importance of each parameter in the empirical trapping efficiency model relative to pesticide organic carbon sorption coefficient, K_{oc}: $K_{oc} \le 147$ and $K_{oc} \ge 9930$. Δ*Q* is the runoff volume reduction (i.e., infiltration), Δ*E* is the sediment reduction, F_{ph} is the phase distribution factor, and %*C* is the percent clay content.

	Coefficient	SE	*t*-Statistic	*P*-value
$K_{oc} \le 147$ (number of observations = 38)				
Constant	29.8	10.2	2.93	0.006
Δ*Q*	0.80	0.06	13.8	< 0.001
Δ*E*	–0.02	0.11	–0.20	0.847
$\ln(F_{ph}+1)$	0.31	0.84	0.36	0.720
%*C*	–0.30	0.25	–1.20	0.237
$K_{oc} \ge 9930$ (number of observations = 8)				
Constant	–223	–0.17	0.31	< 0.001
Δ*Q*	–0.08	0.15	–0.50	0.654
Δ*E*	3.35	0.47	7.07	0.006
$\ln(F_{ph}+1)$	25.0	6.12	4.09	0.026
%*C*	0.00	0.00	0.35	0.747

A simplified empirical model without W_B was then derived:

$$\Delta P = 24.79 + 0.54\left(\Delta Q\right) + 0.52\left(\Delta E\right) - 2.42\ln\left(F_{ph}+1\right) - 0.89\left(\%C\right) \quad [7]$$

which resulted in an R^2 of 0.86, with an adjusted R^2 of 0.84, a standard error of estimate of 8.43, and *P*-value less than 0.001 (Table 7). Each parameter was deemed statistically significant with a *P*-value of 0.001 or less. Measured versus predicted Δ*P* and the linear regression is shown in Fig. 1 for the empirical model given by Eq. [7]. The STDD for model development was 7.8%.

When only considering low K_{oc} (i.e., $K_{oc} \le 147$ L kg^{-1}) compounds considered to have greater mobility, F_{ph}, Δ*E*, and %*C* became statistically nonsignificant factors with *P*-values greater than 0.23, especially compared to Δ*Q* ($P < 0.001$; Table 7). If the function was developed for high K_{oc} (i.e., $K_{oc} \ge 9930$ L kg^{-1}) pesticides (low mobility), F_{ph} and Δ*E* became the only statistically significant parameters (i.e., $P < 0.03$). The statistically nonsignificant parameters for low mobility compounds were Δ*Q* and %*C* with *P*-values greater than 0.65 (Table 7).

For the five model evaluation field datasets, the linear regression between measured and predicted Δ*P* based on the proposed empirical model resulted in an R^2 of 0.82 with a slope of 0.93 and intercept of –3.9% for the empirical model given by Eq. [7], as illustrated in Fig. 2. The STDD for the empirical model was 14.5% based on the model evaluation studies.

A question that can be asked is to what extent the high R^2 in Fig. 1 and Fig. 2 resulted from clustering of a large number of values approaching 100% reduction. When all observations of pesticide reductions above 95% were removed, the R^2 for measured versus predicted pesticide reduction for the model development datasets (Fig. 1) decreased by 0.08 (from $R^2 = 0.86$ to 0.78) and for the model evaluation datasets (Fig. 2) decreased by 0.06 (from $R^2 = 0.82$ to 0.76). Therefore, the clustering did not dominate the resulting R^2.

Comparison of Proposed Trapping Efficiency Equations

The empirical model proposed in Eq. [7] outperformed the empirical model utilized by SWAT, which is based solely on W_B. As shown in Fig. 3, little to no relationship existed be-

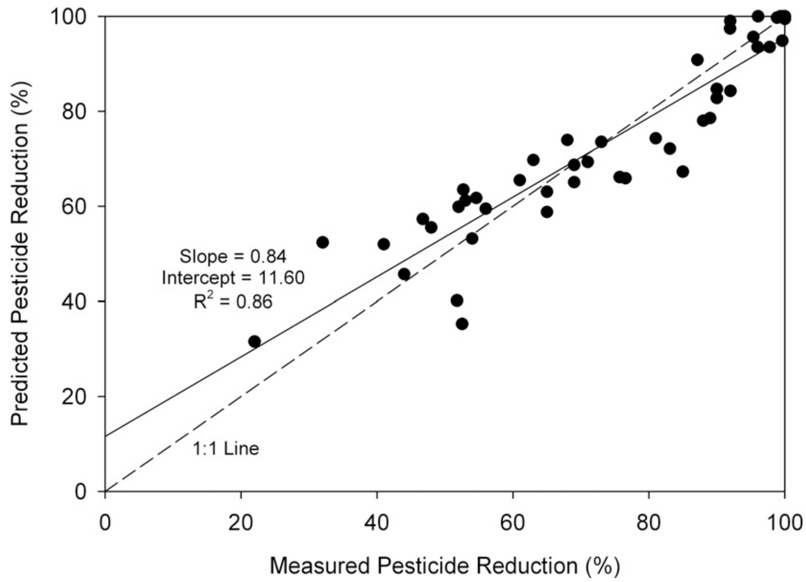

Fig. 1. Linear regression between measured and predicted pesticide removal or trapping efficiency (ΔP), as predicted by an empirical model based on the runoff volume reduction (i.e., infiltration; ΔQ), sediment reduction (ΔE), phase distribution factor (F_{ph}), and percent clay content (%C) for the model development studies in Table 1.

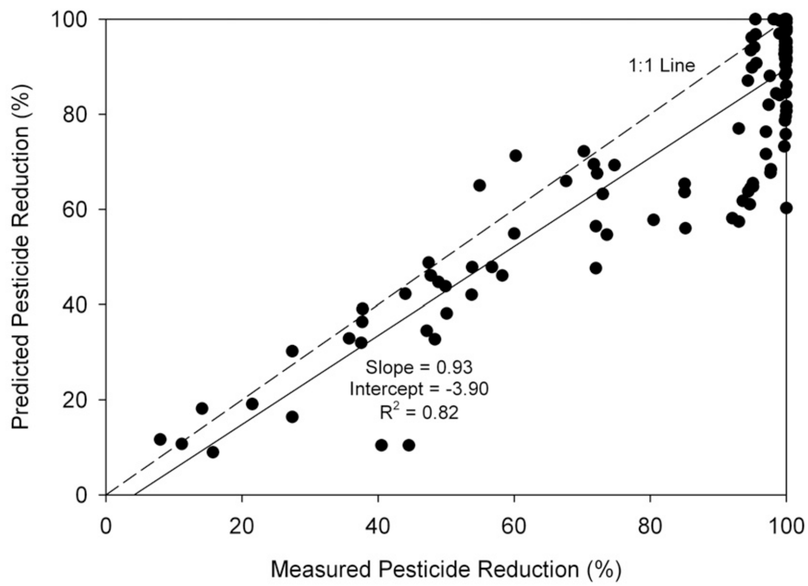

Fig. 2. Linear regression between measured and predicted pesticide removal or trapping efficiency (ΔP) as predicted by an empirical model based on the runoff volume reduction (i.e., infiltration; ΔQ), sediment reduction (ΔE), phase distribution factor (F_{ph}), and percent clay content (%C) for the model evaluation studies in Table 3.

tween the measured ΔP and the predicted ΔP using Eq. [1] above. In fact, a linear regression resulted in a negative slope. The STDD for the SWAT predicted ΔP was 38.7% compared to the empirical model's STDD of 14.5%. These results reemphasize the point that while prediction of pesticide trapping based on buffer width may provide a broad-level estimate, it cannot provide site- and/or event-specific estimates. Also, the USDA (2000) proposed exponential relationship between the range in pesticide trapping and K_{oc} was not observed for these model evaluation studies (Fig. 4). In fact, a grouping of all studies suggested no positive functional relationship between the range in pesticide trapping and K_{oc}. In fact, a negative trend was observed between K_{oc} and the minimum percent of pesticide trapped for K_{oc} less than 220 (Fig. 4). Again, empirical models that do not account for the hydrologic and sedimentological response of the VFS system to runoff events do not properly estimate pesticide trapping. These results verified the research hypothesis: empirical equations with parameters based on the hydrologic response of the VFS to runoff events and the distribution of pesticide between dissolved and sorbed phases were better suited for predicting pesticide trapping than conventional equations based solely on the physical dimensions of the VFS (i.e., width, slope, area ratios, and vegetation) and/or pesticide properties.

This research was not attempting to suggest that K_{oc} was not an important parameter; in fact, K_{oc} was a critical parameter for F_{ph} in Eq. [7], where F_{ph} became statistically significant for low mobility compounds. In fact, one could suggest that separate empirical equations as opposed to Eq. [7] be used for specific compound classes relative to K_{oc}. In fact, users would have the option of using compound specific equations if information on only the specific statistically significant variables was available. However, not enough data were available in this research for developing an equation for compounds with K_{oc} between 147 and 9930. Therefore, we proposed the single empirical equation as a robust equation for the entire range of K_{oc}.

The range of %C (12–48%) was of concern within this study since the datasets on which the empirical model was developed did not include sand or clay soils (i.e., low or high %C). Also, most of the observations used to develop the function were for pesticides with K_{oc} less than 150. Only a few observations were available for pesticides with K_{oc} greater than 1500, and the datasets did not include any observations for pesticides with K_{oc} between 220 and 1355.

Also, it is realized that the use of the model proposed in Eq. [7] is much more difficult than simpler functions based solely on physical characteristics (i.e., W_B). While the F_{ph} and %C can be estimated easily for VFS and the pesticide of interest, the proposed model required prediction of ΔQ (i.e., infiltration) and ΔE (i.e., sedimentation) due to the VFS, suggesting the need for hydrologic modeling within the VFS strip. Hydrological processes occurring on the upland areas must be linked to hydrological processes within the VFS with special consideration for the antecedent moisture content and impact of vegetation on runoff and sediment mass reduction. Watershed scale models usually only perform detailed hydrologic analyses for upland areas.

Based on the pooled data, fairly strong relationships (i.e., R^2 = 0.51) were observed between observed ΔQ and ΔE. If one uses this relationship, then measured ΔQ could predict ΔE, thereby reducing the number of input parameters to predict pesticide trapping. The use of a numerical model, such as VFSMOD, may be the most advantageous approach to predicting ΔQ and ΔE, as demonstrated below.

Estimating Pesticide Trapping Efficiency using VFSMOD/Empirical Equation

Predicted ΔQ using VFSMOD correlated well with measured reductions (R^2 = 0.82, slope of 1.01, and intercept of 1.66%) when using the uncalibrated procedure for estimating critical hydraulic and VFS parameters (Fig. 5). While measured ΔQ ranged between approximately 15 and 100%, measured ΔE was concentrated between 75 and 100% (Fig. 5). With this constricted range, VFSMOD was not able to capture the observed variability in ΔE (R^2 = 0.29, slope of 0.60, and intercept of 38.14%) between the field sites as well as ΔQ (Fig. 5). Using the VFSMOD predicted ΔQ and ΔE with the empirical pesticide trapping efficiency equation (i.e., Eq. [7]), resulted in a highly correlated predicted ΔP compared to measured ΔP (i.e., R^2 = 0.74, slope of 0.84, and intercept of 10.36%), as shown in Fig. 6. Especially when compared with existing pesticide trapping efficiency equations currently utilized in watershed scale models (i.e., Fig. 3), the combined empirical and VFSMOD modeling procedure significantly improved the ability to predict pesticide trapping.

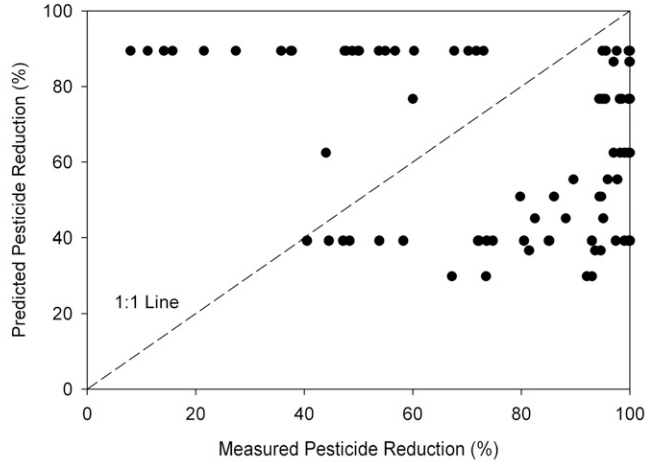

Fig. 3. Linear regression between measured and predicted pesticide trapping (%) when using the Soil and Water Assessment Tool's (SWAT) empirical model based primarily on filter strip width.

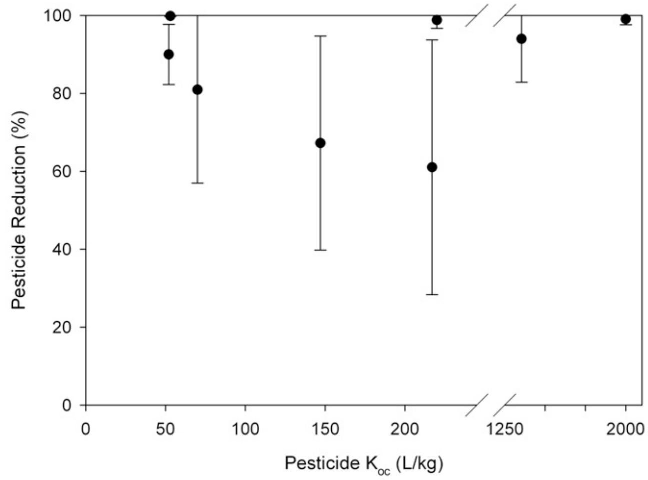

Fig. 4. Relationship between percent of pesticide trapped (%) and the pesticide's organic carbon sorption coefficient, K_{oc} (L kg^{-1}), for the model evaluation studies summarized in Table 3.

Summary and Conclusions

Pesticide trapping cannot be predicted solely from the physical dimensions of the VFS or by considering the chemical properties of the pesticide, but rather from the combined effect of the hydrologic response to the runoff event, which is an implicit function of VFS width, and the distribution of pesticide between the sorbed and dissolved phases. No empirical models currently exist that are functions of the hydrological response of the VFS. An empirical model was constructed in this research using a phase distribution parameter defined as the ratio of pesticide mass in the dissolved phase to pesticide mass sorbed to sediment, the percent reduction in runoff vol-

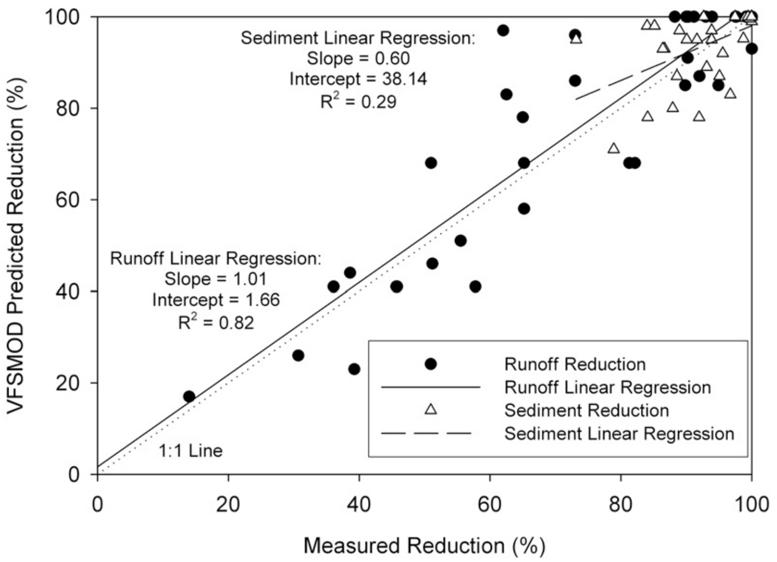

Fig.. 5. Measured versus VFSMOD predicted percent runoff volume reduction (i.e., infiltration) and sediment mass reduction based on model development and validation datasets with sufficient data (Table 5).

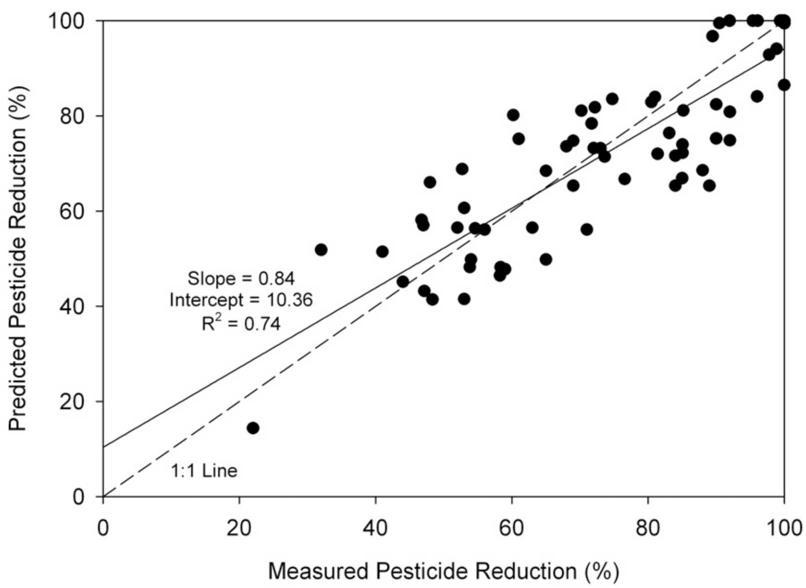

Fig. 6. Measured versus predicted percent pesticide reduction from the vegetated filter strip based on the empirical pesticide trapping efficiency equation developed in this research with percent runoff volume reduction (i.e., infiltration) and sediment reduction predicted by VFSMOD for studies described in Table 5.

ume (i.e., infiltration), percent reduction in eroded sediment (i.e., sedimentation), and the percent clay content of the VFS soil. The empirical model outperformed existing VFS width empirical equations used in watershed scale models and suggested similar observations to previous researchers in regard to the important parameters influencing pesticide trapping for low and strongly sorbed pesticides.

The procedure to link a hydrologic simulation model for the VFS, such as VFSMOD which currently does not possess the capability to physically model pesticide trapping, with the empirical pesticide trapping efficiency equation developed in this research, significantly improved predictions in pesticide trapping over conventional empirical techniques, most of which are based solely on the VFS width. Additional datasets with sufficient data to test the proposed procedure should be identified and evaluated against the modeling procedure proposed in this research.

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