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Dynamics of runoff and sediment trapping performance of vegetative filter strips: Run-on experiments and modeling

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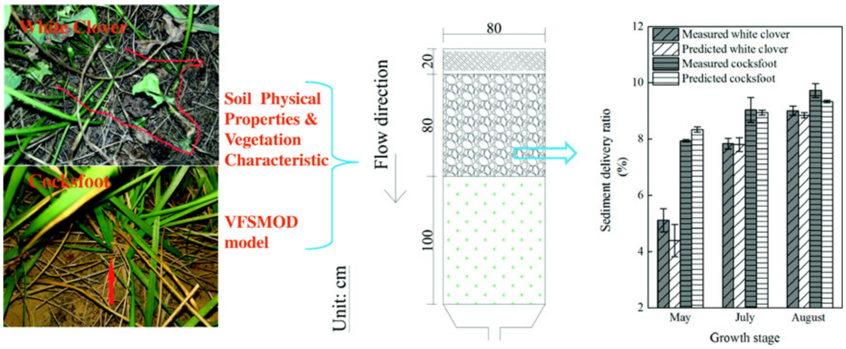
HIGHLIGHTS

- The performance of vegetative filter strips (VFSs) is species- and time-specific.
- Both soil physical properties and vegetation characteristics affect VFS performance.
- Flume experiment and VFSMOD was applied for white clover and cocksfoot VFS.
- Neither soil physical properties nor vegetation characteristics is negligible.
- VFSMOD explained the dynamics of VFS performance well.

GRAPHICAL ABSTRACT



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ABSTRACT

Vegetative filter strips (VFSs) are a labor-saving and cost-effective agricultural best management practice to trap water runoff and sediment from the source areas. They also provide forage and/or fuel and are therefore potentially profitable for land owners. VFSs are however a dynamic system: the runoff delivery ratio (RDR) and sediment delivery ratio (SDR) vary with growth stage and vegetation types. The impacts of vegetation characteristics as well as soil physical properties modified by vegetation growth, on the RDR and SDR of VFS were evaluated by a flume experiment. Two plant species (cocksfoot (*Dactylis glomerata* L.) and white clover (*Trifolium repens* L.)) were tested at three stages in the growing season of 2016 (May, July, and August). The measured RDR and SDR were compared with the simulated results from Vegetative Filter Strip Modeling System (VFSMOD). In the early stages of the growing season, the cocksfoot formed a dense network of stems with high strip Manning's roughness faster than white clover. The runoff and sediment trapping effects of the white clover VFS were greater than that of cocksfoot VFS in all the three stages (lower RDR and SDR). This is likely attributed to strongly tillering, creeping stem posture and high infiltration capacity of the white clover VFS. VFSMOD simulated the RDR and SDR reliably except under low vegetation coverage conditions (white clover in May). The results suggested that (1) both soil physical properties and vegetation characteristics should be

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Acronyms: average wetting front suction, SAV; strip Manning's roughness, RNA; vertical saturated hydraulic conductivity, VKS; saturated water content, OS; average wetting front suction, SAV; initial water content, OI; runoff delivery ratio, RDR; sediment delivery ratio, SDR; vegetative filter strip, VFS; Vegetative Filter Strip Modeling System, VFSMOD; stem spacing, SS; normalized root mean square error, NRMSE; Nash and Sutcliffe coefficient of efficiency, NSE; sensitivity analysis, SA.

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considered for the species-specific, temporally variable performance of VFS; and (2) when using VFSMOD inform the VFS design, modelers should take the dynamics of vegetation, mainly through vertical saturated hydraulic conductivity, stem spacing and strip Manning's roughness into account, and select parameters that reflect the actual field conditions.

1. Introduction

Soil and water loss is a severe environmental problem leading land degradation, flooding, and declines in farm productivity worldwide. Soil and water loss is expected to grow in the context of global climate change and more extreme precipitation events (Francipane et al., 2015; Nearing et al., 2005). Best management practices such as vegetative filter strips (VFSs) can help to reduce surface water runoff and soil erosion (Mekonnen et al., 2015). Vegetative filter strips are vegetated surfaces located in downslope of various urban and agricultural surfaces, where water runoff is produced. As VFS has been demonstrated to be effective, eco-friendly and economically feasible to trap runoff and sediment, it is gaining increasing popularity as an off-site soil and water conservation measure (Mekonnen et al., 2015; Munoz-Carpena and Parsons, 2014; Prosdocimi et al., 2016; Xi et al., 2009).

VFS is a dynamic system with varying performance across vegetation types (Duan et al., 2016; Xiao et al., 2011) and time periods (Dorioz et al., 2006; Lambrechts et al., 2014; Otto et al., 2008). Selection of proper vegetation types and management methods thus become critical issues in the design of VFS (Mekonnen et al., 2016; Otto et al., 2008; Wanyama et al., 2012). Vegetation characteristics, such as plant density, stem diameter, stem posture, plant coverage and height, play significant roles in the runoff and sediment trapping characteristics of VFS (Munoz-Carpena et al., 2010). Because of phenological development and vegetation succession, the vegetation characteristics are constantly changing (Dorioz et al., 2006; Otto et al., 2008; Wanyama et al., 2012). Vegetation characteristics are thus responsible for the species-specific, temporally variable performance of VFS. Further, some soil physical properties such as porosity, soil aggregation, and infiltration capacity could gradually change (Bayabil et al., 2016; Keesstra et al., 2016). Since soil physical properties have direct impacts on soil infiltration and indirect impacts on sediment trapping (Fox et al., 2005; Munoz-Carpena et al., 2010; Xiao et al., 2012), they are another contributor to the dynamic performance of VFS.

To understand the dynamics of VFS performance, several physically based models have been developed, such as GRASSF (Hayes et al., 1984), Vegetative Filter Strip Modeling System (VFSMOD, Munoz-Carpena et al., 1999), TRAVA (Deletic, 2001) or 'Griffith University Soil Erosion and Deposition-Vegetative Buffer Strips 2' (Akram et al., 2015). These models have been widely used to evaluate runoff and sediment trapping mechanisms of VFS and to optimize the design of VFS. Among these models, VFSMOD has been integrated into a design-oriented computer modeling system that includes a graphical and user-friendly interface (Carluer et al., 2017; Munoz-Carpena and Parsons, 2014). To date, VFSMOD has been widely used by decision makers, engineers, and researchers and confirmed to reasonably simulate observations in most cases (Abu-Zreig et al., 2001; Carluer et al., 2017; Fox et al., 2010; Munoz-Capena, 1993). The vegetation characteristics and soil physical properties are mainly parameterized in VFSMOD by: stem spacing (SS), strip Manning's roughness (RNA), and soil vertical saturated hydraulic conductivity (VKS) (Munoz-Carpena and Parsons, 2014). To date, the dynamics of VFS performance under different growth stages and vegetation types are not considered in most of the study cases (Abu-Zreig, 2001; Abu-Zreig et al., 2001; Deletic, 2005; Deletic and Fletcher, 2006; Munoz-Carpena and Parsons, 2004; Yang et al., 2013) using VFSMOD or other physical models except Lambrechts et al. (2014). Thus, there is limited information on whether the current physical models can satisfactorily explain the dynamics of VFS performance.

In this paper, two types of VFS mesocosms (cocksfoot and white clover) were established. The dynamics of runoff and sediment trapping were measured in a flume experiment at three growth stages (May, July, and August 2016) and compared to VFSMOD-simulated results. The objectives of the paper are: (1) to analyze the impact of vegetation characteristics and vegetation-modified soil physical properties on runoff trapping and sediment trapping functions of VFS; and (2) to test the reliability of VFSMOD explaining and predicting the dynamic performance of VFS. We believe that the results will provide information for using physical models such as VFSMOD for the optimized design of VFS.

2. Materials and methods

2.1. Model introduction

VFSMOD is a field-scale, mechanistic, event-based model that describes water transport and sediment deposition and pollutant trapping along the VFS. The model can handle any combination of unsteady storm and incoming hydrograph, spatial distribution of filter parameters such as roughness and slope (along the direction of sloping), and different characteristics of incoming sediments (Munoz-Carpena and Parsons, 2014). VFSMOD involves three main modules: i) kinematic wave overland flow module: a 1-D module for calculating flow depth and rates on the infiltrating soil surface, ii) Green-Ampt infiltration module: a module for calculating the water balance in the soil surface, and iii) sediment filtration module: a module for simulating transport and deposition of the incoming sediment along the VFS. Hydrological model components consist of a quadratic finite element overland flow submodel based on the one-dimensional kinematic wave approximation (continuity and momentum equations) as presented by Munoz-Capena (1993) coupled with an infiltration submodel:

$$\frac{\partial d}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \tag{1a}$$

$$S_0 = S_f \tag{1b}$$

Variables d and q are linked with Manning's uniform flow equation

$$q = q(d) = \frac{\sqrt{S_0}}{n} d^{5/3} \tag{2}$$

where x is the flow direction axis (m), t is the time scale (s), d is the depth of overland flow (m), q is the flow per unit width ($m^2\ s^{-1}$), i_e is the rainfall excess ($m\ s^{-1}$), S_0 is the bed slope ($m\ m^{-1}$), S_f is the slope of the energy gradient or friction slope ($m\ m^{-1}$), and n is the strip Manning's roughness ($s\ m^{-1/3}$). The overland flow module is coupled, for each time step, with an infiltration module based on Green–Ampt's equation for unsteady rain (Chu, 1978):

$$f_p = \frac{K_s + K_s M S_{av}}{F_p} \tag{3a}$$

$$K_s(t - t_p + t_0) = F - MS_{av}\ \ln\left(1 + \frac{F}{MS_{av}}\right) \tag{3b}$$

where f_p is the infiltration rate for ponding conditions ($m\ s^{-1}$), K_s is the vertical saturated hydraulic conductivity ($m\ s^{-1}$), M is the initial soil-water deficit ($m^3\ m^{-3}$), S_{av} is the average wetting front suction (m),