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Impact of plant growth and morphology and of sediment concentration on sediment retention efficiency of vegetative filter strips: Flume experiments and VFSMOD modeling

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SUMMARY

Vegetative filter strips (VFS) implemented downstream to the source of pollution can trap sediments and thus limit sediment export from agricultural fields. However, their retention efficiencies are determined by many factors, among others the type of plant species and its growth stage. The impact of plant growth and morphology, as well as of incoming sediment concentration, on the efficiency of VFS to trap sediments was assessed by means of an experimental flume. Two different plant species were tested, *Lolium perenne* and *Trifolium repens*, after 2 and 4 months of plant growth and for 2 different incoming silty-loam sediment concentrations. Measured retention efficiencies were compared to simulated values using VFSMOD based on goodness-of-fit indicators that take into account uncertainty linked to the measurements.

The sediment storage capacity upstream of the VFS was limited in terms of mass, and therefore an increase in sediment concentration led to a decrease in sediment retention efficiency. After 2 months of plant growth, plant morphology affected the VFS potential to trap sediments, as reflected in the higher retention efficiency of *T. repens* due to its creeping shoot architecture. However, plant growth and development modified the plant morphology and VFS trapping potential. Indeed, *L. perenne* VFS retention efficiency increased from 35% after 2 months of growth to 50% after 4 months, due to the tillering capacity of grass species. Conversely, the trapping efficiency of *T. repens* decreased from 49% to 40% after 4 months. This highlights the possible degradation of VFS with time, which in the case of *T. repens* was due to an increased heterogeneity of plant density within the strips. These modifications of plant characteristics with growth stage, which affected sediment trapping efficiencies, can be effectively integrated into mechanistic models like VFSMOD, mainly through stem spacing and Manning's surface roughness coefficient inputs. Since these parameters were highly conditioned by plant growth and development, modelers should take into account plant dynamics and select plant parameters related to the actual field conditions.

1. Introduction

Vegetative filter strips (VFS) are bands of planted or indigenous vegetation situated downslope of the source of sediment or pollution to provide localized erosion protection and filter sediments from runoff (Dillaha et al., 1989). VFS act on erosion through several mechanisms (Blanco and Lal, 2008; Krutz et al., 2005; Muñoz-Carpena et al., 1999). The increased hydraulic roughness caused by the vegetation and plant debris results in the slowing down of runoff. Plant roots increase the resistance of soils to erosion (Gyssels et al., 2005; Reubens et al., 2007) and may improve the soil permeability, thus decreasing the runoff amount by infiltration as long as the precipitation rate does not exceed the infiltration capacity of the VFS. Reductions in flow velocity and volume jointly decrease the sediment transport capacity of the runoff, thus promoting sedimentation upstream of the VFS as well as within the VFS.

VFS are established best management practices in Europe and the USA to control soil erosion and sediment and agrichemical exports from agricultural fields (Dorioz et al., 2006; USDA, 2000). Many authors have shown the effectiveness of VFS to trap sedi-

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ments. Dorioz et al. (2006) performed a critical review of all the experiments on this topic, and showed that sediment retention ranged from 40% to 100%, with more than 50% reduction in more than 95% of the cases. Dunn et al. (2011) monitored VFS effectiveness in operational farms in Prince Edward Island (Canada) and demonstrated that results under field conditions matched with controlled experiments.

The effectiveness of sediment retention is complex to predict, depending not only on the rainfall and runoff characteristics (rainfall intensity, inflow discharge and velocity, slope, sediment concentration), the VFS area to source area ratio and on the soil and sediment properties (particle size, infiltration, roughness), but also on the vegetation characteristics (width, plant species and density, plant height) as well as on VFS installation and management (Blanco and Lal, 2008; Liu et al., 2008; Muñoz-Carpena et al., 2010; Reichenberger et al., 2007). Some authors focused specifically on the effect of plant parameters. For a given species, it is well-known that an increase in plant cover and density improves sediment retention (Morgan, 2005). However, it is more complicated to quantify the impact of the plant morphology and growth on the trapping efficiency. Fasching and Bauder (2001) tested eight species and showed that plants which produced the greatest amount of shoot biomass in the shortest period of time also produced the greatest basal area and reduced erosion the most. Other studies focused on shoot architecture parameters such as tillering, shoot posture or stem diameter, and demonstrated the impact of shoot architecture on sediment filtration, which acts as a more or less efficient barrier against runoff (Krutz et al., 2005; Melville and Morgan, 2001; Xiao et al., 2011). Therefore, there is a need to better understand the impact of plant morphology for plant species adapted to local environmental conditions. Moreover, differences in plant growth dynamics should be taken into consideration as they impact the efficiency of VFS during the first months after installing the VFS (Dorioz et al., 2006).

Several dedicated models have been developed regarding sediment retention by VFS, such as GRASSF (Hayes et al., 1984), TRAVA (Deletic, 2005) or VFSMOD (Muñoz-Carpena et al., 1999). The Vegetative Filter Strip Modeling System (VFSMOD-W) is a field-scale, mechanistic, event-based numerical model developed to route the incoming hydrograph, sediment and water pollutants from an adjacent field through a VFS and to calculate the resulting outflow, infiltration as well as sediment and pesticide trapping efficiency (Muñoz-Carpena et al., 1999, 2010; Muñoz-Carpena and Parsons, 2004, 2011). Good agreement between observed sediment retention under field conditions and VFSMOD modeling results has been obtained in several studies (Abu-Zreig, 2001; Han et al., 2005; Muñoz-Carpena et al., 1999; Poletika et al., 2009). In conjunction with other tools, the model could be used as a support tool for placement and design of VFS in the field (Dosskey et al., 2006, 2011; White and Arnold, 2009). The impact of plants can be integrated into VFSMOD through several parameters: Manning's roughness coefficient of the VFS (measured in the field or taken from the literature) for the overland flow module of VFSMOD; and the microscale modified Manning's roughness coefficient for cylindrical media, calculated for different plant species (Haan et al., 1994), grass spacing and grass height for the sediment filtration module. Although these parameters change according to plant growth and development, as well as seasons, their variation is not systematically taken into account by modelers.

The main objective of this study was to analyze the impact of plant characteristics on sediment trapping efficiency, taking into account plant growth dynamics, for different incoming sediment concentrations. Both total efficiency and the retention efficiency of the different particle size classes were investigated. An experimental flume was used to assess the sediment retention efficiency of VFS composed of *Lolium perenne* or *Trifolium repens* at different growth stages (2 and 4 months after germination). The experimental results were compared to simulation results from VFSMOD in order to test whether the model could take into account the changes in plant characteristics with growth stage. The use of VFSMOD also helped describe the sediment retention mechanisms by VFS.

2. Materials and methods

2.1. Experimental flume

The experimental flume (Fig. 1) was designed to test the effectiveness of VFS to trap sediments, with the possibility to modify several experimental conditions (slope, runoff discharge, sediment concentration, plant parameters). The device consisted in an inclined board (length: 2 m; width: 1.16 m) coated with small gravel (1–3 mm) with adjustable slope. Runoff (water and a mix of water and sediment) was introduced through 2 inputs at the top of the flume. No water was applied as rainfall. A system of pumps and tubes delivered runoff with a given sediment concentration (coefficient of variation of sediment flow across the board width: 24%).

VFS could be inserted into the experimental flume. They consisted of an iron grid (1 m $\times$ 0.55 m $\times$ 0.05 m) covered with a mosquito net and filled with air-dried, crushed and non-stony silty-loam soil sampled from an agricultural field. For the present experiment, the VFS rested on an impervious substrate, i.e., free drainage was not allowed.

At the outlet of the VFS, water discharge could be measured by means of previously calibrated tipping buckets, and a splitter device (Giboire et al., 2003) allowed collecting a fraction of the runoff for determination of sediment concentration and measurement of sediment physico-chemical characteristics. A detailed description of this experimental flume was reported in Lambrechts (2013).

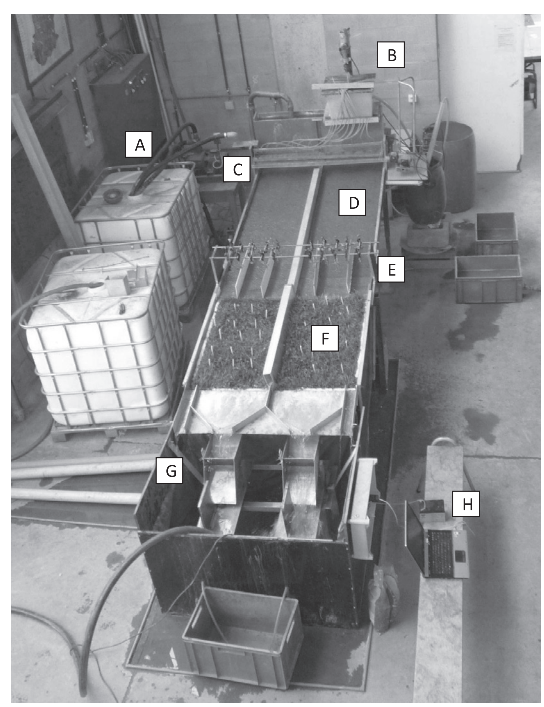

Fig. 1. Experimental flume used to assess the retention efficiency of vegetative filter strips. A: input 1, water tanks + pump; B: input 2, sediment tank + mixers + pump; C: mix and dispersion of inputs; D: inclined rough board with variable slope; E: measurement of water depth; F: vegetative filter strips; G: Measurement of the water discharge and the sediment concentration, tipping bucket with splitter device; H: datalogger.