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Effects of freshly incorporated straw residue on rill erosion and hydraulics

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Abstract

Rill hydraulics (and hence, flow detachment) are modified by the presence of incorporated vegetation residue. Typically, water flow in the rill is retarded due to the extra shear stress generated by the residue. The main objective of this study was to develop an approach to predict soil detachment by rill flow in the presence of freshly incorporated vegetation residue that is compatible with our current understanding of rill hydraulics and requires no additional information on rill geometry. Laboratory experiments were carried out to collect a dataset on rill flow detachment on surfaces with incorporated straw that was compatible with existing dataset on bare soils (Giménez and Govers, 2001).

We found that *effective* unit length shear force, Γ_e, is well related to soil detachment when incorporated residue is present. The determination of Γ_e is based on the recalculation of the wetted cross-section area for a given flow velocity and slope, a hypothetical wetted cross-section area is estimated using empirical relationships defined for rills formed in bare soils. This procedure was also successfully applied to data from former field experiments. The procedure allows estimating erosion rates when flow characteristics (velocity and hydraulic radius) are known. However, the prediction of these flow characteristics remains uncertain.

Keywords: Rill erosion; Straw residue; Vegetation residue; Soil detachment; Rill flow

1. Introduction

Soil erosion by concentrated flow is a serious problem in regions with intense agricultural activity. One of the possible remediation practices is conservation tillage, which is commonly defined as tillage that leaves at least 30% of the soil surface covered by crop (Soil Science of America's Glossary of Soil Science Terms). Many conservation tillage systems for erosion control depend on incorporated residue (*e.g.* straw) from the previous year's crop, which is left in the field as a ground protection against erosion. Recent findings show that the rill hydraulics and erosion can strongly be modified by the presence of different soil cover. Flow velocity is generally lower when soil cover in the form of rock fragments, vegetation or vegetation residue is present (Foster and Meyer, 1975; Foster et al., 1982; Van Liew and Saxton, 1983; Gilley et al., 1987; Prosser et al., 1995; Takken et al., 1998; Nearing et al., 1999; Govers et al., 2000).

Flow detachment in rills without vegetation residue can be well related to flow hydraulic parameters and different flow parameters have been proposed as a measure of rill flow erosivity (see Giménez and Govers, 2002, for an overview). Giménez and Govers (2002) showed that various hydraulic parameters can be used to successfully predict soil detachment in an eroding rill but only total unit length shear force (Γ_t) and shear stress (τ) were capable of directly accounting for variations in bed geometry. The use of other hydraulic parameters, such as stream power, required a separate calibration for different bed geometries.

However, it is obvious that the Γ_t–detachment and τ–detachment relationships developed for bare soil surfaces cannot be used as such when vegetation residue is present in the rill. When vegetation residue is present, the water flow in the rill is retarded due to the extra shear stress generated by the residue. The direct application of a relationship developed for bare soil surfaces would therefore result in the prediction of an increase of soil detachment by rill flow. Yet, various studies have conclusively shown that the increase in friction due to vegetation steams, stones, *etc.*, strongly reduces the erosivity of the flow (*e.g.*, Foster et al., 1982; Van Liew and Saxton, 1983; Govers and Rauws,

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1986; Gilley et al., 1987; Takken et al., 1998). Indeed, the extra shear stress is exerted on the vegetation residue and does not contribute to soil detachment: Additionally, the reduction in flow velocity leads to a reduction of the effective shear stress available for erosion and transport of sediment (Foster and Meyer, 1975; Foster et al., 1980, 1982, Govers and Rauws, 1986).

Considering the importance of the presence of vegetation and/or residue cover for rill erosion, it is not surprising that existing erosion models already contain procedures to account for the effects of vegetation residue on erosion. In empirical models such as the RUSLE or RUSLE-2, effects of residue cover are often accounted for through the application of a so-called cover subfactor (*e.g.*, Renard et al., 1991). Models with more explicit process descriptions such as CREAMS/GLEAMS or WEPP account separately for the different effects of cover (Foster et al., 1980; Gilley and Weltz, 1995). In this type of models, the effect of cover on rill flow and rill erosivity is accounted for by splitting the shear stress into its various components (corresponding to grain, form and/or residue roughness) through attributing a separate friction factor to each of these components. Both procedures based on Manning's equation (*e.g.* Foster et al., 1980) as well on the Darcy–Weisbach friction factor (Gilley and Weltz, 1995) have been implemented. Even more detailed modeling approaches that are based on the explicit description of local modifications in rill hydraulics and erosivity around residue elements have been proposed (*e.g.* Franti et al., 1996a,b) but such approaches are difficult to implement in existing field-scale erosion models due to their high computational and input demands.

The application of existing procedures for shear stress partitioning to rill flow is problematic. It has now been well demonstrated that rill flow is not well described by Manning's equation: When rills can freely erode their bed, velocity is independent of slope due to feedback mechanisms between flow hydraulics and bed morphology (Giménez and Govers, 2001). Similarly, in the WEPP model a constant value for the bare soil Darcy–Weisbach friction factor is proposed (Gilley and Weltz, 1995): Also in this case it is assumed that flow velocity in rills is slope dependent. Thus, existing procedures to calculate effects of vegetation residue on rill flow hydraulics and erosivity are not compatible with recent insights in rill flow hydraulics and its relationship with rill morphology. Another disadvantage is that information on the rill cross-sectional geometry as the hydraulic radius needs to be known: Generally such information is not available.

The main aim of this study was therefore to develop an experimentally tested approach to predict soil detachment by rill flow in the presence of freshly incorporated vegetation residue that is in line with recent insights in rill flow hydraulics and that overcomes these disadvantages. This required the collection of an experimental dataset on rill flow detachment on surfaces with incorporated vegetation residue that was compatible with an existing dataset on flow detachment on bare soils (Giménez and Govers, 2001) so that the effect of incorporated residue on flow hydraulics and erosivity can be isolated as accurately as possible, *i.e.* by reducing effects of soil consolidation, *etc.* to a minimum. These data are presented and analyzed in the first part of the paper. In the second part, an approach to calculate the erosivity of rill flow on surfaces with fresh vegetation residue is proposed: This approach is conceptually similar to existing procedures but accounts for recent advances in our understanding of rill flow hydraulics. Finally, the new procedure is evaluated using field data collected in another study.

2. Materials and methods

2.1. Laboratory experiments

2.1.1. Experimental setup

The experiments were carried out in a 4.30 m long, 0.4 m wide and 0.45 m deep flume using a setup similar to the one described by Giménez and Govers (2001). The upstream part of the flume was filled with soil and then covered with a 1.5 m long plastic sheet over which the water was led to the entrance of the 2.80 m long test section without causing any erosion. The bottom 0.2 m of the test section was filled with a silt loam soil, which was manually compacted to simulate a subsoil. This simulated subsoil was left in place for all experiments. Before each experiment, the test section was filled with a 0.2 m thick layer of the same soil that was used in the bare soil experiments described by Giménez and Govers (2001, Table 1). The soil was air dried and sieved at 0.02 m in order to simulate fine seedbed conditions. On top of this layer a layer with incorporated straw residue was created. In order to do so, a predefined amount of air-dry wheat straw was manually cut in pieces of 0.10–0.15 m long. This was manually mixed with a pre-weighed amount of soil, and put on top of the soil already present in the flume, resulting in a *ca.* 0.01 m thick soil/straw layer. This layer was gently and evenly compacted. This operation was repeated until a homogeneous, 0.07–0.08 m thick layer of a soil/straw mixture was created. The surface was then smoothed with a rake, creating a flat-bottomed longitudinal depression along the centre of the flume of *ca.* 0.15 m wide and *ca.* 0.05 m deep in order to avoid water flowing down along the flume wall. By varying the amount of straw added to the soil various residue application rates were simulated, resulting in a cover percentage between *ca.* 5 and *ca.* 35%. The soil was then gently moistened by spraying until saturation and then left to drain to field capacity. Pictures of the soil surface were taken and the percentage of the surface cover by straw was determined by image process analysis as implemented in the IDRISI software package (Eastman, 1997). Soil moisture, bulk density and vane shear strength were also measured (Table 2).

At the start of the experiment the flume was set at the desired slope and a pre-set discharge was applied at the upper end.

Table 1
Soil characteristics

Grain-size classes (%)			D50 (μm)	Org. matter (%)
<2 μ	>50 μm	2 μm–50 μm		
4.56	23.69	71.75	31.68	0.71

The grain size analysis was done using laser diffractometry (Beuselinck et al., 1998).