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Effect of antecedent soil moisture content on soil critical shear stress in agricultural watersheds

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ABSTRACT

Agricultural fields act as major sources of sediment pollution for surface waters. Grassed waterways are often used as a best management practice to prevent gully erosion and control the amount of sediment delivered from the edge of agricultural fields to receiving water bodies. A widely accepted method for estimating erosion of cohesive soils (excess shear stress equation) involves determining the critical shear stress of the soil and comparing it to the shear stress exerted by the flow. Antecedent soil moisture is an important factor influencing runoff and erosion and understanding the relationship between antecedent moisture and critical shear stress for key features within an agricultural watershed (e.g. field and grassed waterway) can improve soil erosion prediction. Critical shear stress was measured in situ using a Cohesive Strength Meter for varying soil moisture conditions in a 3 × 3 m grid in: (1) a field and (2) a grassed waterway, in an agricultural watershed located in Southwestern Wisconsin. Soil properties including bulk density, organic matter content, plastic limit, liquid limit and plasticity index were also measured. Results showed that critical shear stress in the grassed waterway and in the agricultural field increased as soil moisture increased until the soil moisture content reached a breakpoint that was approximately equal to the plastic limit. Above this breakpoint, critical shear stress of the soil decreased making the soil more susceptible to erosion. Exponential relationships between critical shear stress and soil moisture content below the breakpoint indicate that soil moisture explained more of the variability in critical shear stress for the grassed waterway (68%) compared to the agricultural field (27%). These relationships were used in conjunction with the excess shear stress equation and continuous soil moisture measurements to demonstrate changes in soil erosion rate with changes in soil moisture.

1. Introduction

Sediment is responsible for polluting nearly 11.9% of surface waters in the United States, with agriculture as the most probable contributing source (US EPA, 2013). Accurately estimating the amount of soil eroded and transported from agricultural fields to surface waters is important so that appropriate management practices can be implemented to reduce sediment delivery to receiving waters. Soil erosion can occur in the form of sheet, rill or gully erosion and its magnitude depends on various factors including storm characteristics, soil properties, management and conservation practices (Wischmeier and Smith, 1978; Renard et al., 1991; Pimentel et al., 1995). Soil detachment in rills and gullies occurs when the shear stress exerted by flowing water exceeds the critical shear stress of the soil. The detachment capacity, D_c ($\mathrm{kg \cdot s^{-1} \cdot m^{-2}}$), by flow can be estimated as (Foster et al., 1995),

$$D_c = K(\tau_f - \tau_c) \qquad (1)$$

where, K ($\mathrm{s \cdot m^{-1}}$) is the erodibility parameter, τ_f (Pa) is the flow shear stress acting on the soil particles, and τ_c (Pa) is the critical shear stress of the soil. The erosion process starts when the shear stress exerted by flow surpasses the critical shear stress of soil (Toy et al., 2002).

Ephemeral gully erosion may contribute to high amounts of sediment loss in erosion-prone areas (Laflen, 1985; Thomas et al., 1986; Casali et al., 1999). Grassed waterways are commonly used to convey runoff from agricultural fields and to prevent gully formation. While a properly constructed grassed waterway prevents soil erosion by reducing the runoff velocity and protecting the soil surface, it can also act as a source of sediment through re-suspension of previously deposited material or erosion in areas without sufficient vegetation. For vegetative channels (e.g. grassed waterways), the total shear stress of water is partitioned between vegetal elements (vegetal shear) and soil particles (particle shear) (Einstein, 1950; Graf, 1971; Wilson, 1993; Samani and Kouwen, 2002) and the particle shear stress is used to estimate soil detachment (Eq. (1)).

One of the key factors affecting erosion is antecedent soil moisture (Luk, 1985). Defersha et al. (2011) found that the rate of interrill erosion varied significantly with antecedent moisture content; sediment yield from wet soils was 50% less than from air-dried soils. Le Bissonnais

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and Singer (1992) examined the effects of soil water content and successive rainfall simulations on soil crusting, runoff and erosion from silty clay loam and silt loam soil. They found that runoff and erosion were lower for prewetted soils as compared to initially air dried soils. Le Bissonnais (1996) provides a review of theories of aggregate breakdown, and an analysis of the relations between aggregate breakdown, soil crusting and soil erosion due to water. Le Bissonnais identified slaking (breakdown of soil aggregates due to compression of entrapped air during the sudden intake of water) as one of the major mechanisms for the breakdown of aggregates. Slaking occurs upon rapid wetting of dry aggregates and its effect on aggregate breakdown depends on the volume of air inside the aggregates, the rate of wetting, and the shear strength of wet aggregates (Le Bissonnais, 1996). The review further highlighted the results of other studies (Panabokke and Quirk, 1957; Le Bissonnais, 1988; Truman et al., 1990) that showed that slaking decreases as the initial moisture content increases until saturation. As the water content of the soil increases, the volume of entrapped air decreases. Truman et al. also suggested that disruptive force produced by the entrapped air during the slaking process is greater for drier soil aggregates compared to prewetted aggregates because prewetting reduces the rate of wetting of an aggregate and also increases the cohesion forces that holds aggregates together. Several other studies have shown that antecedent soil moisture condition is an important factor governing runoff generation, erosion and sediment delivery (Truman and Bradford, 1990; Ward and Bolton, 1991; Karnieli and Been-Asher, 1993; Poesen et al., 1999; Mamedov, et al., 2006; Wei et al., 2007; Radatz et al., 2013).

Antecedent soil moisture affects soil shear strength (Luk and Hamilton, 1986). In Luk and Hamilton's rainfall erosion study, soil loss differed by as much as 800 times over a full range of antecedent soil moisture content (wilting point (10%)–saturation (45%)). This difference was attributed to significant changes in soil shear strength with soil moisture content. The authors also showed that the relationship between shear strength and soil moisture changes with wetting and drying cycles. Similarly, Govers and Loch (1993) found that shear strength was higher for soils with initially higher water content compared to initially air dried soils. Manuwa and Olaiya (2012) evaluated the effects of soil moisture and applied pressure on strength indices of soils including shear strength. They observed that shear strength increased with moisture content for soil moistures below the plastic limit; above the plastic limit, shear strength decreased with further increase of moisture content.

While several studies have focused on the relationship between soil moisture and shear strength (Spoor and Godwin, 1979; Luk and Hamilton, 1986; Fan and Su, 2008 and Manuwa and Olaiya, 2012), others have focused on the relationship between soil shear strength and critical shear stress (Krishnamurthy, 1983; Franti et al., 1999; Torri et al., 1987; Rauws and Govers, 1988; Crouch and Novruzi, 1989; Elliott et al., 1989; Merz and Bryan, 1993; Ghebreiyessus et al., 1994; Poesen et al., 1998; Gime'nez and Govers, 2002). Data from these studies were analyzed by Leonard and Richard (2004) and they concluded that a significant linear relationship ($\tau_c = 0.00026\sigma_s$) exists between saturated soil shear strength (σ_s; kPa) and critical grain shear stress (τ_c; Pa).

Critical shear stress is often estimated using soil physical and chemical properties that are assumed to be constant for a given soil, however, critical shear stress can change due to variations in soil moisture, bulk density and composition (Charonko and Wynn, 2010). Critical shear stress has been estimated with relationships developed using physical and chemical properties of soils such as particle size; percent sand, silt, clay, and organic matter; soil water content at 1.5 MPa; and others (Smerdon and Beasley, 1961; Neill, 1973; Simanton et al., 1987; Elliott et al., 1989; Gilley et al., 1993). Given the importance of soil moisture content in runoff generation and soil erosion, understanding the relationship between soil moisture (which can vary significantly both during and between storm events) and critical shear stress is important for accurately estimating soil erosion. To our knowledge no study has focused on the direct relationship between soil moisture and critical shear stress. This relationship is important because critical shear stress is a parameter used in physically-based models for estimating detachment capacity and soil erosion. Furthermore, this relationship may differ among key features within an agricultural watershed (e.g. field and grassed waterway). Agricultural fields can be an important source of soil erosion while grassed waterways represent an important connection between edge-of-field (source) and receiving waters (point of impact).

The overall goal of this study was to further understand the dynamic nature of soil erodibility parameters with moisture content in an

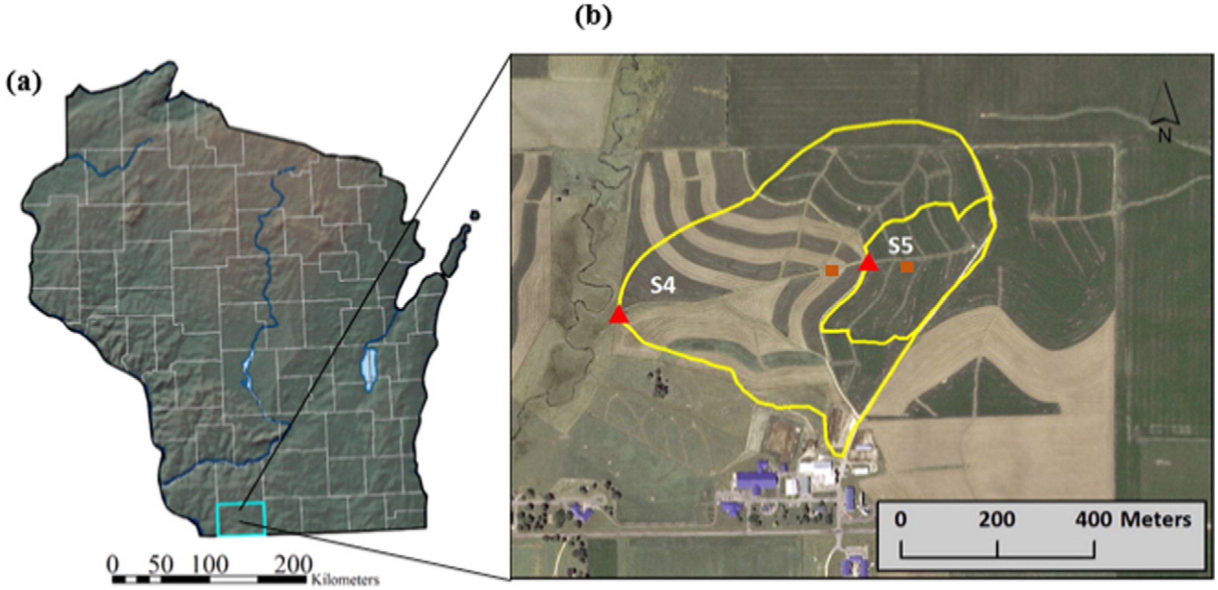

Fig. 1. (a) Location of the UW Platteville Pioneer Farm in Southwestern Wisconsin (b) close up of nested watershed S4 and S5 (basin areas delineated in yellow and locations for water quality sampling stations indicated by ▲) along with the locations of soil moisture and critical shear stress measurements indicated by ■.
Cartography provided by Randy Mentz, Research Program Manager at Pioneer Farm, WI.