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Experimental results and temporal surrogate modeling of particulate organic carbon released during interrill erosion

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ABSTRACT

Despite its temporal nature, the release of particulate organic carbon from soils during interrill erosion lacks high resolution description via experimental datasets and has not been analyzed and predicted with time series approaches that might be adopted research and application. Hence, current research approaches have produced limited success to describe the interrill process that temporally flushes particulate organic carbon off of landscapes and into waterways. Therefore, the goals of this work included three-fold innovative components and was to (i) perform rain simulation experiments and collect a comprehensive particulate organic carbon erosion dataset during erosion; (ii) utilize the dataset to describe particulate organic carbon release as a function of governing transport variables using a multivariate autoregressive model, which is argued as a versatile tool for description of temporal erosion and inclusion within predictive modeling structure; and (iii) to apply a laboratory-based surrogate approach to predict erosion release, in absence of rainfall simulation data, that is coupled with the temporal modeling methodology. Data from the rainfall simulation experiments was collected on agricultural field sites from soils of different textures, including silt and silt loam soils, and with a variety of tillage systems. The experimental datasets reflected both the initial non-equilibrium detachment process followed by near-equilibrium detachment later in the simulations associated with aggregate structure and fluid energy, with the more aggressive tillage systems exhibiting less time to reaching equilibrium. Thereafter runoff and fine sized soil particle release was utilized as predictive variables within autoregressive temporal modeling of the carbon detachment process. The applied variables predicted carbon release well (i.e. 95% of the carbon loss was predicted) and notably both the non-equilibrium and equilibrium phases of erosion was predicted. The surrogate approach was then applied by replacing the variable indicating soil release with a time series of fine soil released during laboratory slaking. Findings show that the temporal stability of the surrogate variables could describe the non-equilibrium and equilibrium detachment for the different soil types and tillage systems. The state space coupled with the surrogate approach proved to be an important and promissory tool to explain the particulate organic carbon release interrill erosion, even in absence of predictive data.

1. Introduction

Interrill erosion is a process that can mobilize large amounts of fine organic carbon within silt- and clay-sized aggregates through selective overland flow (Starr et al., 2000; Polyakov and Lal, 2004; Kinnell, 2012). During rainfall events, the particle size distribution of soil eroded from interrills can change substantially without variation to the total soil loss (Rienzi et al., 2013). The destruction of aggregates in fine particles (or fractionalization) represent a selective means of remove carbon from the terrestrial environment, which is reflected in the temporal distribution of carbon rich silt- and clay-sized aggregates (Rienzi et al., 2013). Surely, the erosion of fine-sized aggregates that lack shear limitations offers a pathway to remove OC continuously from the landscape as well as carry pollutants to waterways (Kjaergaard et al., 2004; Maurice and Hochella, 2008; Rienzi et al., 2015). The high mobility of carbon rich clay/silt sized particles has resulted in numerous study of their widespread occurrence in suspended river sediments (Starr et al., 2000), in the overland flow of croplands (Fox and Papanicolaou, 2007) and also in runoff plots of different dimensions (Polyakov and Lal, 2008). The organic carbon content in clay/silt sized particles from interrills is particularly worthy of quantification because the surface soil carbon will be expected to be composed of more labile, high quality carbon as opposed to more recalcitrant carbon found in deeper rills and gullies (Fox and Ford, 2016). Being an important

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portion of the interrill erosion, the finest particles become a key for explaining the transport of OC, herbicides and other pollutants (Kuhn, 2007; Armstrong et al., 2012; Rienzi et al., 2015). The clay/silt sized particles, different than other particles in the sediment present, provide a large specific surface and electromagnetic charge because the range considered include colloidal properties and hence aggregate structure. Soil colloids are known for their high cation exchange capacity and their ability to facilitate mobilization of pollutants (Estrany et al., 2011; Miller and Karatanasis, 2014). Moreover, this fraction is a natural result of dispersion of aggregates in water (Kjaergaard et al., 2004; Calero et al., 2008), thus always is a component of the soil loss. Yet, there is still much uncertainty surrounding the erosion of clay/silt-sized particles rich in carbon and how to predict their release and movement (Bell et al., 2011; Lal, 2009). The motivation of this paper is towards (i) illustrating the temporal dependence of particulate organic carbon release on hydrologic and sediment parameters through experimental data collection and quantitative statistical modeling and (ii) to work towards a relatively simple lab-based surrogate approach to assist with predicting carbon release during interrill erosion.

The authors find that very little past research has been performed to investigate temporal dynamics of particulate organic carbon released from interrill erosion. Further, the studies that have been performed have been rather qualitative rather than emphasize in depth statistical investigation of time series datasets that might lead to quantitative modeling. For this reason, the authors seek development of an autoregressive description of dynamic organic carbon release during erosion that might allow connectivity with more easily measured and modeled parameters such as the water runoff rate. An autoregressive model is based on the assumption that any process contains information from their recent past. In other words, the present state of a variable measured depends on the past event, the process that brings the variable at the present state, and a certain amount of error.

While application of autoregressive modeling has been thin in the soil erosion literature, the method has been used substantially to study hydrologic processes in streams and across the landscape giving confidence to its applicability to the interrill erosion problem. For example, Worrall and Burt (2004) showed a comprehensive explanation of an autoregressive modeling analysis of the dissolved organic carbon in a river that allowed coupling of dynamic temperature measurements with carbon flux by applying time series decomposition and an impulse function. As another example, Koirala et al. (2010) recently explained the temporal relationship between chloride and dependent variables, including rainfall and water discharge in watersheds, through an autoregressive mobile average model that is coupled with spectral analysis.

The mentioned hydrologic examples where the autoregressive technique was successfully applied share some similarities with the interrill problem, offering the potential for its efficacy, such as (i) measurements that might be used as dependent variables are collected continuously at fixed intervals and (ii) numerous variables can be measured simultaneously as the transport process progress in time. Therefore, it seems that the time is ripe for quantitative methods such as the autoregressive method to be useful for understanding particulate organic carbon release during the interrill erosion of soils (Nielsen and Alemi, 1989; Webster and Heuvelink, 2006).

The authors also find that there is a lack of laboratory calibration measurements that might be useful for assisting with predicting the temporal dynamics of fine organic carbon release from interrill erosion at field sites as well as potentially be useful for more widespread inclusion in hillslope or even landscape scale models in the future. With this need in mind, mechanical shaking and low disturbance slaking tests provide a relatively simple method by which field-based detachment processes can be represented to some degree in the laboratory (e.g., Blanco-Canqui et al., 2009). Mechanical shaking has been suggested to be representative of high kinetic energy erosion-process due to the fact that raindrops impact increases the turbulence of the flowing surface water, and hence the erosive power of overland flow (Bradford et al., 1987; Nimmo and Perkins, 2002; Warrington et al., 2009; Blanco-Canqui et al., 2009). Further, gentle slaking tests with no mechanical energy have been considered to be representative of erosion process under low intensity rainfall (Blanco-Canqui et al., 2009; Blanco-Canqui et al., 2007; Lado et al., 2004). However, the authors find that the particles released during such relatively simple laboratory procedures—or surrogate measurements—has not been investigated for its ability to assist with studying the temporal dynamics of carbon release during interrill erosion.

Understanding the temporal relationship among the different component of the process offers the promise towards uncovering gaps unsolved in the OC release during interrill erosion. In addition, identifying surrogate variables that could help in the modeling of the particulate organic carbon release would be an advantage for soil erosion scientists and practitioners. Therefore, under the hypothesis that the runoff and the amount of fine sediment released from soils holds information to explain the organic carbon mobilization, the objectives of this study were: a) to use a state space approach to gain an understanding of the temporal behavior of clay/silt sized particles and their OC content released from different soils under contrasting tillage systems: and b) to test the efficacy of using surrogate variables for explaining and predicting the OC loss under different scenarios.

2. Material and methods

In order to complete their objectives, the authors follow a series of experimental and analytical steps. First, the authors performed a series of rainfall simulation field-experiments to collect measurements during the interrill erosion process from different soils under varying surface conditions (i.e., till versus no till). Second, the authors performed a set of mechanical shaking and low disturbance slaking tests for the same soils in order that fine sediment released during the laboratory procedures might be tested for predicting organic carbon release during interrill erosion. Third, the authors develop quantitative autoregressive models for their field-based experiments in order to connect the release of particulate organic carbon to hydrologic and sediment variables during the dynamic erosion process. Fourth, the authors test the efficacy of using the results of the mechanical shaking and low disturbance slaking tests as a surrogate within their temporal modeling. As will be discussed in the methods below, and later in the results, the experimental conditions were designed to allow investigation and discussion of both physical and biogeochemical processes impacting OC releases during interrill erosion. Specifically, mechanical energy is well known to represents a primary physical mechanism to cause such interrill erosion, and therefore is focused upon in this paper. Mechanical energy impacts interrill erosion through rainfall intensity, the interrill runoff rate, as well as adjustments for the mechanical energy associated with nozzle variation during experiments (Foster et al., 1995). In our experiments, other physical and biogeochemical processes that can impact interrill erosion were also varied through the selection of numerous soils and management conditions for experimentation. For example, the physical roughness parameter and biogeochemical interrill erodibility parameter will vary from experiment to experiment in our study, and these are known to influence interrill erosion (Foster et al., 1995).

2.1. Rainfall simulation field-experiments of interrill erosion

Rainfall simulation field-experiments of interrill erosion were performed on a silt loam and silt soil in an effort to capture multiple soil types used for agricultural production. The selected soil sites were: a) a continuous corn (*Zea mays L.*) rotation on a Maury silt loam, Typic Paleudalf (Soil Survey Staff, 1999) at the University of Kentucky Agricultural Experiment Station-Spindletop Farm in Lexington, KY, and b) a corn/soybean (*Glycine* max (*L.*) *Merr.*) crop rotation on a Calloway