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Effects of ionic strength, particle size, flow rate, and vegetation type on colloid transport through a dense vegetation saturated soil system: Experiments and modeling

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SUMMARY

Colloids are widely distributed in agricultural runoff, especially from croplands with manure applications. Dense vegetation has been suggested to be effective to reduce surface runoff contaminants, including colloidal particles. In this work, small scale laboratory experiments were used to determine the influence of physical and chemical factors (i.e. solution ionic strength, particle size, surface flow rate, and vegetation type) on the surface transport and removal of colloids in a dense vegetation system without drainage. Conservative tracer studies of bromide were conducted as a control to quantify the deposition of colloids onto grass surfaces and the mass exchange of colloids between the overland flow and soil underneath under various experimental conditions. The deposition of colloids enhanced with increases in solution ionic strength and particle size, and with decreases in flow rate. We also found vegetation type played an important role on colloid transport with more deposition onto Ryegrass than onto Bahia grass under the same experimental conditions. A mathematical model combining overland flow, convection–dispersion equations and exchange layer theory was developed to simulate the transport of colloids in overland flow through the dense vegetation. Simulations of the model fitted the experimental data well and helped to understand the effect of ionic strength, particle size, flow rate, and vegetation type on colloid transport and removal in dense vegetation. Although additional investigations are still needed, findings from this study can inform the installation and maintenance of dense vegetation systems, such as vegetative filter strips, to reduce the loading of colloids in surface runoff.

1. Introduction

Reducing non-point source pollution in agriculture has been one of the most challenging problems for environmental protection. Colloids, which are defined as particles with at least one dimension smaller than 10 μm, are among the most common components in the effluents from agricultural practices (Stumm, 1977). Waste discharges from animal feeding operations may include both abiotic and bio-colloids; agricultural irrigation would mobilize particulate phosphorus and other forms of colloidal particles in soils; rain-fall induced soil erosion on farm land could also bring large amount of colloidal clay minerals into surface runoff and into the adjacent water bodies (Ryan and Elimelech, 1996; Steenhuis et al., 2006). Mobile colloids in hydrological paths can deteriorate the water quality not only because some of them are natural-born contaminants (e.g., pathogenic bacteria and viruses), but also because they can facilitate the transport of other highly reactive contaminants in streams and groundwater (Gao et al., 2011; McCarthy and Zachara, 1989; Sen and Khilar, 2006; Sun et al., 2010). Once entering surface waters and drinking water aquifers, these colloids present a risk to the public health.

Although extensive research has been conducted to reduce the contamination risks of colloids in groundwater, only several studies in the literature have explored the removal and transport of colloids in surface runoff (Fox et al., 2011; Wu et al., 2011; Yu et al., 2011). In addition, previous studies of sediment transport in surface runoff often treated colloidal particles as dissolved phase if they can pass through a 0.45 μm filter (Haygarth et al., 2006; Lead and Wilkinson, 2006). Due to the nature of the surface runoff to rapidly transfer contaminants, mobile colloids in the surface runoff may present high contamination risks to the environment because they can efficiently facilitate the transport of various water pollutants such as nutrients, heavy metals, persistent organic pollutant (POPs) and pathogens (Haygarth et al., 2006; Heathwaite et al., 2005; Kouznetsov et al., 2007; Ren and Packman, 2005). Nutrients attached onto colloids can cause eutrophication in lakes or rivers. Heavy metals' toxicity can result in damage of vital organs of living

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organisms. POPs can also threat the health of whole ecosystem when they are in the food chain. Pathogens in surface water may cause serious problems to public health, particularly with respect to disease outbreaks.

Natural (grasslands and meadows) or implanted (vegetative filter strips, VFS) dense vegetation is widely used in agricultural lands for non-point source pollution control. It is suggested that a well-installed VFS typically removes sediments (up to 90%), phosphorus (50–75%), nitrogen (50–87%), and pesticides (40–96%) (Dosskey et al., 2007; Fox et al., 2010; Koelsch et al., 2006; Muñoz-Carpena et al., 2010; Reichenberger et al., 2007). In addition, dense vegetation has been found to be effective in removing colloidal particles from surface runoff. A number of studies have been conducted to investigate the removal efficiency of VFSs to fecal bacteria from manure and suggested that dense vegetation could reduce the loading of pathogens from surface runoff (Fox et al., 2011; Guber et al., 2007; Trask et al., 2004). Our recent study in a laboratory setting also demonstrated that dense vegetation grown on a sandy soil box (1.5 m by 0.5 m) can effectively remove abiotic colloids from runoff with a total removal rate close to 67% (Yu et al., 2012). This high removal of colloids by the dense vegetation system could be attributed to the combined effects of both the adsorption of colloids in overland flow onto the plant and the filtration of colloids in drainage by the soil underneath (Yu et al., 2012).

Several physicochemical factors have been identified as important to the effectiveness of VFS to remove chemical solutes and sediments from runoff including pollutant characteristics, hydrological loading, preferential flow patterns, vegetation composition and density, soil properties, and the physical dimensions of the filter strip (Barfield et al., 1998; Geza et al., 2009; Fox et al., 2010; Muñoz-Carpena et al., 2010). Although a number of studies have explored the impact of these factors on sediment removal by VFS (Barfield et al., 1979; Tollner et al., 1976, 1977), relatively few investigations have been conducted to determine their impact on colloid filtration and transport in dense vegetation. In laboratory experiments Tate et al. (2004) and Trask et al. (2004) found that land slope, vegetation density, and rainfall intensity are among the most important factors that control the removal of *Cryptosporidium parvum* released from cattle feces on soil surface. Similarly, Fox et al. (2011) demonstrated the importance of inflow rate, infiltration capacity, and initial concentration on filtration of *Escherichia coli* by dense vegetation in a laboratory VFS soil box. Field experiments conducted by Ferguson et al. (2007) showed that colloid size was critical in controlling the mobility of microorganisms (bio-colloids) in dense vegetation. Additional investigations, especially integrated systematic experimental and modeling studies, are thus needed to advance current understanding of the physicochemical determinants of colloid removal in dense vegetation.

This study was designed to explore the impact of dense vegetation and soil mass exchange on the transport and filtration of colloids under various physicochemical conditions. To better understand the interaction of colloids in overland flow with dense vegetation, a small scale vegetation system with grass growing in soil boxes without drainage was used in the experimental study. Laboratory experiments were conducted to determine the effects of flow ionic strengths, flow velocities, colloid sizes, and vegetation types on colloid removal by the vegetative system in overland flow without drainage. The experiment data were interpreted with the aid of a conservative tracer (bromide) study conducted simultaneously on the same dense vegetation system, and with mathematical models. Our objectives were to: (1) understand the effect of physicochemical factors, including ionic strength, colloid size, flow rate and vegetation types, on the attenuation and transport of colloidal particles in the dense vegetation system and (2) develop and test mathematical models to simulate the fate and transport of colloids in overland flow through the dense vegetation system.

2. Materials and methods

2.1. Materials

Carboxylated polystyrene latex microspheres (Magsphere, Inc.) with sizes of 0.3, 2.0, and 10.5 μm were chosen as experimental colloids, because they are commonly used as surrogates for both abiotic and biotic natural colloids (Gao et al., 2006; Morales et al., 2009). The microspheres were labeled with yellow/green fluorescence dye and had a density of 1.05 g/cm^3. In the experiment, colloid input concentration was adjusted to about 11 mg/L by diluting the stock microsphere suspension. Sodium bromide (certified, Fisher Scientific) was used in the experiment as a conservative tracer. The bromide was added to the microsphere suspension to achieve a concentration of 40 ppm, and the inflow solution of bromide and colloids was applied to the surface runoff system.

Quartz (silica) sand (Standard Sand & Silica Co.) was used as experimental soil. The sand had a size range between 0.5 and 0.6 mm and a bulk density of 1.54 g/cm^3. The sand was used as received and was packed in a small size soil box measured 20.3 cm long, 19.1 cm wide, and 9.9 cm deep (Fig. 1). The soil box was made of clear polyvinyl chloride (PVC). Sand was packed in the box to a depth of 5 cm.

Bahia grass (*Paspalum notatum*) and Perennial Ryegrass (*Lolium perenne L.*), which are drought resistant turf grasses, were selected as experimental vegetation, because they require low maintenance and are best for warm and humid climate. Grass seeds were planted 1 cm deep in the soil box with a density of 76 g/m^2. The vegetated soil box was then irrigated and fertilized for about 3 months in green house to create dense vegetation (average distance between the stem was <2 cm). The height of the dense vegetation was maintained at 8 cm by manual clipping.

2.2. Runoff experiment

Surface runoff experiments were conducted using the vegetated soil boxes under different physicochemical conditions (Fig. 1). Because this study was designed to study colloid transport in surface flow, no soil drainage was allowed to prevent subsurface flow during the experiments (different from the experiment setup of Yu et al. (2012) that considered soil drainage flow). To start a transport study, colloid-free water was first applied to the vegetated soil boxes for about an hour using a peristaltic pump to pre-saturate the soil and to ensure all the flow occurred as overland flow after reaching steady flow conditions. Once the overland flow stabilized, the experiment started and the inflow was then switched to the experimental solution containing both colloid and bromide. The solution was injected to the dense vegetation box through the inflow spreader as a 10 min pulse. After that, the inflow was switched back to regular tap water to flush the mobile colloids out of the system. Surface runoff samples were collected during the experiment at small time intervals. A fluorescent spectrophotometer (Perkin Elmer LS 45) was used to determine colloid concentrations in the samples at wavelengths of 488 nm (exciting) and 509 nm (emission). Bromide concentrations in the samples were determined by an ion chromatograph (Dionex Inc. ICS90). Duplicate or triplicate experiments were conducted for the transport experiments. Average breakthrough concentrations were reported with experimental ranges. The effects of flow rates, ionic strengths, colloid sizes, and vegetation types on the microspheres and bromide transport and retention in the dense vegetation were tested. The mean ionic strength of tap water in the US is relatively