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Field flume reveals aquatic vegetation's role in sediment and particulate phosphorus transport in a shallow aquatic ecosystem

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ABSTRACT

Flow interactions with aquatic vegetation and effects on sediment transport and nutrient redistribution are uncertain in shallow aquatic ecosystems. Here we quantified sediment transport in the Everglades by progressively increasing flow velocity in a field flume constructed around undisturbed bed sediment and emergent macrophytes. Suspended sediment <100 μm was dominant in the lower range of laminar flow and was supplied by detachment from epiphyton. Sediment flux increased by a factor of four and coarse flocculent sediment >100 μm became dominant at higher velocity steps after a threshold shear stress for bed floc entrainment was exceeded. Shedding of vortices that had formed downstream of plant stems also occurred on that velocity step which promoted additional sediment detachment from epiphyton. Modeling determined that the potentially entrainable sediment reservoir, 46 g m^{-2}, was similar to the reservoir of epiphyton (66 g m^{-2}) but smaller than the reservoir of flocculent bed sediment (330 g m^{-2}). All suspended sediment was enriched in phosphorus (by approximately twenty times) compared with bulk sediment on the bed surface and on plant stems, indicating that the most easily entrainable sediment is also the most nutrient rich (and likely the most biologically active).

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1. Introduction

1.1. Physical–biological interactions in river and floodplain corridors

Feedbacks between hydrologic and ecologic processes are integral to the function of flowing aquatic ecosystems. Flood pulses deliver dissolved and particulate materials to surrounding floodplains that later slowly release particulate carbon, nutrients, and other energy-rich compounds back to the channel (Tockner et al., 2010; Noe and Hupp, 2009). Exchange between main channels and storage areas (e.g. slowly moving waters at channel margins and in streambed sediments) occurs under all flow conditions, and has similar effects in promoting storage and processing of solutes, fine sediments and associated carbon and nutrients (Newbold et al. 2005; Poole et al., 2008; Harvey et al. 2003). Redistribution of materials and energy between zones of fast moving flow and more slowly flowing areas further influences redox conditions and bacterial activity within sediments that affect metabolism and associated ecosystem functions (Odum et al., 1995; Middleton, 2002). Although coupling between channels, floodplains, and other storage areas is widely recognized (Junk et al., 1989; Bayley, 1991; Galat et al., 1998; Tockner et al., 2000), the transport processes are not necessarily well understood. In particular, there are many uncertainties about the transport of fine organic sediment and associated nutrients, and the role of vegetation in altering sediment transport. Yet the physical–biological interactions and resulting effects on sediment and nutrient redistribution are arguably some of the principal drivers of ecological function and hydrogeomorphic evolution of aquatic systems (Larsen et al., 2007; Bendix and Hupp, 2000; Tabacchi et al., 2000) and deserve more study. Attention is needed to understanding hydraulic, hydrogeomorphic, and biological controls on sediment and nutrient transport if the valuable functions of stream and river corridors are to be effectively preserved under increasing stresses of urbanization and climate change (National Research Council, 2002).

Compared with mineral particles, organic and organic–mineral sediment mixtures generally have lower densities and lower thresholds for entrainment from the sediment bed (Larsen et al., 2009a) and tend to be more varied in their sources and composition. Organic-rich sediment is typically composed of aggregates of detrital organic material and bacteria joined with varied types and sizes of mineral material (Lick et al., 1992; Sterling et al., 2005). Flocculation significantly influences fluxes and redistribution of sediment and associated nutrients or contaminants (Walling and Moorhead, 1989; Droppo, 2003, 2004). Predicting floc transport presents many challenges, as floccules vary widely in size, porosity, and density as determined by the type of organic matter, mineral sources and the nature of interparticle bonds (Logan and Wilkinson, 1990). Additional complexities include precipitation of minerals such as calcium carbonate which often occurs in periphyton mats and contributes to floc formation in hard water ecosystems (Browder et al., 1994) and

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also bacterial release of large quantities of extracellular polymeric substances that increase the strength of individual flocs (Simon et al., 2002; Battin et al., 2003; Wotton, 2007) and raise the bed shear stress needed to entrain floc (Gerbersdorf et al., 2008).

Emergent vegetation in shallow aquatic ecosystems plays a major role in determining flow velocity and turbulence characteristics that influence transport of flocculent sediment (Leonard and Luther, 1995; Leonard and Reed, 2002) and could also play a role as a source or sink for sediment (e.g. Elliott, 2000). Whether vegetation increases or decreases suspended sediment transport depends on how drag, near-bed turbulence, and entrainment are affected by flow interactions with stem diameter, density, and variability in the spatial arrangement and vertical changes in plant architecture (Nepf, 1999; Nezu and Onitsuka, 2001; Harvey et al., 2009). Most field investigations have observed that vegetation decreases suspended sediment concentrations (Braskerud, 2001; Leonard and Reed, 2002), either by increasing sediment deposition rates (Leonard and Reed, 2002; Leonard et al., 2006), or by direct trapping of sediment on stems and leaves (Saiers et al., 2003; Palmer et al., 2004; Huang et al., 2008). Vegetation also is suspected to serve as a source of suspended particles due to sloughing or hydraulically-driven detachment of fine sediment trapped by epiphyton on plant leaves, although direct observations of that process are scant.

1.2. Hydrogeomorphology of the Everglades, a low-gradient floodplain ecosystem

The Everglades is comprised of elongated, flow-parallel ridges and sloughs that formed several thousand years ago (Willard and Cronin, 2007; Bernhardt and Willard, 2009) (Fig. 1). The topographic and vegetation features are strikingly similar to other low-gradient, floodplain wetlands found worldwide that are valued for their relatively high biodiversity and high connectivity of habitats (e.g. Ellery et al., 2003; Stanturf and Schoenholtz, 1998). The past century has seen a rapid disappearance of the ridge and slough landscape pattern over large areas of the Everglades including flattening of the topography, greater homogeneity in vegetation, lower species diversity, and disruption of the connectivity of sloughs that otherwise provide migration corridors for aquatic organisms (National Research Council, 2003). Degradation of the Everglades ridge and slough ecosystem is in part attributable to altered water levels, though ridge-slough pattern loss has also occurred in areas where water levels have not changed substantially from historic conditions (National Research Council, 2003; Zweig and Kitchens, 2009). A leading hypothesis for ecosystem change is that the diminished peak flow velocities in the central Everglades that are presently on the order of 1 cm s^{-1} (compared with peak velocities approximately 6 times higher in the historic Everglades) are now insufficient to entrain floc and redistribute its associated carbon, nutrients, and mineral material from sloughs to the ridges (Larsen et al., 2007). The result in many areas is that ridge vegetation is expanding into the remnant sloughs, contributing to vegetative homogenization and topographic flattening over a significant proportion of the Everglades in just a century (Givnish et al., 2008), with a resulting loss of biodiversity and connectivity of Everglades habitats, two of the highly valued functional attributes of the Everglades.

This paper presents a flow experiment quantifying entrainment, size, and particulate phosphorus characteristics of naturally mobilized Everglades sediment as a function of flow velocity and bed shear stress (Fig. 1a). Our goal was to gain a better overall understanding of how flow affects organic sediment and phosphorus redistribution, a topic that is of crucial importance to Everglades restoration and more generally to streams and wetlands that are managed to optimize retention of suspended sediment and nutrients (Kadlec and Knight, 1996). We tested whether the higher flow velocities representative of the historic Everglades are sufficient to redistribute sediment and associated phosphorus from sloughs to ridges and thus contribute to long-term preservation of this topographically and biologically diverse landscape. Our study was needed because previous flume studies conducted in the Everglades either did not examine sediment transport (Gaiser et al., 2005), did not manipulate flow (Huang et al., 2008), used introduced “model” sediments that are not representative of the size and density characteristics of natural floc (Saiers et al., 2003), or, were conducted in laboratory flumes where the role of vegetation could not be examined (Larsen et al., 2009a, 2009c).

We increased flow in steps in a field flume and simultaneously measured floc mobilization, which allowed us to estimate the size of several important floc reservoirs (e.g. floc associated with epiphytic coatings on plant stems and floc on the bed surface) and to determine distinct hydraulic thresholds for entrainment from each of those reservoirs. Working in a field flume rather than a laboratory flume also had the advantage of minimizing disturbance that disrupts biofilms that strengthen floc. Our experiment allowed us to determine, possibly for the first time, the role of sediment resuspension from epiphyton and its contribution to downstream fluxes of suspended sediment and associated phosphorus. The results provide insight how future water management changes in the Everglades and elsewhere in other low-gradient aquatic ecosystems could affect redistribution of sediment and associated nutrients.

2. Materials and methods

2.1. Field site

The USGS experimental flumes are located in central Water Conservation Area 3A (26° 03′ 23.7″ N, 80° 42′ 19.2″ W) (Fig. 1). The Water Conservation Areas (WCAs) are large basins enclosed by levees that were constructed during the 1950s and 1960s for the dual purpose of managing water supply for the growing population of southeastern Florida while also allowing regulation of water flow to Everglades National Park farther to the south. The WCAs helped water managers ameliorate the excessive drying of the Everglades that occurred in the early and mid 1900s as a result of drainage and flood control measures. However, the WCAs also have drastically reduced flow velocities compared to pre-drainage conditions. Central WCA-3A was selected for the experiments because it has the best preserved area of the parallel-drainage ridge and slough landscape (Fig. 1a). These characteristic features consist of elongated sawgrass ridges (300–1000 m long by 60–160 m wide) interspersed with somewhat wider and less densely vegetated sloughs (140–360 m wide) in approximately a NNW–SSE alignment (Fig. 1b). Sloughs have a diverse assemblage of vegetation such as water lily (*Nymphaea odorata*), spikerush (*Eleocharis elongata*, with sparse *E. cellulosa*) with associated epiphyton, and floating bladderworts (*Utricularia purpurea*) and associated metaphyton (Fig. 1c). Ridges are typically 20–30 cm higher than intervening sloughs and are densely colonized by a nearly monospecific stand of sawgrass (*Cladium jamaicense*) (Fig. 1d). The ground surface in sloughs currently is approximately 20 cm lower than ridges with the transition from slough to ridge vegetation occurring over a 10–20 m horizontal distance.

The Everglades substrate is composed of organic peat formed by incomplete decomposition of plant material. On the surface of the peat is a layer of loosely consolidated floc that is dominantly organic matter (65% according to Bazante et al., 2006) and includes a range of floccule sizes (Larsen et al., 2009a) that are derived from various sources (Noe et al., 2007). Periphyton is a ubiquitous source of floc on submerged plant stems. It is composed of algal cells, macrophyte pieces, microbial cells, extracellular polymer substances, animal feces, and geochemical precipitates (principally calcium carbonate). When attached to stems and leaves of rooted aquatics, periphyton is referred to as epiphyton and when present in thick coatings on floating vegetation at the water surface it is referred to as metaphyton.