Wetlands (2010) 30:39–54
DOI 10.1007/s13157-009-0002-5

ORIGINAL PAPER

Controls of Suspended Sediment Concentration, Nutrient Content, and Transport in a Subtropical Wetland

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Received: 12 August 2008 / Accepted: 17 August 2009 / Published online: 9 December 2009

Abstract Redistribution of largely organic sediment from low elevation sloughs to higher elevation ridges is a leading hypothesis for the formation and maintenance of the native ridge and slough landscape pattern found in peat wetlands of the Florida Everglades. We tested this redistribution hypothesis by measuring the concentration and characteristics of suspended sediment and its associated nutrients in the flowpaths of adjacent ridge and slough plant communities. Over two wet seasons we found no sustained differences in suspended sediment mass concentrations, particle-associated P and N concentrations, or sizes of suspended particles between ridge and slough sites. Discharge of suspended sediment, particulate nutrients, and solutes were nearly double in the slough flowpath compared to the ridge flowpath due solely to deeper and faster water flow in sloughs. Spatial and temporal variations in suspended sediment were not related to water velocity, consistent with a hypothesis that the critical sheer stress causing entrainment is not commonly exceeded in the present-day managed Everglades. The uniformity in the concentrations and characteristics of suspended sediment at our research site suggests that sediment and particulate nutrient redistribution between ridges and sloughs does not occur, or rarely occurs, in the modern Everglades.

Keywords Entrainment · Everglades · Nitrogen · Particle · Phosphorus

Introduction

Wetlands are known to effectively trap suspended sediment from flowing waters (Boto and Patrick 1979; Phillips 1989). This process has been employed in treatment wetlands, which are often designed to remove suspended sediment from inflowing waters and typically have high sediment removal efficiency (e.g., Kadlec and Knight 1996; Coveney et al. 2002). The loading of sediment-rich waters to coastal wetlands also is used as a restoration tool to enhance sediment accumulation and thereby alleviate soil subsidence (DeLaune et al. 2003). Within wetlands, the fluxes of suspended sediment are controlled by vegetation, water flow, and wind (Kadlec and Knight 1996). Wetland vegetation decreases water velocity (Leonard and Luther 1995; Leonard and Reed 2002; Leonard et al. 2002), decreases turbulence intensity (Leonard and Luther 1995; Leonard et al. 2002), and also directly traps suspended sediment on stems and leaves (Saiers et al. 2003; Palmer et al. 2004). These vegetation-induced changes can result in lower concentrations of suspended sediment (Braskerud 2001; Leonard and Reed 2002), greater sediment deposition rates (Leonard et al. 2002), or decreased resuspension of sediments in densely vegetated portions of wetlands (Braskerud 2001). These dynamics of suspended sediment also are important for controlling phosphorus (P) cycling and transport in aquatic ecosystems (Fox 1993; Froelich 1988; Kadlec 1999), with intermediate removal rates of particulate P compared to faster soluble reactive P removal or slower dissolved organic P removal in wetlands (Davis 1981; Farve et al. 2004; White et al. 2004).

Suspended sediment transport and retention also likely have important roles in the ecosystem dynamics of subtropical Everglades wetlands and other patterned peat-

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lands. The pattern of alternating peat-based ridges and sloughs was the dominant landscape type in the pre-drainage Everglades (Davis et al. 1994). This mosaic was typified by a 'corrugated' topographic pattern, comprised of long strands of low-elevation sloughs of sparse vegetation adjacent to higher-elevated ridges of dense *Cladium jamaicense*, with both patterns oriented parallel to the primary direction of water flow (Science Coordination Team 2003). However, recent human activities have altered hydroperiods and water depths and reduced surface-water velocities, resulting in decreased peat elevation differences between ridges and sloughs and encroachment of wet prairie and *C. jamaicense* vegetation into sloughs (Davis et al. 1994; Sklar et al. 2002; Ogden 2005). One of the goals of the Comprehensive Everglades Restoration Plan is to restore the ridge and slough mosaic by returning the hydrology to a more natural pattern of water depths and flow velocities (Sklar et al. 2005). Successful restoration will rely on understanding the mechanisms for ridge and slough maintenance and degradation. Redistribution of sediment from sloughs to ridges—greater rates of downstream sediment transport in sloughs and greater sediment deposition rates in ridges—in conjunction with control of autochthonous peat production by water level is the leading conceptual model for the regulation of spatial patterning of ridge and slough topography (Science Coordination Team 2003; Larsen et al. 2007).

Despite the hypothesized role of suspended sediment, the rainfall-driven, oligotrophic, and P-limited Everglades does not receive meaningful inputs of terrigenic sediment (Noe et al. 2001). As a result, suspended sediment in Everglades wetlands is composed of small and largely organic particles that are not abundant (Bazante et al. 2006; Noe et al. 2007). Surface water flow in the Everglades typically has a very low velocity (Leonard et al. 2006; Harvey et al. 2009) that should in general minimize sediment entrainment. The greater aboveground biomass of vegetation in ridges than sloughs (Childers et al. 2003; Noe and Childers 2007) leads to reduced water velocities in ridges (Harvey et al. 2009) and should result in greater sediment deposition rates. The greater water velocities in sloughs also likely increase sediment entrainment rates relative to ridges (Larsen et al. 2009a). These ecohydrological processes should lead to lower suspended sediment concentrations in ridge than in slough flowpaths. In addition to water velocity and vegetative controls, winds and daily thermal stratification/destratification of the water column in Everglades wetlands (Schaffranek and Jenter 2001) could influence suspended sediment dynamics. Suspended sediment has been shown to be important to P cycling (Noe et al. 2003) and surface water P concentrations in the Everglades (Noe et al. 2007). Since P controls primary productivity and decomposition, and ultimately geomorphology in the peat-based Everglades, sediment-associated P transport and redistribution may have important consequences for ridge and slough dynamics. In summary, the factors that control redistribution of the autochthonous organic sediment in the Everglades are likely critical to understanding and restoring ecosystem processes.

Little is currently known about the vegetative, hydrologic, or meteorological controls of the abundance and biogeochemical characteristics of suspended sediment in the Everglades or other wetland ecosystems. Here we present a study with the goals of testing for differences in the concentrations and downstream flux of suspended sediment and its associated nutrients in ridges and sloughs of Everglades peatlands, and identifying controls on the dynamics of suspended sediment. We specifically tested the following hypotheses in an area of the Everglades with a well preserved remnant ridge and slough mosaic: 1) suspended sediment and particulate nutrient concentrations are lower in ridge than slough flowpaths, 2) spatiotemporal variation in suspended sediment and particulate nutrient concentrations are controlled mostly by surface water velocity, and 3) downstream flux of suspended sediment and particulate nutrients is greater in sloughs than ridges.

Methods

Site Description

The USGS research site (WCA3A-5; 26° 03.366′ N, 80° 42.331′ W) was chosen because it is representative of the remnant ridge and slough landscape in central Water Conservation Area 3A (WCA-3A) of the Everglades (Fig. 1). Reconnaissance verified that the site has typical topography, landscape orientation, water quality and clarity, vegetation, and peat soils for central WCA-3A. The site also was chosen because the slough has relatively great connectivity with other sloughs, minimal encroachment by *C. jamaicense*, and a distinct and abrupt ridge-slough transition (Fig. 1; Harvey et al. 2009). The ridge and slough permanent sampling locations at site WCA3A-5 were positioned 14 m apart on the upstream side of installed instrumentation platforms where they were minimally disturbed by research activities. Dominant vegetation was *C. jamaicense* in the ridge and *Eleocharis elongata*, *Nymphaea odorata*, *Bacopa caroliniana*, and periphyton in the slough, with greater aboveground biomass and biovolume in the ridge than the slough (Harvey et al. 2009). Peat surface elevation was 20 cm greater on the ridge than the slough. The ridge and adjacent slough on which the sampling platforms were installed were 90 m and 85 m

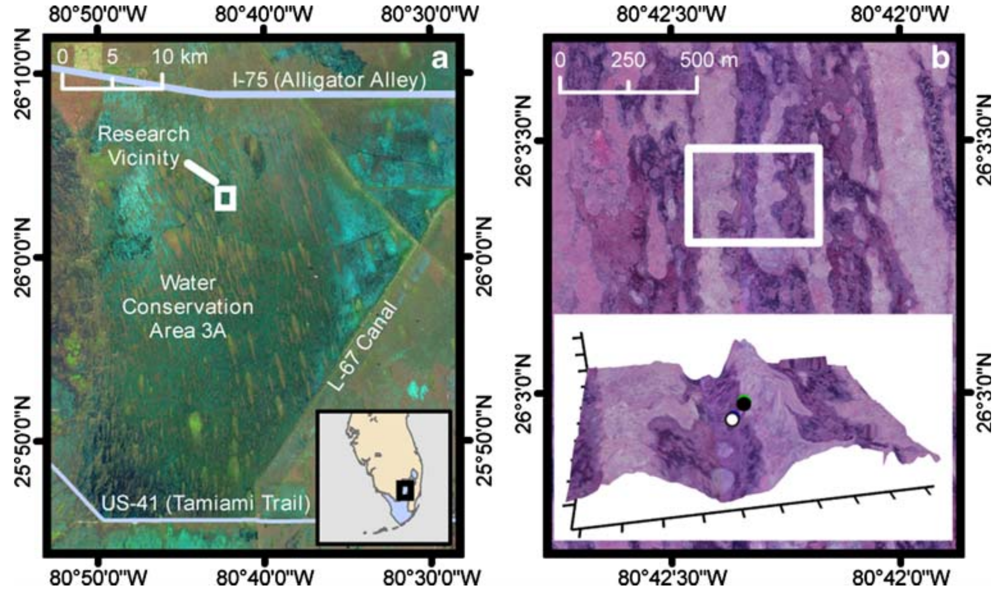

Fig. 1 Location of research site WCA3A-5 in the remnant ridge and slough landscape of Water Conservation Area 3A in the central Everglades, Florida. **a** Aerial false-color photograph of the patterned wetland landscape in Water Conservation Area 3A showing general location of research. The inset in panel A shows the location of Water Conservation Area 3A in south Florida. The *rectangle* indicates the research area shown in panel B. **b** False-color digital orthophoto quadrangle (DOQ) image of the research vicinity that defines outlines of ridges (*lighter*) and sloughs (*darker*). The inset in panel B shows a three-dimensional image of landscape topography for the 500 × 300 m area surrounding the velocity measurement sites in the slough (*white circle*) and ridge (*black circle*). The vertical and horizontal scaled increments of the topographic plot represent 0.1 and 50 m, respectively. Sloughs are the *darker shade of grey* and ridges are *lighter grey*

wide, respectively, and followed a roughly north-south bearing that was oriented parallel with the dominant direction of surface water flow (Fig. 1). We chose a strategy of intensively sampling a single, representative paired ridge and adjacent slough as the best test of our objectives to relate suspended sediment dynamics to vegetation as well as hydrology and meteorology, which are not feasibly measured at both sufficiently detailed time scales and multiple locations in this low flow and low sediment concentration setting.

Suspended Particle Sampling

Sampling generally occurred every 4–5 weeks throughout the 2005 and 2006 wet seasons when water levels were sufficient to allow access to the field site by airboat (Fig. 2). Samples at both the ridge and slough sites were collected between 0900 and 1400 hr on the same days, typically from three depths of the water column (i.e., upper, middle, lower). In addition to the normal daytime sampling, night-time sampling occurred from 2200–2400 hr (timed after the water column had thermally destratified) in conjunction with a daytime sample collected from 1100–1300 hr on 8 November 2005. During times of higher water depths (generally >30 cm), the upper sampling depth was located 10 cm below the layer of floating *E. elongata* stems with periphyton or 10 cm below the water surface when floating periphyton was absent. The bottom depth was located 10 cm above the floc layer, and the middle depth was located exactly one-half the distance between the upper and lower depths. During times of lower water depths (generally <30 cm), the distance between the upper sampling depth and the water surface and lower sampling depth and the floc layer was reduced to 5 cm. Very shallow water conditions (<10 cm) at the ridge site occasionally necessitated collection of three replicate samples from the same depth in the middle of the water column. One L of surface water was collected with a peristaltic pump at a slow pump rate (~70 mL min^{-1}) from each site and depth on each sampling day. The peristaltic tubing (4.8 mm inner diameter fitted with a 100 μm Nitex prefilter) was connected to a PVC pole that was gently inserted vertically into the water column and then attached to a permanent aerial support. The purpose of the prefilter was to exclude zooplankton, periphyton, or organic debris that potentially became detached due to sampling disturbance. We refer to suspended sediment sampled with use of the prefilter as fine (<100 μm) suspended sediment. We then waited 5 min to allow natural flushing or settling of any detached particles that were introduced by placement of the sampling equipment, let the pump run for 5 min, and then began collecting samples. Samples were collected in low-density polyethylene (LDPE) bottles and then stored on ice until filtration later in the evening. All materials in contact with the samples were acid-washed and rinsed three times with sample water before the final sample was collected.

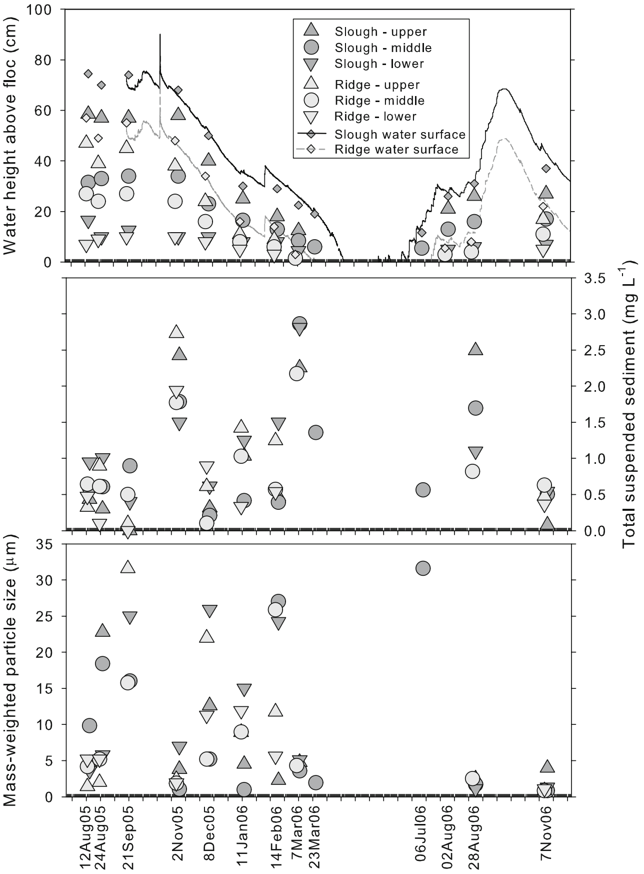

Fig. 2 Water depths, suspended sediment concentrations, and mass-weighted average particle sizes at the three sampling depths (*upper*, *middle*, *lower*) in the ridge and slough. Sampling in ridge and slough occurred on the same days but the symbols for each are offset to better show the data

The mass and elemental composition of suspended particles was directly analyzed from the concentrated sediment collected on filters. Samples were only gently mixed prior to filtration to minimize disaggregation of flocculent particles. Each sample was serially filtered through 10 μm (Pall polypropylene), 2.7 μm (Whatman GF/D), 0.45 μm (Pall polypropylene), and 0.2 μm (Pall polypropylene) filters (all 47-mm diameter) by vacuum filtration. The volume of filtrate from each size filter was measured and then a sample of the final filtrate (<0.2 μm) was collected in a 60-mL LDPE bottle. The mass concentration of suspended sediment in each size class was determined by drying and weighing each filter on a microbalance before and after filtration. Particulate P and nitrogen (N) were measured directly by digesting filters and their accumulated particles with potassium persulfate in an autoclave (Noe et al. 2007). Total dissolved P (TDP) and total dissolved N (TDN) concentrations in the filtrate samples were also measured by persulfate digestion. Total particulate P and N concentrations were calculated as the sum of the amount of P or N on the four particulate size classes (0.2–0.45, 0.45–2.7, 2.7–10, and 10–100 μm) divided by the volume of filtrate. The mass-weighted, P-weighted, and N-weighted average sizes of particles were calculated using the mass, particulate P, and particulate N concentrations in each particle size class weighted by the geometric mean size of each of the four size class ranges. The percent of total water column N and P held by suspended sediment was calculated as total particulate N or P divided by total particulate N or P plus TDN or TDP concentrations.

Additional sampling occurred on 29 November 2006 with the goal to characterize the mass and nutrient content of coarse suspended particles (>100 μm). Surface water was collected as before, but without a prefilter on the peristaltic tubing, and then was filtered through 100 μm Nitex filters (4.7 cm diameter). One sample was collected from each of the upper, middle, and lower water column at the slough site and three replicate samples were collected from the middle of the water column at the ridge site. The coarse suspended sediment samples were analyzed for mass, total P, and total N using the standard analytical methods.

Suspended sediment concentrations were measured continuously using a LISST-100X sediment analyzer (Sequoia Scientific, Inc.) for 22 hr diel deployments in early November 2006. The LISST-100X measures diffraction of a laser to estimate the in situ volume concentration and size distribution of suspended sediment. The particle size measurement range of the LISST-100X instrument was 1.25 to 250 μm over 32 log-spaced size classes. The first deployment, in the slough (total water column depth above floc = 37 cm), occurred from 1255 hr on 7 November to 1129 hr on 8 November 2006. The second deployment, in the ridge (total water column depth above floc = 22 cm), occurred from 1427 hr on 8 November to 1237 hr on 9 November 2006. The LISST-100X was suspended horizontally with the optical path placed in the middle of the water column. Measurements of suspended particle volume concentration (μL L^{-1}) and size distribution were made every minute for 5 second bursts. The LISST-100X size classes were aggregated into four size classes to correspond with the particle sampling size classes used in the pumped water sampling. Total particle volume was calculated as the sum of all size classes and the volume-weighted average particle size was also calculated. Background scatter was corrected by measuring deionized water before and after deployment.

A second deployment of the LISST-100X occurred in the middle of the slough water column in late November 2006. Sampling was similar to the first deployment in early November, except that the LISST-100X was programmed to collect data every 10 min and the optical path was located 5 cm above the floc layer (total water column depth above the floc layer was 15 cm at deployment). Biofouling of the instrument's optics was evident after 3 days of deployment, and we present only data collected during the first 48 h.

Hydrological and Meteorological Measurements

Surface water velocity, direction, and the other ancillary hydrological and meteorological data used in this study are from a companion study by Harvey et al. (2009). Briefly, surface water velocity was measured every 30 min using three-component, downward looking 10 MHz Sontek acoustic Doppler velocimeters (ADV) deployed at both the ridge and slough sites. Depth of sensor deployment varied but was typically 5/8 of the total depth. In addition, vertical profiling of water velocity occurred during each sampling trip when suspended sediment was sampled. Although the low flow velocity and suspended sediment concentration make velocity measurements difficult in the Everglades, rigorous QA/QC of the ADV output ensures data accuracy by eliminating questionable data (Harvey et al. 2009).

Water depths at both ridge and slough sites were measured every 15 min using pressure transducers. Water depth and floc depth also were measured each sampling trip at locations adjacent to the particle sampling sites. Vertical profiles of water temperature and air temperature in both the ridge and slough were measured with 10 cm spacing every 15 min using thermocouple chains. Wind speed and direction were measured every 15 min using an anemometer deployed on a platform between the ridge and slough sites.

Suspended Sediment Load Estimation

Transported loads of suspended sediment, particulate nutrients, dissolved nutrients, and chloride were calculated for both the ridge and slough flowpaths. Load calculations are based on a unit-width cross section (a 1-m wide section of water column with height equal to water depth). To determine loads, flow- and depth-weighted sediment and chemical concentrations were determined by assigning chemical measurements at a given depth to vertical intervals in the water column separated at midpoints between the sampling depths. Suspended sediment, nutrient, and chloride concentrations (measured in each sample by ion chromotography) were then flow-weighted using the vertical profile of water velocity measured that day (Harvey et al. 2009). Flow-weighted concentrations were then interpolated linearly between sample dates. Daily load estimates were calculated as the product of cumulative daily water discharge and flow-weighted concentration. Cumulative discharge and loads over the duration of the study were calculated for both the period of record and for periods with concurrent data availability for both ridge and slough.

Statistical Analyses

All data were first log-transformed (except water and wind direction which were both transformed into their cosine and sine components [Zar 1996]) to meet the assumptions of parametric statistical tests and then analyzed using SAS 9.1. First, associations among suspended sediment and nutrient variables were tested using Pearson product-moment correlations. Second, differences in suspended sediment and nutrient variables between ridge and slough and among sampling depths were tested using 2-way repeated-measures analyses of variance that included 2-way interaction terms. Only sampling dates that included all three sampling depths at both sites were included in this analysis. Differences among the three sampling depths, when significant, were evaluated using Tukey's HSD post-hoc tests. Third, the influences of the hydrologic and meteorological variables (sample height above floc, water velocity and water temperature at each sampling depth, time of sampling, total depth of water column, air temperature, and the mean, minimum, maximum, and direction of wind velocity at the time of sampling) on suspended sediment and nutrient variables over the duration of the study was tested using Pearson product-moment correlations. Wind data were not available for nine samples at the beginning of the study, resulting in analysis of a smaller dataset than for the other hydrologic and meteorologic variables. Fourth, the influences of hydrologic and meteorological variables (water velocity and direction, air, water, floc, and peat temperature, temperature stratification [water-floc temperature], total depth of water column, and wind velocity parameters) on each of the short-term LISST-100X suspended sediment datasets were evaluated using Pearson product-moment correlations. Fifth, night vs. day differences in suspended sediment and nutrients during the diel particle sampling were tested using paired *t*-tests. Sixth, night vs. day and ridge vs. slough differences in LISST-100X sediment data obtained during diel deployments were tested using nested analyses of variance with time of day nested within sampling sites. Finally, night vs. day differences during the late November 2006 deployment of the LISST-100X in the slough were tested using independent *t*-tests.

Results

Particle Characteristics

Fine suspended sediment (0.2–100 μm) was generally not abundant at the WCA3A-5 ridge and slough research site. Total suspended sediment mass concentrations were on average 0.94 mg L^{-1} over the duration of the study (Fig. 2). Total particulate N (Fig. 3) and total particulate P concentrations (Fig. 4) were 4.2 and 0.10 μmol L^{-1}, respectively, on average. Despite the low concentrations of suspended sediment and particulate P, 28% of all surface water P was associated with suspended sediment. In contrast, only 5.6% of surface water N was associated with suspended sediment, in part due to the relatively high average TDN concentrations (75 μmol L^{-1}) relative to TDP (0.29 μmol L^{-1}). The mass-weighted, N-weighted, and P-weighted average particle sizes decreased from 8.6, to 5.2, to 2.9 μm, respectively. In other words, smaller particles held relatively less mass but more P compared to larger particles.

Total suspended sediment mass, particulate N, and particulate P concentrations were positively associated. The mass and N content of particles were more strongly correlated (Pearson product-moment correlation, $n=66$, $r=0.62$, $P<0.001$) than the mass and P content of particles ($r=0.33$, $P=0.010$), and the N and P content of particles were intermediately correlated ($r=0.44$, $P<0.001$). Total suspended sediment mass concentrations were also positively associated with the proportions of surface water N and P held by particles ($r=0.38$, $P=0.002$ and $r=0.48$, $P<0.001$, respectively). However, the proportions of surface water N and P held by suspended sediment were uncorrelated with each other ($P>0.9$). Finally, mass-weighted average particle size was unrelated to total suspended sediment mass concentrations ($P>0.4$), N-weighted average particle size was strongly negatively related to total particulate N concentrations ($r=-0.73$, $P<0.001$), and P-weighted average particle size was weakly positively related to total particulate P concentrations ($r=0.30$, $P=0.013$). To summarize, locations and times with greater abundance of suspended sediment were associated with relatively more mass from all particle sizes, more particulate N from smaller particles, and more particulate P from larger particles.

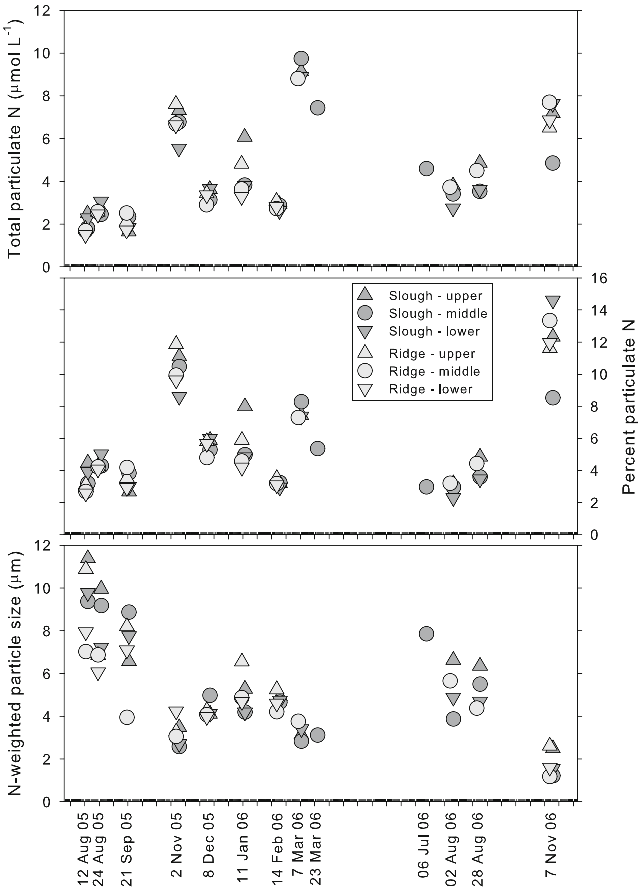

Fig. 3 Concentrations of particulate N, proportions of water column total N held by suspended sediment, and N-weighted average particle sizes at the three sampling depths (*upper*, *middle*, *lower*) in the ridge and slough. Sampling in ridge and slough occurred on the same days but the symbols for each are offset to better show the data

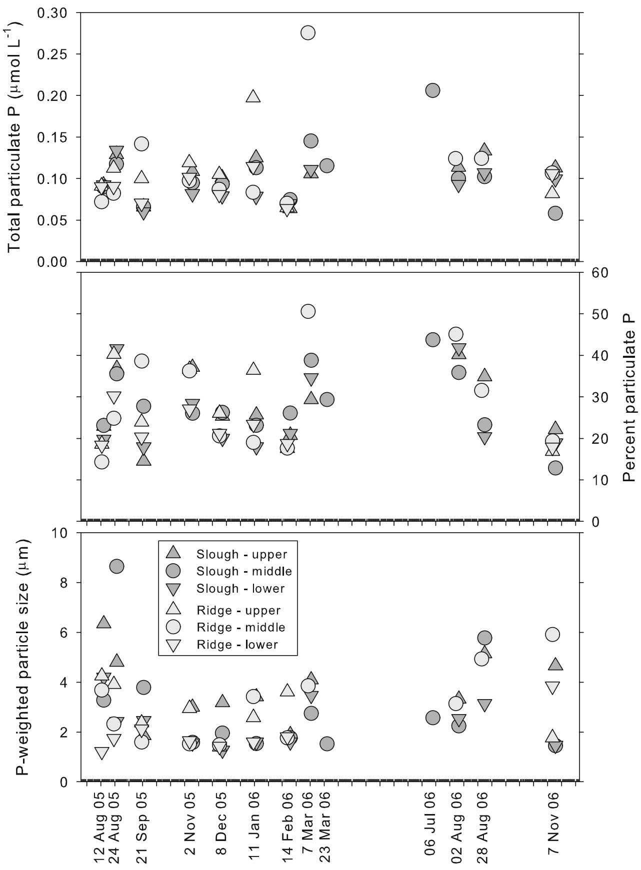

Fig. 4 Concentrations of particulate P, proportions of water column total P held by suspended sediment, and P-weighted average particle sizes at the three sampling depths (*upper*, *middle*, *lower*) in the ridge and slough. Sampling in ridge and slough occurred on the same days but the symbols for each are offset to better show the data

Ridge vs. Slough, Depth, and Temporal Trends

Simultaneous sampling over two wet seasons found no differences in sediment concentrations or characteristics between the ridge and slough (Figs. 2, 3, 4). No suspended sediment variables significantly differed between the adjacent ridge and slough sites, including suspended sediment mass, particulate N, and particulate P concentrations, mass-weighted, N-weighted, and P-weighted average particle sizes, and the percent surface water N and P held by suspended sediment (Table 1). However, water column TDP concentrations were marginally significantly greater (by an average of 8%) in the ridge compared to the slough, although TDN did not differ.

Relative sampling depth in the water column influenced all parameters of particulate N (Table 1). Particulate N concentration, N-weighted average particle size, and the proportion of surface water N held by suspended sediment were all significantly greater in the upper portion of the water column compared to the middle and lower depths (Fig. 3). Total particulate P concentration and the P-weighted average particle size also were also marginally significantly greater in the upper water column and decreased with depth (Fig. 4). In contrast, particle mass characteristics did not differ by sampling depth (Fig. 1). Total suspended sediment mass concentration, however, did have a significant site-by-depth interaction term. Concentrations of total suspended sediment mass decreased with sampling depth in the ridge but increased with depth in the slough. The more abundant mass of suspended sediment in the lower third of the slough water column (close to the layer of floc) consisted of relatively large particles that did not hold more total particulate nutrients, indicating that they had lower nutrient density, compared to the upper and middle slough water column. Sediment in the upper third of the ridge water column had similar mass-weighted average particle size but was more abundant and held more total particulate nutrients and was thus compositionally similar, compared to the middle and lower ridge water column.

Out of all measured suspended sediment and nutrient attributes, only the P-weighted average size of particles did not change over time (Table 1, Fig. 4). All other attributes (Figs. 2, 3) had significant temporal variation. Time-by-depth interactions were marginally significant for total particulate N and the proportion of surface water N held by suspended sediment. Time-by-site interaction was also marginally significant for the proportion of surface water N held by suspended sediment. In general, particulate P characteristics were less temporally variable than for particle mass or N.

The effects of the passage of Hurricane Wilma over the study site (24 October 2005) on suspended sediment concentrations and characteristics were evident 15 days later when sampling occurred. Hurricane Wilma's winds and barometric pressure effects caused water levels to temporarily increase about 20 cm (Fig. 2), accompanied by a temporary increase in surface water velocity (Harvey et al. 2009), and vegetation disturbance and detritus transport (personal observations by authors). Total suspended sediment mass concentrations increased 4× and the mass-weighted average size of particles decreased 4× compared to all sampling prior to the hurricane (Fig. 2). Similarly, total particulate N and the proportion of surface water N held by suspended sediment increased 3× and the N-weighted average size of particles decreased 3× (Fig. 3). Particulate P, TDN, and TDP, however, did not change after the hurricane (Fig. 4). The weighted average size of mass and N bearing particles decreased to a similar size as P bearing

Table 1 Two-way repeated measures analyses of variance on suspended sediment and nutrient data. Analyses were restricted to dates when all three water depths were sampled in both ridge and slough

	P values					
	Depth effect	Site effect	Site* depth effect	Time effect	Time* depth	Time* Site
Total suspended sediment (mg L^{-1})	0.894	0.889	**0.007**	**<.0001**	0.123	0.837
Total particulate N (μmol L^{-1})	**0.028**	0.311	0.237	**<.0001**	0.080	0.187
Total particulate P (μmol L^{-1})	0.078	0.370	0.907	**0.015**	0.391	0.171
Mass-weighted average particle size (μm)	0.745	0.455	0.717	**0.002**	0.416	0.538
N-weighted average particle size (μm)	**0.004**	0.203	0.157	**<.0001**	0.347	0.125
P-weighted average particle size (μm)	0.052	0.453	0.819	0.164	0.973	0.494
% Particulate N	**0.032**	0.182	0.314	**<.0001**	0.065	0.095
% Particulate P	0.120	0.708	0.655	**<.0001**	0.134	0.114
Total dissolved N (μmol L^{-1})	0.798	0.312	0.472	**<.0001**	0.648	0.351
Total dissolved P (μmol L^{-1})	0.470	0.054	0.404	**<.0001**	0.227	0.389

P-values <0.05 are highlighted in bold particles after the hurricane. Thus, Hurricane Wilma generated many small particles that had similar N density but lower P density compared to before the hurricane.

Hydrologic and Meteorological Controls

Water velocity (0.02 to 0.79 cm s^{-1} range; Harvey et al. 2009) measured at each depth of sampling had no association with any of the measured suspended sediment and nutrient parameters (Pearson product-moment correlation, $n=57-66$, $P>0.05$). The mean and maximum of wind velocity at WCA3A-5 at the time of sampling also were uncorrelated with suspended sediment concentrations and characteristics ($P>0.10$). However, wind direction more from the north along the north-south axis (cosine term; wind blew down the slough and ridge) was relatively strongly and positively correlated with suspended sediment mass concentration ($r=0.537$, $P<0.001$) as well as weakly correlated with the percent of surface water P held by particles ($r=0.321$, $P=0.015$) and the P-weighted average size of particles ($r=0.269$, $P=0.043$). Wind direction along the east-west axis (sine term) was not associated with any sediment parameters ($P>0.05$). Higher water temperature at each sampling depth was associated with more surface water P held by particles ($r=0.323$, $P=0.008$), larger P- and N-weighted average particle sizes (P: $r=0.360$, $P=0.003$, N: $r=0.288$, $P=0.019$), and smaller mass-weighted average particle sizes ($r=-0.289$, $P=0.028$). Finally, shallower surface water depth at each site on the day of sampling was associated with greater concentrations of total particulate P ($r=-0.458$, $P<0.001$) and total particulate N ($r=-0.348$, $P=0.004$), greater percent of surface water P held by particles ($r=-0.301$, $P=0.014$), smaller N-weighted average particle size ($r=0.288$, $P=0.019$), as well as higher concentrations of TDN ($r=-0.710$, $P<0.001$). Overall, these hydrologic and meteorologic variables generally had little influence (as indicated by low r) on suspended sediment and particulate nutrient concentrations and characteristics over the two wet seasons. Exploratory multivariate analysis identified relationships among the independent variables but did not better explain temporal variation in suspended sediment concentrations.

Diel Changes

Direct Sampling Diel sampling revealed changes in some suspended sediment characteristics from mid-day (1100–1300 hr, during water column stratification) to night (2200–2400 hr, after water column destratification) on 8 November 2005. Mass concentrations of total suspended sediment decreased from 1.50 mg L^{-1} in the day to 0.90 mg L^{-1} at night (Paired t-test, $n=6$, $P=0.005$), total particulate N decreased from 5.53 μmol L^{-1} in the day to 4.91 μmol L^{-1} at night ($P=0.002$), and the percent of surface water N held by suspended sediment decreased from 9.4% in the day to 7.8% at night ($P=0.003$), while TDN marginally increased from 56.6 μmol L^{-1} in the day to 59.0 μmol L^{-1} at night ($P=0.078$). No other sediment concentrations (i.e., total particulate P) or characteristics (i.e., percent particulate P, weighted average sizes of particle mass or N or P, or TDP) significantly differed between day and night.

Early November 2006 LISST-100X Deployment The volume concentration of suspended sediment (μL L^{-1}), measured by the LISST-100X in the middle of the water column during non-concurrent diel deployments in November 2006, statistically differed between ridge and slough and between day and night, although the magnitudes of differences were small (Table 2, Fig. 5). Sediment volume concentrations in the slough were greater than the ridge for cumulative total sediment concentration (1.25–250 μm), the second largest size class (9.11–92.4 μm), and the smallest size class of particles (1.25–2.42 μm). The ridge had larger volume-weighted average particle size and greater sediment volume concentrations in the second smallest size class (2.42–9.11 μm) and the largest size class (92.4–250 μm) of particles. Particle volume concentrations and volume-weighted average particle size also differed between day and night. The volume of the smallest particles was greater in the day than the night at both sites, particularly in the slough where the volume of smallest particles decreased quickly after sunset and increased quickly after sunrise (Fig. 5). The direction of diel changes in suspended sediment differed between ridge and slough for all other size classes of particles. Volume-weighted average particle size also increased at night in both sites.

Large spikes of elevated sediment volume concentrations occurred during the night in the slough. These spikes occurred for 11 min resulting in a 10× increase in the largest (92.4–250 μm) and second largest particle size classes (9.11–92.4 μm), and for 26 min with a 2× increase in all but the smallest size class of particles (1.25–2.42 μm; Fig. 5). One period of intermittent high particle abundance occurred at night on the ridge for 16 min with a 2× increase in the two largest size classes of particles. The timing of these spikes in sediment concentrations did not coincide with any changes in surface water velocity, wind velocity, or water temperature. Thermally-driven overturn of the water column, measured by vertical destratification of water temperature, occurred at around 1900 hr on 8 November 2006 during the ridge deployment and did not occur during the slough deployment. If the spikes of elevated sediment are excluded from the analysis, night-time total sediment volume concentrations averaged 2.08 μL L^{-1} in the slough and 2.28 μL L^{-1} in the ridge, lower values than observed in the day at each site.

Table 2 Average (±1 standard error [S.E.]) volume concentrations of suspended sediment in different particle size classes and average particle size measured by a LISST-100X in early November 2006. Deployments in the slough (1255 hr, 11/7/06 to 1131 hr, 11/8/06) and ridge (1427 hr, 11/8/06 to 1237 hr, 11/9/06) are separated into daylight and night-time sampling periods. Data were collected every 1 min

Variable	Ridge day		Ridge night		Slough day		Slough night		Site	Diel (site)
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	*P*	*P*
Total concentration (μL L^{-1})	2.49	0.02	2.31	0.02	2.29	0.02	2.62	0.14	<0.001	<0.001
1.25–2.42 um concentration (μL L^{-1})	0.01	0.00	0.00	0.00	0.21	0.01	0.02	0.00	<0.001	<0.001
2.42–9.11 um concentration (μL L^{-1})	0.12	0.00	0.12	0.00	0.09	0.00	0.14	0.00	<0.001	<0.001
9.11–92.4 um concentration (μL L^{-1})	1.23	0.01	1.14	0.01	1.11	0.01	1.26	0.03	0.018	<0.001
92.4–250 um concentration (μL L^{-1})	1.13	0.02	1.05	0.02	0.88	0.02	1.20	0.11	<0.001	0.014
Volume-weighted average particle size (μm)	89.8	0.4	91.1	0.4	83.7	0.5	85.8	0.5	<0.001	<0.001

P-values for a nested ANOVA are provided. Ridge day: n=553, Ridge night: n=778, Slough day: n=578, Slough night: n=778

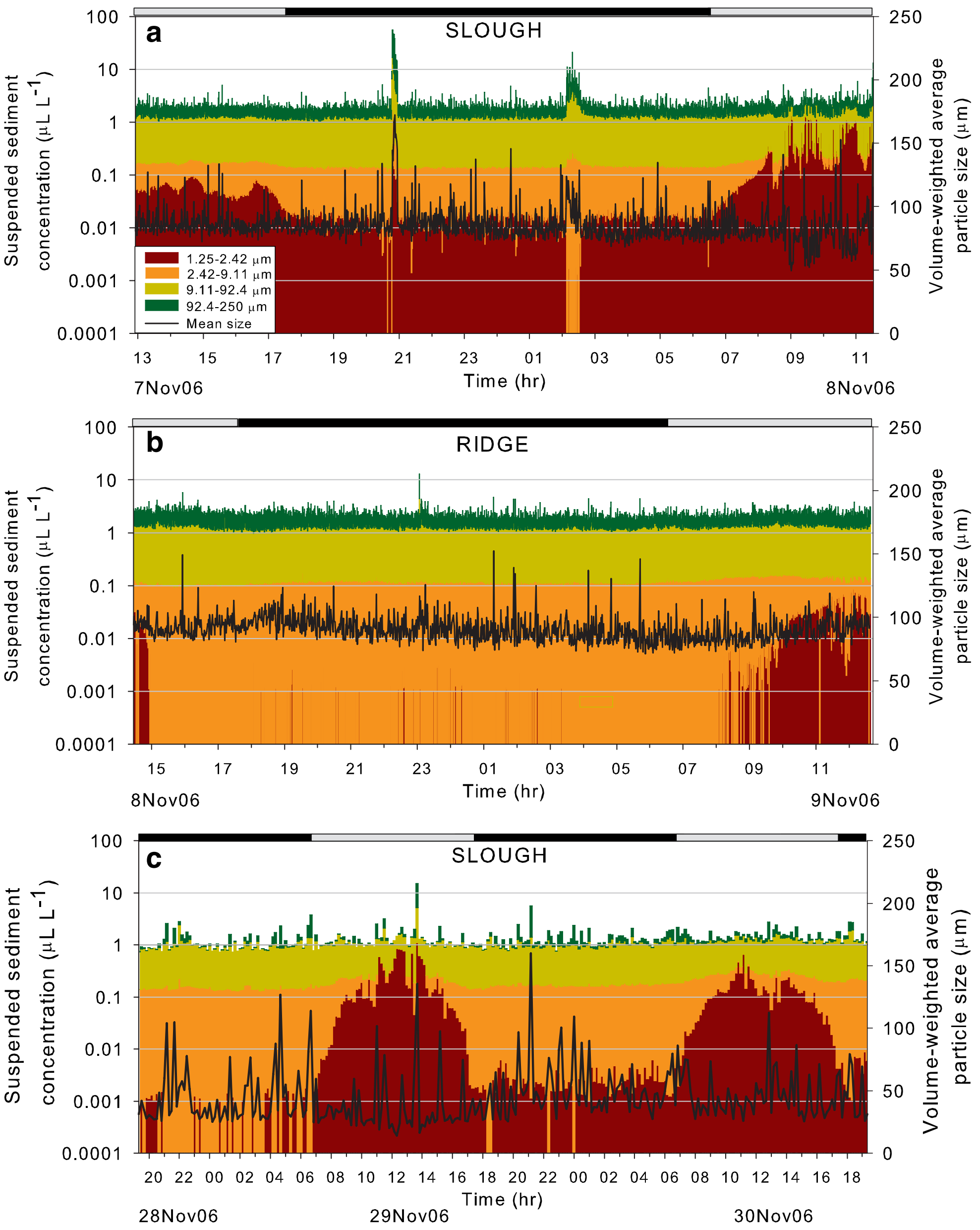

Fig. 5 Concentrations of suspended sediment in four composited particle size classes (*stacked bars*) and volume-weighted average particle size (*line*) measured by a LISST-100X during diel deployments. Periods of daylight and nighttime are indicated by a *grey* and *black bar*, respectively, above each graph. **a** Slough deployment in early November 2006 (measurements every 1 min), **b** ridge deployment in early November 2006 (measurements every 1 min), and **c** slough deployment in late November 2006 (measurements every 10 min)

Therefore, typical sediment volume concentrations decreased at night in both ridge and slough and were greater in the ridge than slough.

From 1600 on 8 November through 0800 on 9 November 2006 (largely excluding daylight times), water velocity, wind, and temperature data were available for comparison with the LISST-100X measurements in the ridge. Total volume concentration of suspended particles was not correlated with water velocity or direction (Pearson product-moment correlation, $n=33$, $P>0.05$), but increased with wind velocity ($r=0.536$, $P=0.001$), air temperature ($r=0.542$, $P=0.001$), water temperature ($r=0.553$, $P=0.001$), floc temperature ($r=0.518$, $P=0.002$), and water temperature stratification ($r=0.441$, $P=0.010$). The volume-weighted average particle size was correlated with largely the same variables, increasing with wind velocity ($r=0.548$, $P=0.001$), air temperature ($r=0.474$, $P=0.005$), water temperature ($r=0.601$, $P<0.001$), and floc temperature ($r=0.690$, $P<0.001$), but was not associated with water velocity or direction ($P>0.05$).

Late November 2006 LISST-100X Deployment Total sediment volume concentrations were much lower and consisted of smaller particles during the late November 2006 deployment compared to the early November 2006 deployments. Nonetheless, suspended sediment concentrations also changed from day to night during the late November 2006 LISST-100X deployment in the slough, as they did in early November 2006. The cumulative total volume concentration of suspended sediment (Independent *t*-test; day: mean = 1.45 μL L^{-1}, $n=128$; night: mean = 1.26 μL L^{-1}, $n=161$; $P=0.004$), smallest particle size class (1.25–2.42 μm; $P<0.001$), and second largest particle size class (9.11–92.4 μm; $P=0.015$) were all significantly greater in the day than at night (Fig. 5). Volume-weighted average particle size (day: mean = 40.7 μm; night: mean = 47.2 μm; $P=0.012$) and the volume concentration of the second smallest size class (2.42–9.11 μm; $P<0.001$) were both significantly greater at night than day, whereas the volume of particles in the largest size class (92.4–250 μm) was similar in day and night ($P>0.4$). Similar to the early November deployment, the second largest size class of particles held the greatest volume concentration compared to other size classes. Furthermore, the smallest size class of particles exhibited sharp increases following sunrise and decreases following sunset (Fig. 5), as in early November 2006. A weak thermal destratification of the water column occurred around 0100 hr on 29 November 2006 and a stronger event occurred around 2100 on 29 November 2006. The stronger destratification was associated with a single LISST measurement with high abundance of the largest size class and an increase in volume-weighted average particle size.

The total volume concentration of suspended sediment measured by the LISST-100X during the late November 2006 deployment in the slough was uncorrelated with water velocity or direction (Pearson product-moment correlation, $n=49$, $P>0.4$), water depth ($P>0.4$), air and water temperatures or water temperature stratification ($P>0.5$), and wind velocity or direction ($P>0.1$). Similarly, the volume-weighted average particle size was uncorrelated with any water velocity metrics ($P>0.1$), water depth ($P>0.2$), or wind velocity metrics ($P>0.05$), but was negatively correlated with air temperature ($r=-0.285$, $P=0.047$) and water temperature stratification ($r=-0.330$, $P=0.021$) which is consistent with the diel pattern of the smallest particles increasing in abundance during daylight.

Characteristics of Coarse Suspended Particles

Sampling by the LISST-100X during the diel deployments in early November 2006 indicated that the coarse suspended particles measured by this instrument (92.4–250 μm) held on average 43% and 45% of total suspended sediment (1.25–250 μm) volume concentration (μL L^{-1}) in the slough and ridge, respectively. In contrast, during the late November 2006 slough deployment, the coarse particles held only 19% of total suspended sediment volume concentration. At the same time, concentrations of particulate P held by coarse suspended particles (>100 μm), measured directly in a single step digestion of captured particles, averaged 0.011 μmol L^{-1}. In contrast, in fine particles (0.2–100 μm), average total particulate P was 0.10 μmol L^{-1} over the duration of the study. Therefore, coarse particles constituted 10% of typical fine + coarse particulate P. The average concentration of coarse particulate N was 1.52 μmol L^{-1}, compared to 4.22 μmol L^{-1} in fine particles throughout the study (coarse particles were 26% of fine + coarse particulate N). The mass concentration of the coarse particles also was very small, 0.03 mg L^{-1} on average, but was biased by many zero estimates (mean = 0.10 mg L^{-1} not including zeros), while the long-term average fine suspended sediment mass concentration was 0.94 mg L^{-1}. In summary, coarse suspended particles (>100 μm) held little P or mass but some N, and had low P density and intermediate N density compared to fine particles (0.2–100 μm).

Material Loads

From shortly after the onset of the first wet season through the end of the first wet season and the entire second wet season, unit-width (1-m wide section of wetland) discharge of surface water was greater in the slough than the ridge (Table 3), with a slough:ridge ratio (S:R) of 2.15. This ratio was somewhat smaller (2.08) when daily data were available for both ridge and slough. The greater slough

Table 3 Cumulative unit-width discharge and material loads in the slough and ridge flowpaths for the study period of record and for days when both ridge and slough data were available over wet seasons 2005 and 2006. Water discharge was reported in Harvey et al. (2009)

	Period of record			Concurrent record		
	Slough	Ridge	Slough:Ridge	Slough	Ridge	Slough:Ridge
Number of days	250	211	1.18	211	211	1.00
Water discharge ($m^3 m^{-1}$)	353	164	2.15	341	164	2.08
Suspended sediment ($g\ m^{-1}$)	366	144	2.55	349	144	2.43
Cl^- ($mol\ m^{-1}$)	330	140	2.37	317	140	2.27
Total particulate N ($mmol\ m^{-1}$)	1621	714	2.27	1555	714	2.18
Total particulate P ($mmol\ m^{-1}$)	35.7	17.2	2.07	34.5	17.2	2.00
Total dissolved N ($mol\ m^{-1}$)	23.8	10.9	2.18	22.6	10.9	2.07
Total dissolved P ($mmol\ m^{-1}$)	105	47.9	2.20	103	47.9	2.15

discharge relative to the ridge resulted from the longer hydroperiod in the slough and the resulting shorter record of ridge data. The ratio S:R was greater for the load of suspended sediment, and also for particulate N and TDP and Cl^- loads to a lesser degree, than for water discharge when both ridge and slough were wet. In contrast, the loading ratios for particulate P and TDN were similar to the water discharge ratios. These differences in S:R among dissolved and particulate nutrient loads were due to slightly greater flow-weighted concentrations of suspended sediment and particulate N in the slough than the ridge. Flow direction was generally parallel to the orientation of the ridge and the slough. Using mean flow directions and velocities each wet season and the geometry of the ridge and the slough at WCA3A-5, the average flowpath projected upstream from our slough sampling point traveled through 210 m (19 hr travel time) and 230 m (20 hr) of the slough subsequent to emerging from adjacent ridge in the 2005 and 2006 wet seasons, respectively. In the ridge, upstream flowpaths were 20 m (2 hr) and 90 m (10 hr) long subsequent to emerging from adjacent slough in the 2005 and 2006 wet seasons, respectively.

Discussion

Counter to expectation, the concentrations and characteristics of suspended sediment and its associated particulate nutrients over two wet seasons of inundation were the same in ridge and slough plant communities located in one of the best remnant ridge and slough areas in the central Everglades. Only the concentration of TDP differed between ridge and slough, with more dissolved P in the ridge. Furthermore, variations in suspended sediment and particulate nutrient parameters were not related to surface water velocity. However, the flux of suspended sediment and nutrients were greater downstream through the slough flowpath than downstream through the ridge flowpath, as expected.

Controls on Suspended Sediment and Nutrient Concentrations

Two wet seasons of water sampling generated no significant differences between ridge and slough for any suspended sediment or particulate nutrient parameters. The lack of differences was not due to low statistical power. Differences in means were proportionally small compared to the means and within site variability due to factors other than vegetation (see following). However, we found significant ridge/slough differences in the volume concentrations of suspended sediment as measured by in situ laser diffraction. During the sequential diel deployments of the LISST-100X suspended sediment analyzer, typical (not including large night-time spikes) total suspended sediment volume concentrations were 9% and 10% greater in the ridge than the slough during daylight and nighttime, respectively. During the daytime, the difference was largely due to the largest LISST-100X size classes (92.4–250 μm), particle sizes that were not measured during the long-term water sampling. It is likely that the small difference between ridge and slough was apparent due to the large number of measurements and greater measurement precision of the LISST-100X compared to water sampling using a peristaltic pump, filtering, and subsequent analysis of filters in the low sediment environment of the Everglades. Alternatively, the apparent LISST-100X differences between ridge and slough may be due to temporal variation among the nonconcurring deployments.

The general similarity of suspended sediment between the ridge *Cladium* and slough *Eleocharis*/*Nymphaea* plant communities was surprising given the greater biomass and vegetative biovolume and lower water velocity found in ridges than sloughs at this site (Harvey et al. 2009) and throughout the Everglades (Childers et al. 2003; Leonard et al. 2006; Noe and Childers 2007). Based on these hydrologic and vegetation differences, and the long flowpaths through the slough and through the ridge at WCA3A-5, we predicted that suspended sediment removal would be greater and result in lower concentrations of suspended sediment in the ridge compared to slough. We speculate that the lack of a difference was due to the overall low abundance of suspended sediment, small particle sizes, and low water velocities in the Everglades. Alternatively, we could have missed bed load transport of floc occurring below our lowest sampling depth in the water column (5 to 10 cm above the top of the floc layer). Sampling ridges and sloughs at other locations would increase the generality of our intensive sampling at WCA3A-5. However, the concentrations and characteristics of suspended sediment at this site were similar to those collected in Everglades National Park (Bazante et al. 2006) and throughout the Everglades (Noe et al. 2007). Others have also failed to detect differences in sediment accumulation rates among wetlands plant communities of differing productivity (Fennessy et al. 1994; Anderson and Mitsch 2006). Yet others found that sediment accumulation rates (Leonard et al. 2002, 2006), sediment filtration by vegetation (Huang et al. 2008), or suspended sediment concentrations (Braskerud 2001; Leonard and Reed 2002) differed among plant communities within wetlands.

Although suspended sediment concentrations were similar in ridge and slough, sediment fluxes could still have differed. The ridge could still have greater rates of sediment capture or deposition that was balanced by greater entrainment of sediment into the water column. However, removal of 1-μm artificial particles from the water column was not rapid in the ridge at our study site, with a mean filtration rate of 0.58 hr^{-1} before capture on plant stems and leaves (Huang et al. 2008). In contrast, artificial particles (0.3 μm) were filtered at a rate of 3.6 hr^{-1} in a slough located in the southern Everglades (Saiers et al. 2003). Suspended particles at our research site were typically generated from bacteria and periphyton 'rain' and occasionally from benthic floc (Noe, unpublished data). The greater abundance of periphyton and floc in the slough at WCA3A-5 suggests that sediment production was lower in the ridge and that the suspended sediment sampled in the water column of the ridge had been advected from the adjacent slough. More information on organic particle creation, entrainment, capture, and settling rates are necessary to identify conclusive differences in sediment fluxes in ridge and slough.

We observed marginally statistically significant but only slightly elevated (8% greater) TDP concentrations in ridge compared to slough surface water. This pattern was predicted by Davis et al. (2006) based on greater plant productivity and P leaching rates from fresh detritus in *C. jamaicense* (ridge) than *Eleocharis* spp. (slough) dominated habitats in the Everglades. Most of the TDP at our oligotrophic research site was in the dissolved organic P fraction (DOP, mean = 72%; Noe, unpublished data). The slow degradation of dissolved organic matter (DOM) in the Everglades (Qualls and Richardson 2003) compared to the relatively fast time scales of hydrologic mixing of surface water and DOM between ridge and slough (Larsen, unpublished data) may limit the bioavailability of this elevated DOP to the ridge ecosystem. Nonetheless, leaching of abundant *C. jamaicense* litter (e.g., Childers et al. 2003) represents an important redistribution of the limiting nutrient in the oligotrophic Everglades landscape.

Counter to our second hypothesis, spatiotemporal variation in suspended sediment was unrelated to surface water velocity. The lack of any relationship between surface water velocity and suspended sediment abundance, and overall low sediment concentrations, suggests that velocities at our station WCA3A-5 were well below the rate needed to entrain particulate matter. Observed surface water velocities were on average 0.28 cm s^{-1} in the ridge and 0.36 cm s^{-1} in the slough (Harvey et al. 2009). Surface water velocities are somewhat faster in Shark River Slough to the south of WCA3A in Everglades National Park (Leonard et al. 2006; Harvey et al. 2009), but suspended sediment concentrations also are low in that region of the Everglades (Bazante et al. 2006). Typical water velocities in the modern Everglades, where human management largely controls hydrology and has dampened hydrologic fluctuations (Light and Dineen 1994), are not sufficient to entrain meaningful amounts of suspended sediment.

In contrast, suspended sediment concentrations were elevated 15 days after Hurricane Wilma passed over the research site on 24 October 2005, and were likely much greater during and immediately after the hurricane. Water flow velocity reached a maximum of 4.89 cm s^{-1}, wind gusted as high as 14.2 m s^{-1}, and water levels increased by up to 20 cm during the hurricane (Harvey et al. 2009). We observed large amounts of plant detritus from ridge and slough species deposited in a wrack line several meters into the edges of every ridge near the research site. Hurricane Wilma also deposited large quantities of mineral marine sediments into the estuarine mangroves of the southern Everglades (Whelan et al. 2009). Suspended sediment mass and N concentrations were 3–4 times greater when sampled on 8 November 2005, after the hurricane, compared to the sampling events prior to the hurricane. Suspended sediment concentrations also were higher at the end of the first and beginning of the second wet seasons, but water depths were much shallower at those times compared to during and after the hurricane indicating that the greatest standing stocks of suspended sediment in the water column were associated with the hurricane. The weighted average sizes of mass- and N-bearing particles also decreased 3–4× to less than 5 μm after the hurricane, suggesting that many small particles remained suspended in the water column for many days after disturbance. However, particulate P concentration, P-weighted average particle size, and proportion of surface water P held by suspended sediment did not change after the hurricane, indicating that the density of P decreased in these small particles. This study and others (Cahoon 2006; Turner et al. 2006) identify infrequent tropical cyclones as important but episodic generators of suspended sediment in tropical and subtropical wetland ecosystems.

Larger pulses of suspended sediment concentrations were also measured by the LISST-100X during the night in the Everglades. These periods of enhanced suspended sediment abundance had 2–10× greater sediment volume concentrations than other times, lasted for up to half an hour, and were largely due to increases in particles larger than 10 μm. The measured hydrologic and meteorological parameters could not explain these pulses. Instead, it is likely that bioturbation by aquatic invertebrates or fish generated the increase in suspended sediment concentrations (e.g., Chow-Fraser 1999; Angeler et al. 2001).

It is likely that disturbance of periphyton was the reason for greater suspended sediment concentrations during periods of lower water. Shallower water columns concentrate periphyton on the surface of the water where they are exposed to wind and rainfall that could generate suspended sediment. Suspended sediment mass concentrations also were greater when wind blew from the north, which was aligned with the direction of ridge and slough topography, resulting in longer fetches. The high filtration rate of suspended particles in the Everglades (Huang et al. 2008) suggests that evaporative concentration of particles is not the responsible mechanism.

The typical pattern of elevated concentrations of particulate nutrients in the upper water column was also observed for the concentrations of suspended sediment mass in the ridge. However, an opposite pattern was observed in the slough, which sometimes had greater concentrations at the lowest sampling depth. The thickness of the floc layer was greater in the slough (mean = 3.6 cm) than ridge (mean = 1.5 cm), placing the lower slough sampling depth close to more floc than the similar sampling depth in the ridge. The more abundant mass of suspended sediment at the bottom of the slough water column was not matched with elevated particulate nutrient concentrations; in fact the opposite pattern occurred, indicating that these abundant particles were less dense in nutrients than most suspended particles.

The water column of Everglades and other wetlands frequently develops thermal stratification during the day followed by destratification at night that generates vertical flow and turbulence (Schaffranek and Jenter 2001). In this study, thermal destratification of the water column was not associated with enhanced suspended sediment concentrations. The night-time water sampling, timed to coincide with thermal destratification, found lower sediment concentrations. In addition, LISST measurements typically also found lower suspended sediment concentrations during the night. However, the LISST deployment in late November 2006 found a very brief increase in the concentrations of the largest suspended particles around the time of thermal overturn of the water column. It is unlikely that the night-time overturn of the water column in the Everglades has sufficient energy to cause meaningful increases in the rate of sediment entrainment, a conclusion also reached by Larsen et al. (2009a). In fact, daylight was associated with increases in the abundance of the smallest particles, possibly because of greater wind velocities.

Suspended Sediment and Nutrient Transport in the Landscape

The downstream unit-width flux of suspended sediment in the slough was twice that of the ridge. Flow was generally parallel to the orientation of the ridge and slough, indicating the transport was more longitudinal down sloughs rather than laterally across ridges and sloughs. The downstream fluxes of dissolved and particulate nutrients were also substantially greater in the slough. These differences in sediment and nutrient transport were due to differences in water discharge. The water column in the slough was deeper, faster flowing, and had a longer hydroperiod, resulting in more water discharge compared to the ridge (Harvey et al. 2009). Flow-weighted sediment and nutrient concentrations, however, were similar in the ridge and slough. The slough-to-ridge ratio of unit-width total P discharge detected in this study (2.16) is similar to a previous estimate (1.9) derived from P budgets in the Everglades (Noe and Childers 2007). Interconnected sloughs are therefore important landscape conduits for water, solute, sediment, and particulate nutrient transport in the Everglades. Elsewhere this pattern of preferential material transport through deeper, less vegetated portions of wetlands has been described as hydrologic short-circuiting (Kadlec and Knight 1996; Braskerud 2001; Dierberg et al. 2005).

Sloughs typically occupy 67% (ranging from 45% to 88%) of the ridge and slough landscape throughout the Everglades (Wu et al. 2006). With twice the unit-width downstream material fluxes in sloughs compared to ridges, four times as much water, sediment, and nutrients are currently transported downstream in sloughs than ridges. Thus, current and future models of material transport in the Everglades need to incorporate differential down-gradient transport in ridges and sloughs and changes in the relative proportion of ridge and slough in response to management actions. The Comprehensive Everglades Restoration Program has the goal of increasing water inputs into the Everglades and restoring the landscape by increasing the proportion of sloughs in the landscape compared to current managed, degraded conditions. These restoration goals could have the unintended consequence of increasing the transport of nutrients and contaminants from the agricultural areas and P-enriched marshes of the northern Everglades, where managed water inputs occur (e.g., Reddy et al. 1998; Childers et al. 2003), to the more natural and oligotrophic southern Everglades.

Implications for Ridge and Slough Geomorphology and Restoration

The monitoring of suspended sediment under the typically slow surface water velocities in this study suggests that conditions necessary to entrain and redistribute significant amounts of suspended sediment and associated nutrients rarely occur at our study site. Most suspended sediment particles in this study were found to be very small (mass-weighted mean = 8.6 μm) and not abundant (mean = 0.94 mg L^{-1}). These small particles have very low settling velocities (Ulén 2004; Leonard et al. 2006; Larsen et al. 2009b), and most removal from the water column is caused by capture by plants or periphyton (Huang et al. 2008). In contrast, benthic floc consists of larger particles with fast settling velocities (Larsen et al. 2009b). The average standing stock of floc across the Everglades is 1,686 and 863 g m^{-2} in slough and ridge, respectively (Noe and Childers 2007), but was only 374 and 295 g m^{-2} in slough and ridge, respectively, at our site. The average standing stock of suspended sediment was only 0.375 and 0.250 g m^{-2} in slough and ridge at WCA3A-5, respectively, with the difference due to deeper water in the slough. Despite the three orders of magnitude greater standing stock of benthic floc compared to suspended sediment, the slow downstream movement of the fine suspended sediment is cumulatively a large flux over the wet season. Expressed as an average annual flux, the unit-width loading of suspended sediment was 183 and 72 g m^{-1} down the slough and ridge flowpaths, respectively (Table 3). The equivalent suspended sediment flux per unit area of marsh is 42.6 kg m^{-2} yr^{-1} in the slough and 22.1 kg m^{-2} yr^{-1} in the ridge.

Suspension and redistribution of the larger, more abundant benthic floc particles likely requires greater water velocities than typically occur in the modern managed Everglades (Larsen et al. 2009a). Possible exceptions include during or after tropical cyclones (Harvey et al. 2009), briefly during the common convective thunderstorms or by animal bioturbation, and near water input structures; or during times of greater water velocities that more likely occurred throughout the Everglades prior to drainage and compartmentalization. Experimental enhancements of flow in an Everglades slough demonstrated that velocities from 3–5 cm s^{-1} were necessary to entrain benthic floc (Harvey, Noe, and Larsen, unpublished data), although the velocity necessary to generate sufficient bed shear stress to entrain floc is also a function of vegetation characteristics and water depth (Larsen et al. 2009b). Redistribution of the coarse, benthic floc sediment, much less redistribution of finer suspended sediment, from sloughs to ridges appears to be uncommon under current ambient conditions. In fact, Leonard et al. (2006) observed greater accumulation rates of locally produced autogenic sediment (floc) in sloughs than ridges of Everglades National Park. Neto et al. (2006) also concluded that Everglades floc is likely generated in situ from the dominant vegetation at a site.

Larsen et al. (2007) concluded that sediment redistribution from sloughs to ridges, in conjunction with differential net peat production (primary production—decomposition), is necessary to maintain deeper water sloughs and shallower ridges with parallel patterning, and hence ridge-slough landscape geomorphic pattern in the Everglades. Other proposed mechanisms for the formation and maintenance of ridge and slough topography include differential net peat accumulation rates alone, accumulation of P at higher peat elevations, underlying bedrock patterns, and fire (Science Coordination Team 2003; Ross et al. 2006). However, these other mechanisms alone cannot produce the flow-parallel patterning of the ridge-slough landscape without sediment redistribution from sloughs to ridges (Larsen et al. 2007). We conclude that current hydrologic conditions in the Everglades are not conducive to maintaining ridge-slough geomorphology. Further degradation of ridge and slough geomorphology and vegetation should be expected in the future at our site under current water management. Thus, restoring ridge and slough patterning in the Everglades will likely require greater water velocity than currently occurs.

Acknowledgments We thank Dan Nowacki, Jennifer O'Reilly, Ami Riscassi, Joel Detty, and Leanna Westfall for their assistance with field and laboratory work, and Forrest Dierberg, Kurt Kowalski, and anonymous reviewers for their valuable comments on an earlier draft of this manuscript. This work was funded by the Everglades Priority Ecosystem Science Program and National Research Program of the USGS and a Canon National Parks Science Scholarship to LGL. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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