Documenting the Importance of Water Flow to Everglades Landscape Structure and Sediment Transport in Everglades National Park

Project Final Report

Submitted to:

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EXECUTIVE SUMMARY

The Everglades wetland landscape is characterized by a heterogeneous wetland mosaic of strand-shaped sawgrass marsh and tree islands interspersed by deeper water sloughs. This landscape structure appears to be a result of the once historic, regular flow of water downslope from Lake Okeechobee to the Gulf of Mexico. Compartmentalization and canalization of the landscape has either greatly reduced or eliminated water flow, though. A primary result has been the loss of the "corrugated" ridge and slough topography, of slough connectivity along general flow paths, and of many tree islands in much of the remaining Everglades. In 2003, the Science Coordination Team suggested that flow conditions in the slough and ridge system be examined in order to assess the progress of the Comprehensive Everglades Restoration Plan (CERP). In this report, we present results from the first phase of our research quantifying how water flow affects particle transport, and how both are affected by vegetation and topography, in the Shark River Slough region of Everglades National Park.

Water velocities and flow rates were nearly always less than 2 cm sec^{-1}, and were typically below 1 cm sec^{-1}. Water flow through sloughs tended to be higher than across sawgrass ridges, but this difference was often not significant. We found close coupling between water flow in central Shark River Slough and the status of the S-12 structures on Tamiami Canal: Peak flows occurred when all 4 structures were open (August – October) while minimum flows coincided with the S-12 structures being closed (after November). Although Shark River Slough is an expansive landscape, and although it receives considerable direct rainfall, the management of canal inflows at the S-12 structures plays a dominant role in the water flow environment.

The particulate sediment dynamics of Everglades wetlands are unique in several ways: 1) there is no source of terrigenous-clastic sediments to this largely ombrotrophic landscape; 2) the water column in Everglades freshwater marshes is typically clear and devoid of visible particulate loads, and; 3) virtually all of the particles in this landscape are organic, are, autochthonously derived, and are referred to as "floc". Floc has a very low bulk density and is typically found as a nearly neutrally buoyant organic layer just above the soil surface. Floc layers are typically thicker in sloughs than on sawgrass ridges, and slough floc has greater P content than sawgrass floc. Seasonally, floc depths tend to be greatest in mid-wet season. We found that the new production of floc, largely from decomposing *Utricularia* and *Eleocharis* and from periphyton, only slightly exceeds the metabolic turnover of floc. The balance is presumably floc that may be transported down-slough, if water velocities are great enough. We found the empirical measurement of this actual floc transport to be difficult, and are developing new field techniques to meet this challenge in our Phase II research.

We quantified water flow rates and floc production rates along a landscape-scale (<100 m) transect that included several sawgrass ridges and sloughs, and found that water velocities were typically higher in the sloughs. Because sloughs also had deeper water, this equated to considerably greater water flow (in m^3 sec^{-1}) through sloughs, compared with over sawgrass ridges. Interestingly, though, vertical velocity profiles were not typical of most wetlands—the canopy architecture of the entire plant community caused non-systematic variation in profiles both on sawgrass ridges and in sloughs. On sawgrass ridges, velocity profiles varied largely in response to differences in the amount and configuration of the standing dead litter. In sloughs, we expected typical wetland velocity profiles because of the regular architecture of Eleocharis stems. However, the frequent presence of other plant species that have non-cylindrical

morphologies (i.e. *Panicum haematomon*) and floating mats of *Utricularia, periphyton*, or a complex of both, were all responsible for variable velocity profiles in slough marshes. Floc production was highest at the slough sites along this transect, verifying the pattern of both deeper floc depths and greater production rates that we observed at our long-term slough and sawgrass ridge sites.

One key objective in this study was to use an ecosystem-scale field manipulation to enhance ambient flow rates through an experimental area of marsh. We used large plastic walls permanently installed in the experimental slough marsh to focus flow into a flow-enhanced flume, and to reduce flow behind flow-blocking walls. We used this experimental flume to also manipulate emergent vegetative cover. We found that the *Utricularia*-periphyton complex tended to not occur where there were no emergent plant stems, and that floc production was considerably lower in these no-stem experimental areas.Although we were able to slightly increase flow rates, the differences were typically not significant. We were able to significantly decrease flow rates with our manipulation, though. Based on our two-year efforts with this pilot flow manipulation, we decided to try a different approach to flow manipulation in Phase II. In this new research, we will be locating much of our observational studies in marshes immediately downstream of the anticipated location of the future Tamiami Trail Bridge. This 4-mile gap in the Tamiami Canal levee will allow unhindered water to flow from the Tamiami Canal south into northeastern Shark River Slough, and to our marsh sites. We plan to collect 2-3 years of pre-bridge (e.g. pre flow manipulation) data to compare with the higher flow, post-bridge situation. This kind of BACI approach will allow us to effectively quantify the effects of increased water flow without the expensive logistical considerations of manipulating flow ourselves.

In accordance with Cooperative Agreement #1443CA 5280-01-021 between the U.S. Department of the Interior, Everglades National Park (ENP) and Florida International University (FIU), this report describes specific activities undertaken by FIU and by the University of North Carolina – Wilmington (UNC-W) as a subcontractor, during the duration of this project. As per the Project Work Plan, this report fulfills all final project deliverables. Close contact was maintained with Sherry Mitchell-Bruker, Co-Investigator and Project Manager at the South Florida Natural Resources Center (SFNRC-ENP) throughout the duration of the project.

PROJECT OVERVIEW AND INTRODUCTION

The Everglades wetland landscape is as distinctive as it is heterogeneous. This landscape is characterized by teardrop-shaped tree islands in a wetland mosaic of strand-shaped sawgrass marsh and deeper slough systems. Increasingly, evidence shows that this landscape structure is a result of the once historic, regular flow of water downslope from Lake Okeechobee to the Gulf of Mexico. Even an untrained observer can tell you the predominant direction of historical water flow through the Everglades by simply looking at the landscape from the air. The last 100 years of water management has compartmentalized the landscape and impounded water, though. In most of the remaining Everglades, flow is either greatly reduced and sporadic or is non-existent. Analyses of historical data support the hypothesis that the Everglades wetland landscape was structured and maintained by regular water flow, probably in a disequilibrium state (McVoy and Crisfield 2001, SCT 2003). This type of flow-mediated topographic maintenance has been demonstrated for other peat-based wetland systems (Nungesser 2003, McMullen et al. 2004). In the Everglades Ridge and Slough landscape, equilibrium trajectories should tend to fill in deep sloughs with organic sediments, while the elevations of the higher sawgrass strands would be mediated by hydroperiod. Flow thus kept the sloughs scoured, maintaining pathways for downstream movement of large volumes of water in a landscape analogous to braided streams. The loss of the “corrugated” ridge and slough topographic features, of slough connectivity along general flow paths, and of many tree islands in much of the remaining Everglades point to the validity of this hypothesis (Aumen, 2003). In 2003, the Science Coordination Team suggested that flow conditions in the slough and ridge system be examined in order to assess the progress of the Comprehensive Everglades Restoration Plan (CERP).

Tree islands are an important component of the central Everglades ridge and slough landscape. Restoration of the Everglades will not be successful without protecting the place and character of these tree islands. However, our knowledge of tree islands is insufficient to predict how they will respond to changing water management and restoration. There are hypotheses about how tree islands form, and about how they develop over time from these beginnings, but we know little about what conditions will enable tree islands to persist in a changing hydroscape (Van der Valk and Sklar, 2002). Because of the uniformity of their orientation and shape across the central Everglades, it seems apparent that water flow has played a vital role in tree island dynamics, but at present we lack functional understanding of how water flow controls the sedimentation processes that build or maintain tree islands. For this reason, we focused considerable attention in this study on water flow and particulate transport dynamics around tree islands in Shark River Slough.

Important questions still remain regarding the extent to which these processes impact materials transport and the extent to which these processes may influence the maintenance of landscape morphology in the Everglades. The research we summarize in the report addresses some of the mechanisms needed to maintain and/or restore the historic Everglades landscape of strand-shaped sawgrass marsh and deeper sloughs scattered with teardrop-shaped tree islands. An enhanced understanding of the interaction between morphologic structure, vegetation characteristics and flow is especially crucial to the future of Everglades Restoration, which is focused on restoring water fluxes to levels most beneficial to ecosystem function.

The purpose of this study was to quantify flow velocities and particulate transport in the Shark River Slough region of the Everglades National Park, and to model those dynamics. Our general project objectives were: 1) to document the dynamics of flocculent organic matter production, fate, and transport in Everglades wetlands; 2) to document biotic and abiotic controls on water flow regimes in freshwater marshes; 3) to experimentally manipulate water velocities and flow rates in an Everglades slough in the context of Objectives 1 and 2; 4) to quantify water flow and particle transport phenomena near tree islands; 5) to relate these flow dynamics to sedimentation/erosion and forest productivity on tree islands, and; 6) to simulate water flow and particle transport in complex ridge and slough landscapes. This report is divided into three sections: (I) Marsh Flow Dynamics (which addresses Objectives 1 – 3); (II) Tree Island

Dynamics (which addresses Objective 5; Objective 4 was addressed in a separate report to ENP from the University of Miami); and; (III) Modelling Results.

MARSH FLOW DYNAMICS

INTRODUCTION

Flows across vegetated marsh surfaces are inherently complex (Nepf et al. 1997, Järvelä 2002). Previous studies have described how plant/geomorphology/flow interactions can influence particulate transport in tidal wetlands (e.g. Leonard and Luther 1995; Friedrichs and Perry 2001), but few such studies exist for freshwater wetlands, including Everglades wetlands. Fine scale flow dynamics and turbulent exchanges affect: 1) oxygen and nutrient exchanges at the soil-water interface (Escartin and Aubrey 1995); 2) microclimate regulation between plant stems (Dade 1993); 3) the nutritional environment for suspension-feeding animals (Irlandi and Peterson 1991); 4)larval recruitment (Eckman 1983), and; 5) sediment deposition and retention processes (Leonard and Luther 1995). Hydrodynamic exchanges may also influence aquatic faunal dynamics in a number of ways (Butman 1987, Palmer 1986, Peterson and Turner 1994, Shimeta et al. 1995).

Previous (e.g. Leonard et al., 1995, Leonard 1997, Leonard et al. 2002) and on-going (Leonard and Reed 2002) work in other marsh systems has shown that fine scale flow structure controls suspended particle distribution over both vertical and horizontal scales. Saiers et al. (2003) found similar relationships in Shark River Slough, ENP. Flow patterns resulting from the synergistic interactions of channel morphology, marsh microtopography, and length of inundation exert significant control over the spatial distributions of suspended and deposited particulate matter in many vegetated systems (Leonard, 1997, Christiansen et al., 2000). Similar interactions may be responsible for the dysequilibral maintenance of the geomorphic framework of the tree island/ridge and slough system in the Everglades.

Another complexity in understanding sediment transport in Everglades wetlands arises because the vertical structure of marsh flows is strongly related to canopy architecture. Vertical flow profiles from canopies in Gulf of Mexico saltmarshes are not uniform and deviate from the logarithmic profile typical of areas lacking vegetation (Leonard and Luther 1995). We have found similarly complex vertical profiles in Everglades sloughs. In many cases, flow conditions in wetland canopies are neither fully turbulent nor fully laminar because of plant/flow

interactions, (Kadlec, 1990; Leonard and Luther, 1995). Consequently, microturbulence and flow energy in a vegetated canopy may be most strongly affected by plant canopy architecture and available biovolume (Stephan and Gutknecht 2002). This is of particular interest to flow through Everglades marshes because plant density and morphology in sloughs often vary greatly, exerting strong controls on flow characteristics—and both flow rate and flow character directly control rates of both sediment entrainment and transport.

Unlike most wetlands, Everglades marshes contain very little inorganic sediment; most particles are organic. The bulk of this particulate organic matter takes the form of flocculent detritus ("floc") found in an unconsolidated layer just above the soil surface and the transport of this material is primarily a bedload phenomenon. Notably, the material we refer to as "floc" is not analogous to the microparticulates produced by traditional flocculation processes (i.e. Stone and Krishnappan 2003).

METHODS – MARSH FLOW DYNAMICS

We studied the dynamics of water flow and particle transport in a variety of field settings and conditions in upper Shark River Slough (SRS), Everglades National Park, FL (ENP; Figure 1). Shark River Slough is a ridge and slough landscape. This landscape is characterized by a "corrugated" topography in which deeper sloughs (most often vegetated by spikerush; *Eleocharis sp.*) are interspersed among higher ridges, that are dominated by sawgrass (*Cladium jamaicense)*, and tree islands that are often high enough to support a rich terrestrial flora.

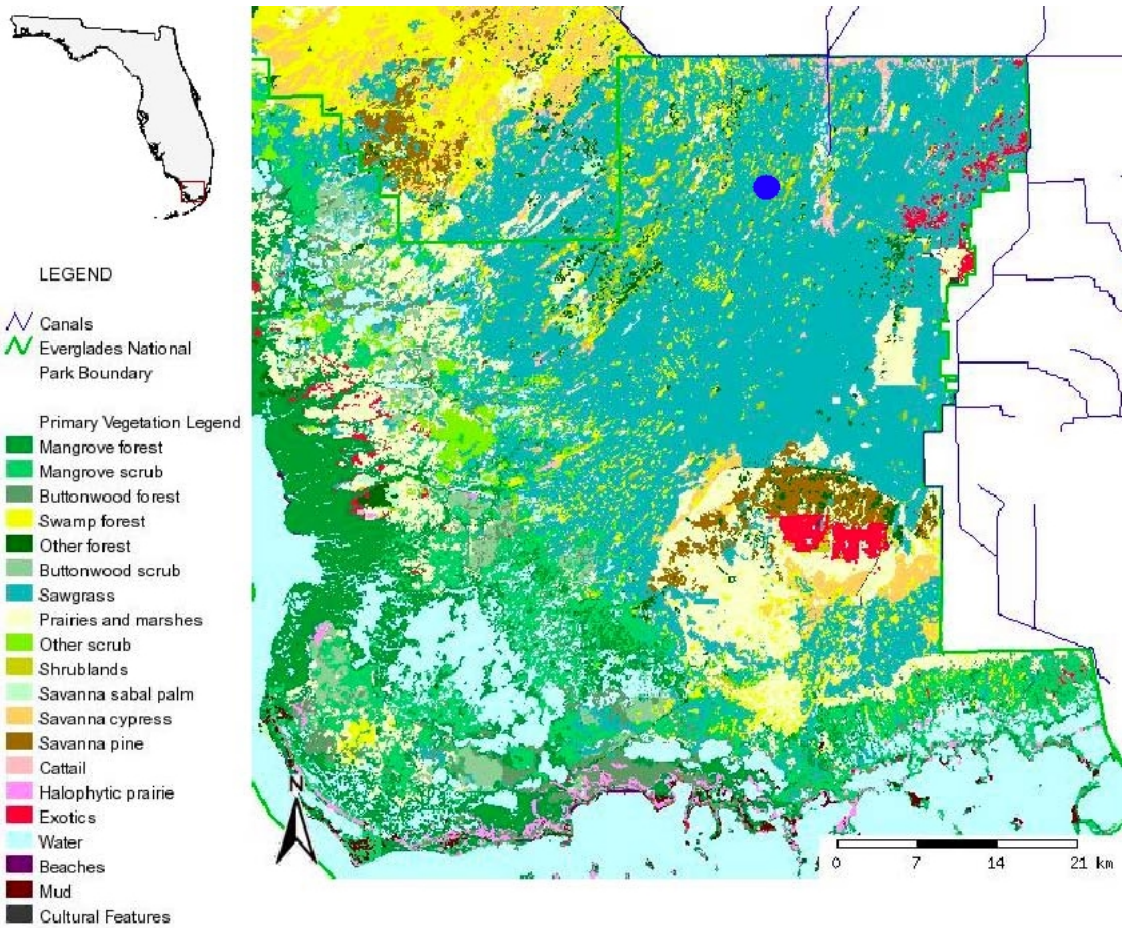

Figure 1: Map of the Shark River Slough region of Everglades National Park. The blue dot marks the area where the Marsh Flow Dynamics research was conducted (near Gumbo Limbo Tree island).

Throughout much of central SRS, this ridge and slough landscape fits a braided stream or an anabranching river configuration (Wende and Nanson 1998), suggesting that the advective movement of water through this landscape [at one time] played a strong role in the distribution and maintenance of landforms and topographic variability. Within the slough environments, submerged vegetation (bladderwort; *Utricularia sp*., periphyton mats, and *Bacopa* sp.) is often present in high densities. On the ridges, the plant community is typically dominated by often dense stands of sawgrass. Both emergent and aquatic vegetation represent potential impediments to water flow and particle transport, and we directed considerable attention to these phenomena.

The Marsh Flow Dynamics research was divided into four focus areas: 1) The characterization of water velocity profiles and net water flow; 2) The dynamics of floc and soil production, fate, and transport in slough and ridge landscapes; 3) The effects of vegetation in a variety of configurations, on water velocity profiles, flow dynamics, and particle transport, and;

4) The potential effects of increased flow, such as that likely to result from planned restoration activities, as measured by experimentally enhancing water velocities and flow in the field. The Marsh Flow Dynamics section of this Final Report is organized by these four focal areas.

1. Water Velocity Measurements

State-of-the-art Acoustical Doppler Velocity meters (ADV, SonTek Handheld FlowTracker ADV, San Diego, CA) were used for measuring water velocity (Figure 2). These

Figure 2: Picture of a Sontek hand-held Flowtracker ADV used to measure water velocity.

instruments generated highly reliable and accurate water velocity measurements in 3 dimensions for the exceedingly low velocity values that are characteristic of Everglades marshes. The Flowtracker units are designed with a "side-looking" orientation where the acoustical signal is transmitted to the side of the instrument rather than below, thereby allowing for measurements in water as shallow as 15 cm. According to the manufacturer, the handheld ADV was capable of measuring velocities in the range of 0.01 to 500 cm sec^{-1}.

Measurements of water velocity were typically made at a depth of 60% of the total water depth. Vertical profiles were obtained by taking measurements at 2 to 4 equally spaced depths from the water surface to the soil surface. The handheld ADV was configured to average data over 30 seconds of sample collection. The ADV transmitted 10 acoustical signals or "pings" per

second. The average of these 10 pings was stored as a one second sample, such that each 30 second sampling consisted of 30 data points. The instruments are capable of generating data in units of both water velocity (cm sec^{-1}) and water flow (m^3 sec^{-1}). We also calculated water flow for the entire water column by integrating velocity measurements made from depth profiles over the full water depth. Unless otherwise stated, all water velocity and flow data were generated with these Flowtracker instruments.

2. Floc and Soil Dynamics

Particulate transport in SRS marshes, and in ridge and slough wetlands in general, is dominated by organic "floc", which moves largely as bedload near the soil surface. Thus, floc dynamics were central to our particulate transport research. We used a conceptual model of those dynamics to guide this research (Figure 3). Key processes in this conceptual approach in included floc production, floc turnover or metabolism, floc deposition to the soil surface, and floc transport as bedload driven by water flow.

Preliminary examinations of floc showed that it is a mixture of organic constituents that appeared to be derived of sloughed periphyton cells, small pieces of dead *Utricularia*, and small fragments of other slough plants (particularly *Eleocharis* stems). These components are all found in the upper water column, while floc is largely a benthic phenomenon. For this reason, we quantified the production of new floc using sediment traps that captured the vertical "rain" of new floc particles throught the water column (Figure 4). Sediment traps were modeled following open ocean instruments, and included an array of 1 cm diameter baffles within the 8 cm cups designed to baffle any resuspension of captured particles by water advecting across the top of the traps. Traps were held in place with a 30 cm stainless steel pin that was attached to the cup. The pin was inserted into the soil such that the top of the trap cup was just above the floc layer. A lid was put on the traps when deployed, and we removed the lid after 15-30 minutes, to allow an disturbance of the floc layer to settle. After deployment for variable periods of time (typically 2 – 24 hours), the lid was gently placed on the trap and the trap was removed. The contents were poured into field containers, and the contents were dried, weighed, and analyzed for organic and nutrient content in the lab. Floc production was calculated as mg dw m^{-2} hr^{-1}.

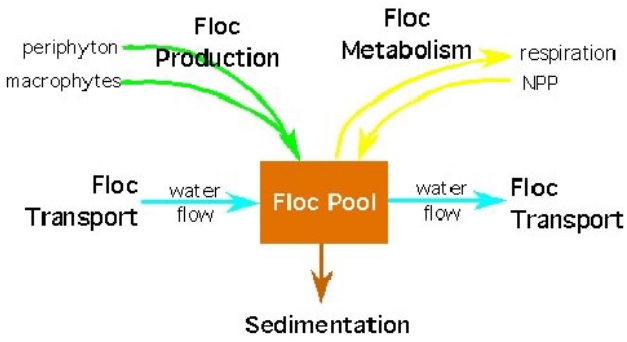

Figure 3 (left): Conceptual model of floc dynamics.
Figure 4 (right): Picture of sedimentation traps used to collect floc production.

Floc turnover is a key variable in understanding floc dynamics, and our floc metabolism measurements. We used standard light-dark bottle oxygen flux measures to quantify the rate of floc decomposition—as net oxygen consumption—and floc primary production—as net oxygen evolution (Figure 5). Floc was collected using the technique described below (see Floc Pool methods), and poured into triplicate light and dark BOD bottles. For all experiments, we also incubated only marsh water in triplicate light and dark BOD bottles as a control. Oxygen and temperature were measured in all bottles initially and after incubation (typically 2 – 4 hours). The floc in the BOD bottles was collected in Whirlpac bags and returned to the lab for dry weight, organic content, and nutrient content analysis. Oxygen change measurements were converted to mg dw loss (negative NPP) or gain (positive NPP) mg dw floc^{-1} hr^{-1} using standard oxygen:carbon:dry weight stoichiometric relationships.

Floc transport was the most difficult dynamic process to quantify. We developed a passive trap technique (which we refer to as a "flocculator"; Figure 6) to capture floc bedload transport. Flocculators were deployed with the doors (see Figure 6) in place by placing the flocculator gently on the soil surface. The doors were gently removed 15 – 30 minutes after deployment, to allow any disturbance of the floc layer to settle. After variable incubation times (30 minutes to 6 hours), the doors were re-inserted, the flocculator was removed, and the contents were returned to the lab for dry weight, organic content, and nutrient content analysis. Theoretically, the floc contained in the flocculator represented the mass of material moving horizontally along the soil surface as bedload across the width of the flocculator over the time of

incubation. We anticipated that the mass of floc trapped would increase with increasing incubation times, to the point where steady state was reached (where the mass of floc entering the flocculator = the mass leaving). When plotted against incubation time, the derivative of the floc mass/incubation time curve should represent floc transport. As we discuss in the Results and Discussion section, these results proved to be equivocal.

Figure 5 (left): Picture of the BOD bottle and oxygen change apparatus used to quantify floc turnover/metabolism. The light bottles with floc are on the right; the control light bottles are on the left.

Figure 6 (right): Picture of a "flocculator" used to quantify floc transport. Note that the leading edge of floc bedload, which was moving from left to right, has not completely passed through the flocculator during this incubation.

We used a simple technique to quantify potential floc incorporation into the soil while also measuring long-term changes in soil elevation (due to soil development or erosion). Periodic dry-down events likely control the incorporation of the floc layer into the soil while high-flow events likely erode unconsolidated slough soils. We quantify these dynamics by long-term monitoring of fiberglass pins (5mm dia.) that were inserted into the soil to bedrock (Reed 1992). Temporal change in the height of the pin above the soil surface equated to either erosion or increases in soil elevation. We installed and monitored 6 such pins at all field sampling sites.

The final component of our conceptual floc model (Figure 3) was the size of the floc pool itself. We quantified this at all field sampling sites using a 2.5 cm lexan tube fitted with razor blades on the bottom edge. The tube was gently inserted through the floc layer, and we cut a soil plug for the tube by gently rotating the tube to cut through the soil. The tube was stoppered and removed. The height of the floc in the tube was measured and the water was decanted off. The floc sample was returned to the lab for dry weight, bulk density, organic content, and nutrient

content analysis. We collected triplicate floc cores during all sampling events to quantify the standing pool of floc at all study sites (reported in g dw m^{-2}). Once a year, we retained the soil from these cores and returned the soils to the lab for analysis.

3. Effects of Vegetation and Landscape Position on Flow Rates and Floc Dynamics

Many of our time-series measurements of water velocity, flow, and floc dynamics were made at our long-term sampling sites. To scale these measurements up to a broader, landscape perspective, it was important that we understand how water velocity profiles, flow rates, and floc production dynamics changed in different ridge and slough environments. We addressed this data scaling issue by establishing a transect near our long-term sampling sites that was oriented normal to the direction of mean water flow. At 10 m intervals along this roughly 300 m transect, we measured water velocities and flow, water depth, floc production, and emergent vegetation density. We sampled this transect three times between October 2003 and January 2004. Due to material limitations, we were unable to deploy sediment traps at all sites along this transect. We deployed traps at select sites to optimize for different vegetative characteristics, and only one trap was deployed at each site. During our October 2003 transect sampling, we surveyed vegetation at each transect station for which floc production data were collected. We counted the number of live and dead emergent stems of all plants present in a 0.25 m^2 quadrat at these locations. Quadrat locations were selected blindly to allow for random sampling. In December 2003, we also measured the elevations of these transect stations relative to each other using a Leica laser Total Station.

We used a series of small-scale field experiments to investigate how vegetative characteristics control water velocity profiles and flow rates in Everglades sloughs. In these experiments, we related the densities of emergent biomass (mostly *Eleocharis* sp.), of floating periphyton mat, and of aquatic vegetation (mostly *Utricularia* sp.) to measured velocity profiles. The influence of standing biomass on flow was determined two ways: 1) in a descriptive sense, by quantifying stem densities in the locations where water velocities were measured, then correlating flow rates with vegetation densities, and; 2) in an experimental sense, by manipulating plant biomass. This was done by first simultaneously measuring velocity at two heights in the water column (12 and 38 cm below the water surface), assuming that water flow was zero at the soil surface. We then removed all aquatic plant biomass (*Utricularia* sp. and

periphyton) from a 1 m^2 area centered on the Flowtracker sensor array, and repeated the velocity profile. Finally, we cut all emergent plant stems from the 1 m^2 area and measured velocity profiles for a third time. These data allowed us to establish which components of the vegetation matrix affected which components of water flow integrated from the surface to the soil interface, and thus to make inferences about resistance to water movement in Everglades slough environments.

4. Experimentally Enhancing Flow

Various aspects of the Everglades Restoration effort are expected to increase water depths and water flow in Shark River Slough. A key objective of this study was to understand how increased water flow may affect Everglades slough environments. Central to this objective was a field manipulation in which we attempted to experimentally increase flow through an isolated section of slough marsh (see Figure 1 for the location of this experiment). We did this by constructing a flow enhancement structure that used permanent plastic walls to focus water flow into a flume while using the same walls to isolate a slough sampling area from flow (Figure 7). The walls were constructed of 6 mil plastic cut into 1 m strips and attached to PVC poles set into the soil. The plastic walls were placed to minimize water flow around or under the experimental structure. The walls were approximately 70 m in length and the experimental flume was 30 m long and 3 m wide. Boardwalks allowed us to access the flow-enhanced flume area and the no-flow sampling area without disturbing the soil, floc, or vegetation. We accessed both areas by spanning the boardwalks with 4 m ladders and sampling from these horizontal platforms. The flow-enhanced flume had three permanent vegetation manipulations as well: A 1 m wide region in which we removed all emergent vegetation, a 1 m region in which we removed roughly half of all emergent stems, and a region in which we did not manipulate stem densities. The no-vegetation area was downstream of the half-vegetation area, and both were downstream of the unmanipulated vegetation area. All of the parameters discussed below were sampled in all three enhanced-flow flume zones, in the no-flow area, and at two control sites that were located in an adjacent slough. Both control sites had a slough sampling site and a sawgrass ridge sampling site.

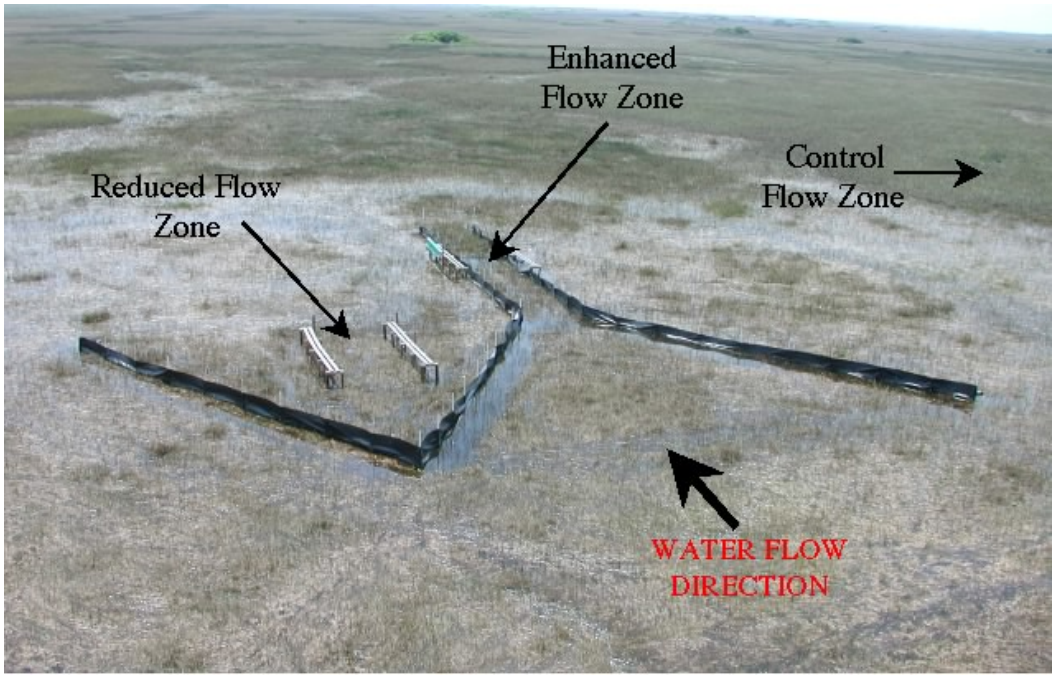

Figure 7: Aerial photograph of the flow-enhancement experimental set-up. The experimental flume is shown as the "enhanced flow zone", the no-flow area is shown as the "reduced flow zone", and the control sites are located to the right, in the adjacent slough.

Water velocity, water flow, floc transport, floc production, floc metabolism, floc pool size and characteristics, soil characteristics, and soil elevation change were monitored in the experimental flume and at nearby slough and ridge control sites. These data were collected approximately bi-monthly from December 2002 until February 2003, from June 2003 until January 2004, and in August 2004. Triplicate samples were collected for all data, and details of the sampling protocols are presented in separate sections (above).

RESULTS & DISCUSSION

1. Water Velocity and Flow Characteristics

We began our assessment of ambient water velocity and flow characteristics at the two control sites used in the flow enhancement experiment. Each contained a slough and a ridge sampling area (Table 1). Flow velocities in the study area were very low, less than 2 cm sec^{-1}, and laminar to sublaminar. Velocities measured at the slough control sites were generally higher than at the sawgrass ridge control sites, with mean velocities of 0.50 cm sec^{-1} and 0.34 cm sec^{-1}, respectively (Figure 8). A t-test, however, showed no significance difference in velocity between the two landscape types over the entire study period.

Table 1: Water velocities (cm sec^{-1}) measured at the flow enhancement experiment control sites.

	Sawgrass 1	Sawgrass 2	Slough 1	Slough 2
12/18/2002	0.208	0.055	No Data	0.246
1/10/2003	0.049	0.218	0.238	0.257
1/23/2003	0.088	0.349	0.233	0.279
2/15/2003	0.115	0.081	0.080	0.199
6/24/2003	0.720	0.477	0.302	0.711
8/22/2003	0.466	0.892	0.988	1.015
10/15/2003	0.480	0.437	0.888	0.960
12/10/2003	0.462	0.221	0.784	0.435
1/29/2004	0.191	0.668	0.356	0.492
8/30/2004	0.458	0.643	0.374	0.505

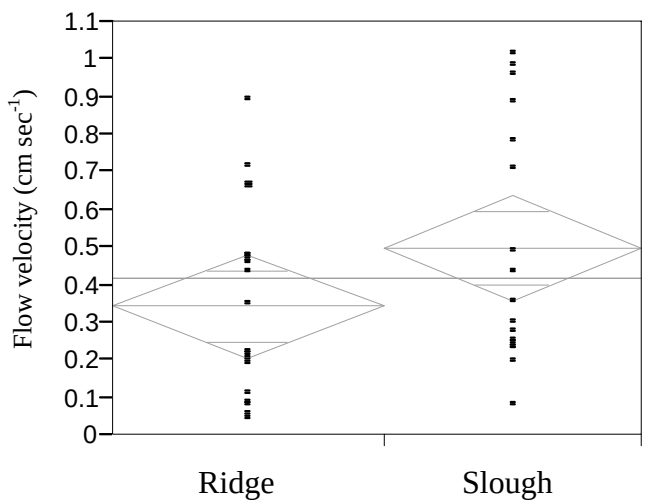

Figure 8. Mean flow velocities measured at sawgrass ridge and slough control sites over the study period. Means were calculated from all bi-monthly measuring periods between June 2003 and January 2004. The diamonds represent the mean (widest point), SD (smaller lines), and 95% confidence interval (top and bottom of the diamonds) of each data distribution.

Flow velocities were seasonally variable at all sites, and that seasonality was closely related to management of the S-12 water control structures and availability of water to SRS. For example, we measured the highest velocities at the slough and ridge control sites during peak wet season (August and October 2003), when water levels were highest and all four S-12 structures were open (Figure 9). Conversely, the lowest mean velocities occurred early and late in the wet season, when water levels were lower and the S-12 structures were mostly or completely closed. This trend was more apparent for the slough sites than the ridge sites (Figure 9). We expanded

this dataset to include the ridge and slough sites sampled along the landscape transect, and found a significant positive correlation between water level and flow velocity for all sampling dates combined for both the slough ($p<0.0001$) and ridge ($p<0.005$) control sites (Figure 10).

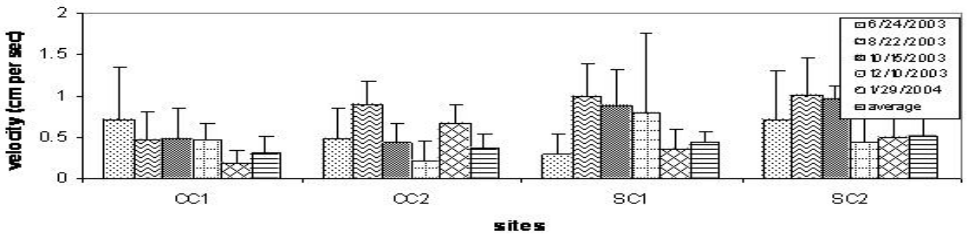

Figure 9. Mean bi-monthly flow velocities measured at selected sawgrass ridge control sites (CC = Cladium control) and slough control sites (SC = slough control) over the entire study duration. Error bars represent one standard deviation of the mean velocity.

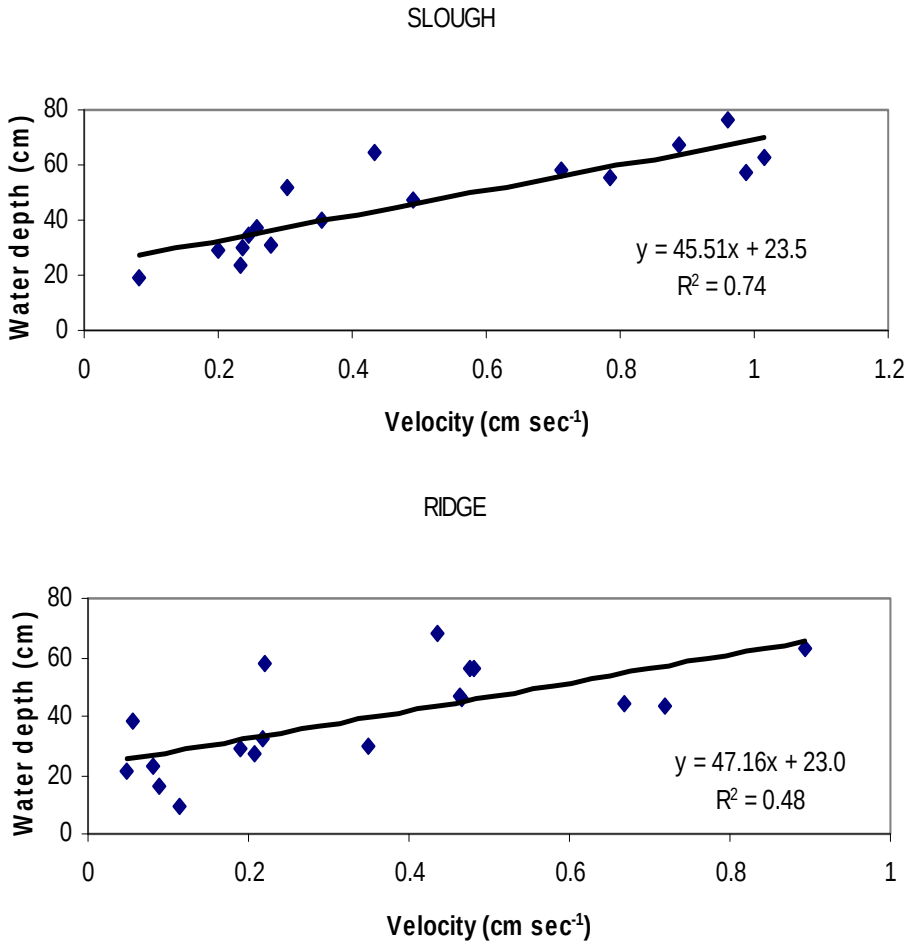

Figure 10. Regressions of flow velocity versus water depth for slough and ridge sampling sites along the Gumbo Limbo landscape transect. Both regressions are significant.

2. Floc and Soil Dynamics

The production of new floc, as measured in benthic sediment traps, showed little seasonality. Although there was a tendency towards lower floc production late in the wet season, this trend was not significant (Figure 11A). The overall average production of floc was greater at our slough sites (25.9 and 35.7 gdw m^{-2} d^{-1} for SC1 and SC2, respectively) relative to at the sawgrass ridge sites (15.4 and 21.6 gdw m^{-2} d^{-1} for CC1 and CC2, respectively). However, these differences in floc production were not significant (Figure 11A). This latter finding is surprising, given that microscopic analysis of floc showed it to be derived from fragments of periphyton, *Utricularia*, and *Eleocharis*, all of which are much more prevalent in sloughs than on sawgrass ridges. It is possible that some floc captured in our sediment traps was transported onto the

ridges from the sloughs, but this is likely a more episodic phenomenon that likely did not occur during all of our samplings. The phosphorus (P) content of newly produced floc was more variable than the bulk production rates, and these data showed a tendency for new slough floc to contain more P than new sawgrass ridge floc (Figure 11B). Overall, the P component of new slough floc averaged 17.5 and 15.8 mg P m^{-2} d^{-1} (SC1 and SC2, respectively), compared with 9.4 and 13.1 mg P m^{-2} d^{-1} at our sawgrass ridge sites (CC1 and CC2, respectively). This difference was not statistically significant. In general, newly produced floc was 0.5 to 1% P by weight.

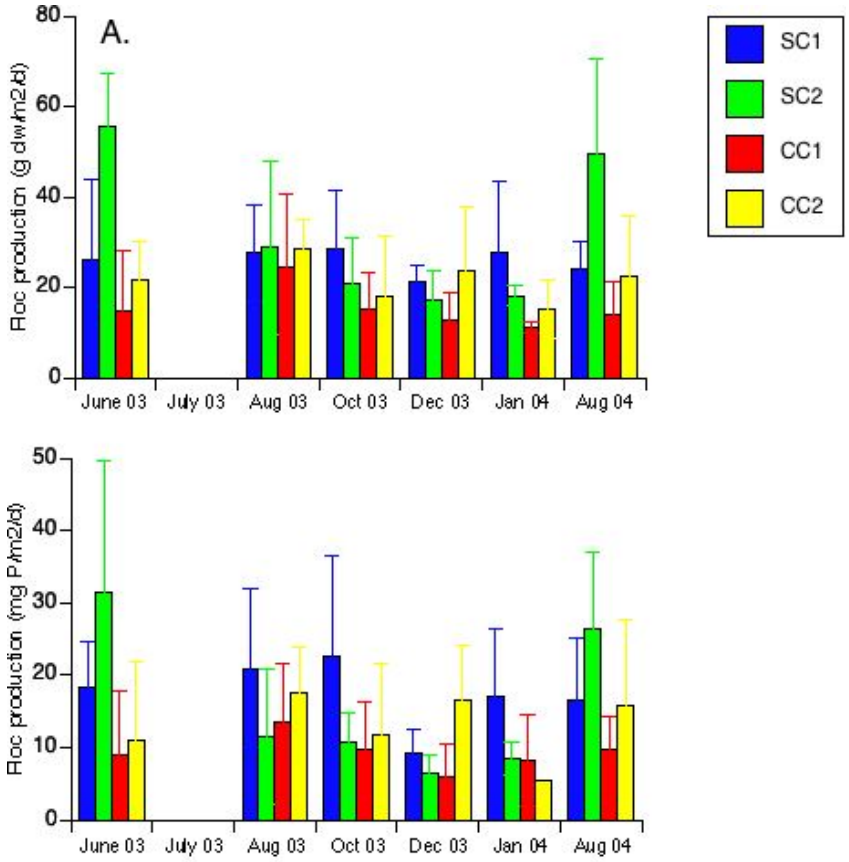

Figure 11. Floc production (A) in g dry weight and (B) in mg P, as measured in benthic sediment traps at the enhanced flow control sites. SC = slough control; CC = *Cladium* control. Error bars are standard deviations of triplicate sediment traps.

We define floc turnover as the metabolic change associated with decomposition, which we assume is dominated by aerobic processes, and with primary production, which we measure as net ecosystem production (oxygen change in the light bottles) but assume will be a minor component. As such, floc metabolism as shown in Figure 12 is effectively floc turnover. Our BOD incubations generated metabolic data in mg O_2 g AFDW $floc^{-1}$ hr^{-1}. We converted these to raw values in mg C evolved (respiration) or taken up (primary production) using standard C:O_2

stoichiometry. These values were scaled up to daily rates, and to a representative m^2 of marsh based on the floc pool size (g dw m^{-2}) measured at each site on the same day (the floc pool data are reported below). We converted g AFDW to g dw based on the average organic content of our floc samples (85%), assuming that 85% of dry weight was AFDW (Figure 12A). We converted the carbon component of floc metabolism to a P turnover rate by first converting the C flux to a g dw flux using the average %C from our floc samples (42%), then multiplying this rate by the P content of the floc samples collected at that site on that day (data presented below, in µg P g dw^{-1}; Figure 12B).

During all samplings, net ecosystem metabolism (NEP; defined as the whole-system balance of autotrophic and heterotrophic activity and measured as the balance of oxygen evolution and consumption by these respective processes) was negative, indicating that the floc was net heterotrophic. In January 2004, though, the magnitude of NEP was considerably less than the respiration rate at the sawgrass ridge control site (CC). This suggested that considerable gross primary production occurred in the floc on that day (Figure 12A). In most samplings, we measured a higher turnover rate in the slough floc compared with the sawgrass ridge floc, suggesting that slough floc may be more labile. Interestingly, though, this difference did not show in the phosphorus turnover rates associated with floc metabolism (Figure 12B). This may be associated with higher P content in the floc pool at the sawgrass ridge site (see floc pool data below), or it may be associated with a preferential remineralization of P relative to C in this habitat. The general trend, when comparing C metabolic rates with P metabolic rates, is that the latter are about 0.05 – 0.10% of the former (Figure 12). Newly produced floc is approximately 0.5 to 1.0% P by weight (on a dry weight basis). If about 42% of floc dry weight is C, this suggests that new floc has a C:P mass ratio of 1.2 to 2.4. This range of values is much greater than the 0.1% of C turnover via metabolism that is P remineralization, suggesting some mechanism by which biotic activity in the floc is strongly conserving P within the floc (rather than releasing it to the water column).

Floc transport proved to be the most challenging parameter to quantify in our conceptual model. There were problems with our experimental sampling technique for quantifying actual floc bedload movement (the “flocculator). We anticipated that we could deploy the flocculators for variable incubation periods, generating a hypothesized curve such as that shown in Figure 13. The derivative of this hypothetical curve would be the advective movement of floc per unit width

of a slough (in gdw m^{-1} d^{-1}). The data generated from numerous flocculator trials proved to be extremely variable, and rarely fit this expected pattern. We are currently working on modifications to our design and approach, and expect to have a usable field sampling apparatus soon. For this report, we will estimate a possible floc transport rate by difference, using a budget approach applied to our conceptual model (Figure 3). This is merely an estimate, however, as it assumes that we have accurately estimated all other fluxes of floc. We do not recommend the use of this estimate in models or other decision-making venues at this time.

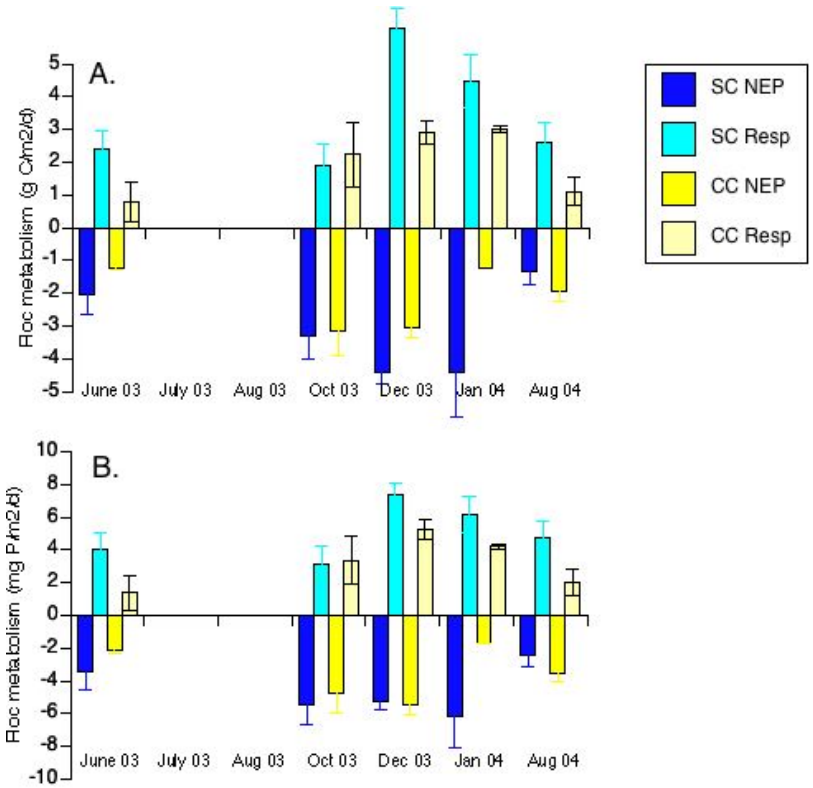

Figure 12. Floc metabolism (A) in g C m^{-2} d^{-1} and (B) in mg P m^{-2} d^{-1}, as measured via oxygen change in BOD bottle incubations at the enhanced flow control sites. Respiration is based on oxygen depletion rates in dark bottles, and net ecosystem metabolism (NEP) is based on oxygen change in light bottles (=gross primary productivity less respiration). SC = slough control; CC = *Cladium* control. Error bars are standard deviations of triplicate bottles.

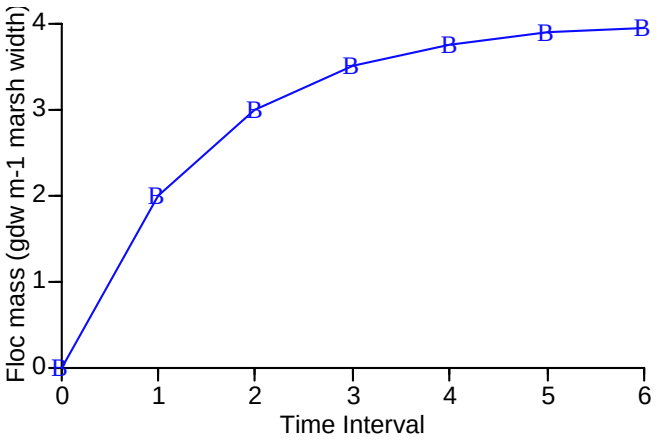

Figure 13. Hypothesized flocculator data showing an increase in floc mass captured with increased incubation time to an asymptote that represents the steady state condition, where mass of floc entering = mass leaving. The derivative of this curve would thus be floc transport per unit width of slough (g dw m^{-1} d^{-1}).

We quantified the size of the floc pool at all experimental sites during all sampling events. In most cases, floc bulk densities were similar in time, and the variation in floc pool sizes was largely driven by differences in the depth of the floc layer (Figure 14). Floc mass showed a tendency to be higher in the mid-wet season, when water flow and [potentially] transport down the system are greatest. In many samplings, we found significantly more floc mass at the #2 control site compared with the #1 control site—particularly in the slough. We attributed this to the relative orientations of the two sites—SC1 and CC1 are on the slough margin parallel to the general flow direction while SC2 and CC2 are located at the downstream end of the same slough. At this point, a sawgrass ridge largely blocks connectivity of this slough with sloughs further downstream. We interpret higher floc pool sizes here to mean that this floc is accumulating at this point of flow constriction. It appears to be accumulating on the sawgrass ridge as well as in the slough (Figure 14).

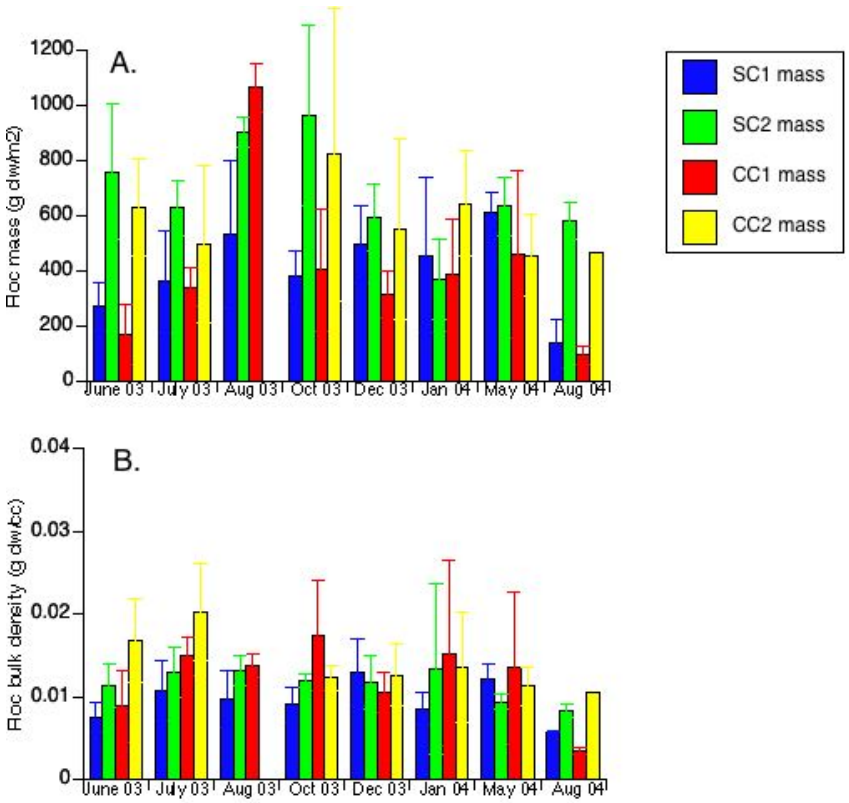

Figure 14. Floc (A) pool size, in g dw m^{-2} and (B) bulk density, in g dw cc^{-1}, at the enhanced flow control sites. SC = slough control; CC = *Cladium* control. Error bars are standard deviations of triplicate cores.

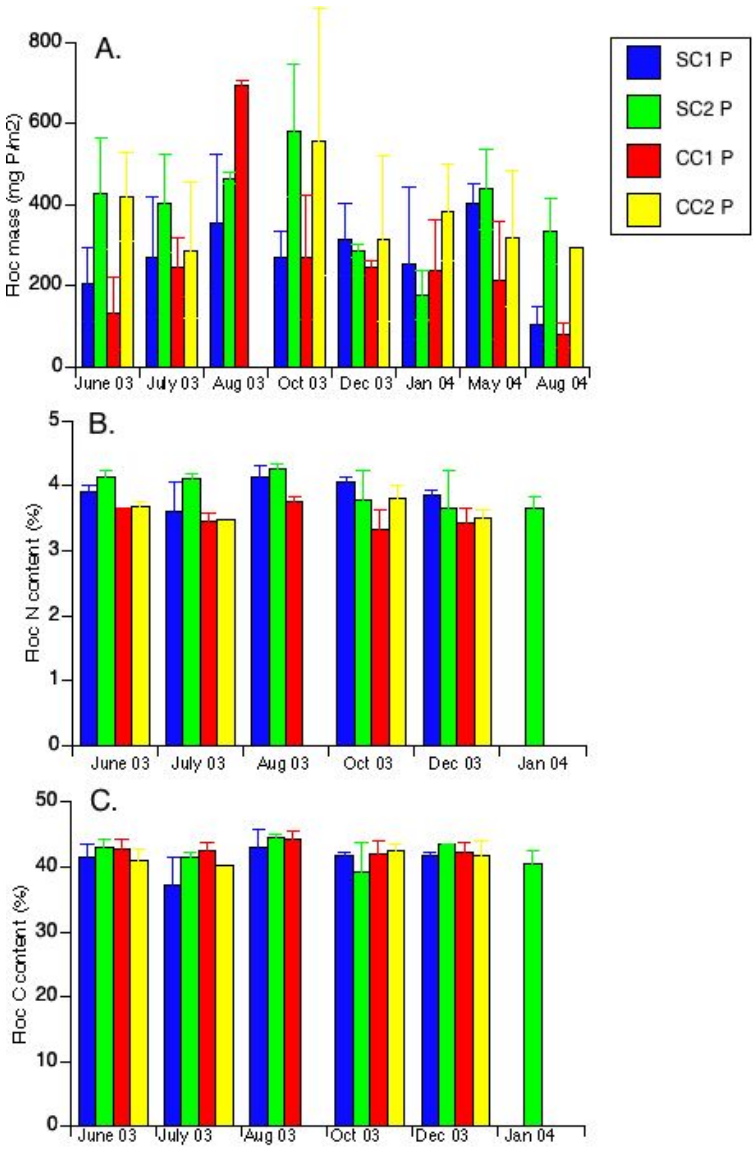

Figure 15. Floc nutrient content (A) phosphorus; (B) nitrogen, and; (C) carbon, at the enhanced flow control sites. SC = slough control; CC = *Cladium* control. Error bars are standard deviations of triplicate cores.

The nutrient content of floc at the slough and sawgrass ridge sites showed some interesting inter-constituent patterns. The carbon and nitrogen content was remarkably consistent among sites and across time (Figure 15B and C), while the P content varied as much as three-fold across time and sites (Figure 15A). There was a tendency for the floc P content to be similar at a given location (SC1/CC1 versus SC2/CC2), and often the P content of floc at the #2 control site was higher. These data were variable enough, though, that few of these patterns were statistically significant.

Long term changes in soil elevation could reflect the incorporation of floc into the surficial soil layer (positive change) or erosion (negative change). As we note above, we did not anticipate substantial incorporation of floc into the permanent soil column except during drying events (which did not happen during this study). Soil elevation data are notoriously variable, and must be cautiously interpreted over short time periods and when replication is low (Childers et al. 1993). Our data from the slough (SC) and sawgrass (CC) control sites showed no significant changes, because of high variability, and no trends over our 18 months of sampling (Figure 16). There is some suggestion of declining soil elevations during the wet season, but longer term data are needed to make any conclusions.

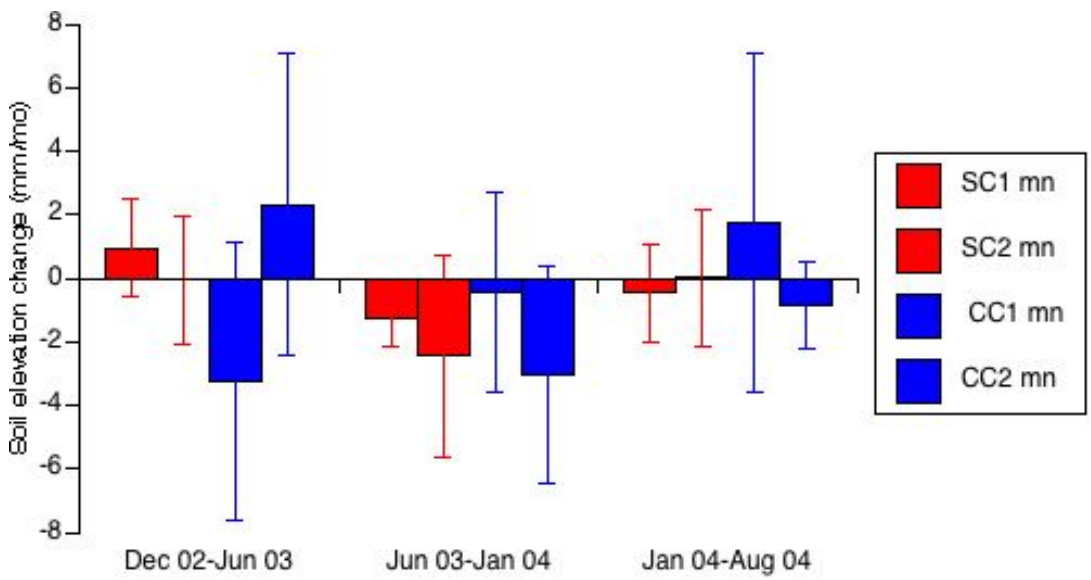

Figure 16. Change in soil elevations as measured with soil pins. SC = slough control, ambient plant density; CC = *Cladium* control, ambient plant density. Note that SC1 is the left-most red bar and CC1 is the left-most blue bar in both cases.

3. Controls on Flow Rates and Floc Dynamics by Vegetation and Landscape Position

We examined variations in flow over a larger scale by measuring flow velocity, sediment trap data, and water depth bi-monthly along a transect located near our permanent sites. We sampled this transect in October and December 2003 and in January 2004. Transects sites were classified as either slough or ridge by the vegetation present. For the most part, ridge sites were topographically higher than slough sites with the mean elevation of the ridge sites being approximately 12.8 cm higher than the slough sites (Figure 17). Mean water depth for the ridge and slough environments were significantly different ($p<0.0001$, $F=44.7$) with means of 53.6 and

61.9 cm, respectively. Over the sampling period, which was conducted near the end of the wet season, mean water depth decreased from 64.2 to 42.2 cm for the ridge sites and from 74.7 to 51.2 cm for the slough sites.

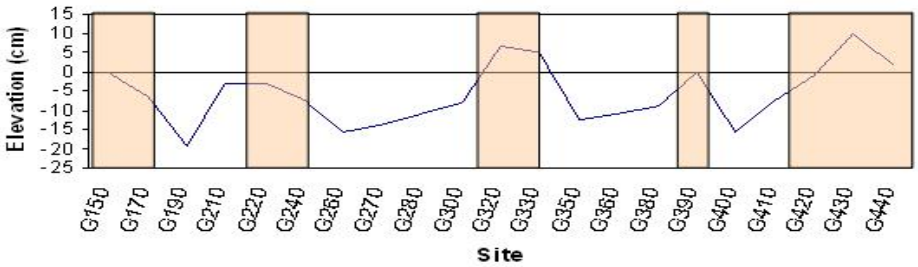

Figure 17. Topographic profile of the Gumbo Limbo Transect. Shaded areas indicate areas along the transect consisting of sawgrass ridge and white areas indicate spikerush slough.

In spite of the greater water depths, flow speeds in the sloughs were still quite low and never exceeded 1.8 cm sec^{-1}. Flow velocities in the sloughs also exhibited no systematic variation with respect to position in the slough, although higher velocities were often observed near the center or in the topographically lowest area of the slough (Figure 18). These results are consistent with velocity data collected along cross-sections of random sloughs in Shark River Slough which also show some tendency for the highest velocities to be centralized in the slough (Figure 19).

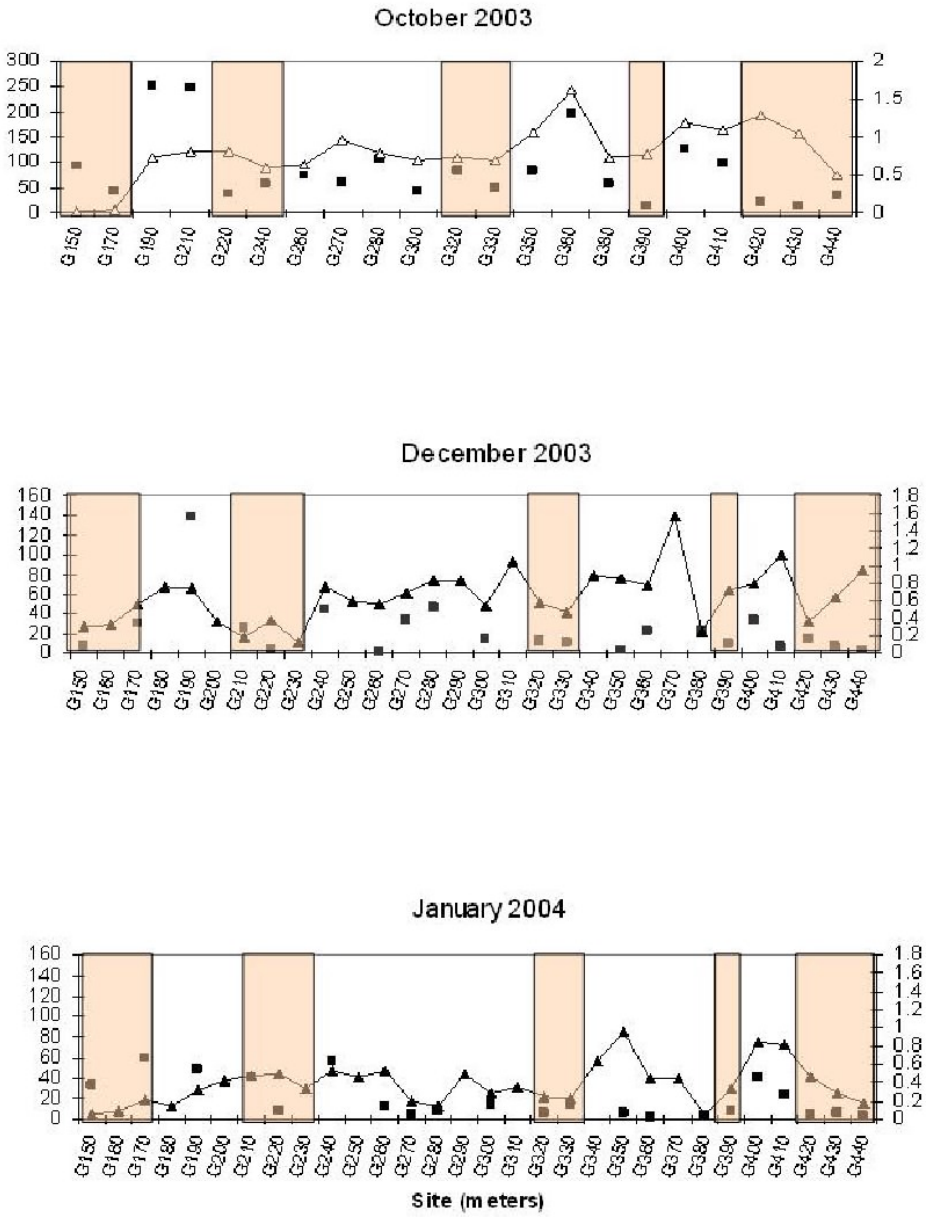

Figure 18. Flow velocity (triangles) and particulate accumulation (squares) along the Gumbo Limbo transect from samplings in October 2003, December 2003, and January 2004. Shaded areas depict sites on ridges and light areas are sites in sloughs. The X-axis shows site locations, with distances in meters from an arbitrary starting point.

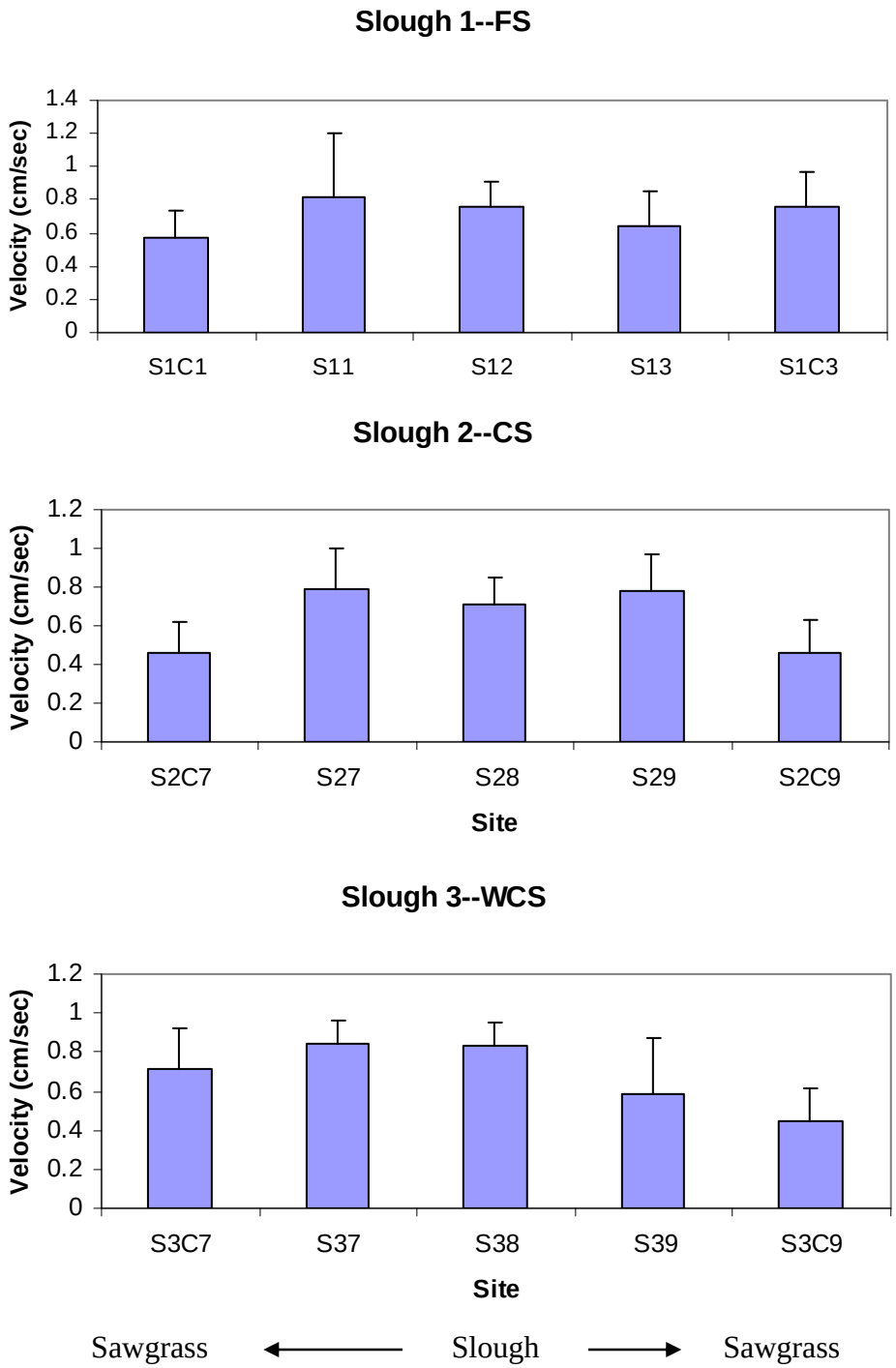

Figure 19. Mean (x,y,z) flow velocities measured across 3 sloughs near the transect shown in Figure 17. Transects were initiated from a sawgrass ridge at one edge of the slough and completed at a sawgrass ridge on the other edge. The other measures were taken at distances of 0.25, 0.5 and 0.75 the width of the slough.

The mean daily rate of floc production collected in the sediment traps ($p<0.05$, $F=6.67$) and the mean flow velocity ($p<0.05$, $F=5.37$) measured at the ridge sites were significantly lower than at the slough sites (Figure 20). We found similar trends when we compared the ridge and slough environments made during separate samplings (Figure 21). The mean daily rate of floc production in the ridge environment (44.8 g m^{-2} d^{-1}) was significantly lower ($p<0.01$, $F=9.42$) than in the slough (122.4 g m^{-2} d^{-1}). Similarly, mean flow velocities for ridge (0.65 cm sec^{-1}) sites were lower than those measured at slough (0.93 cm sec^{-1}) sites, however, these rates were not significantly different ($p=0.7$, $F=3.62$). During the second sampling month (December 2003) mean floc production on sawgrass ridges (12.71 g m^{-2} d^{-1}) was lower than in sloughs (33.57 g dy^{-1} m^{-2}), but this difference was not statistically significant. Mean velocities for this sampling showed a significantly higher rates in the sloughs (0.78 cm sec^{-1}) compared with the sawgrass ridges (0.47 cm sec^{-1}; $p<0.005$, $F=9.56$). In the final sampling month (January 2004), we found no difference in mean floc production between the ridge (18.33 g m^{-2} d^{-1}) and slough (20.07 g m^{-2} d^{-1}) environments. However, at this time mean velocity was significantly lower ($p<0.05$, $F=5.37$) on the ridges (0.41 cm sec^{-1}) compared with in the sloughs (0.60 cm sec^{-1}).

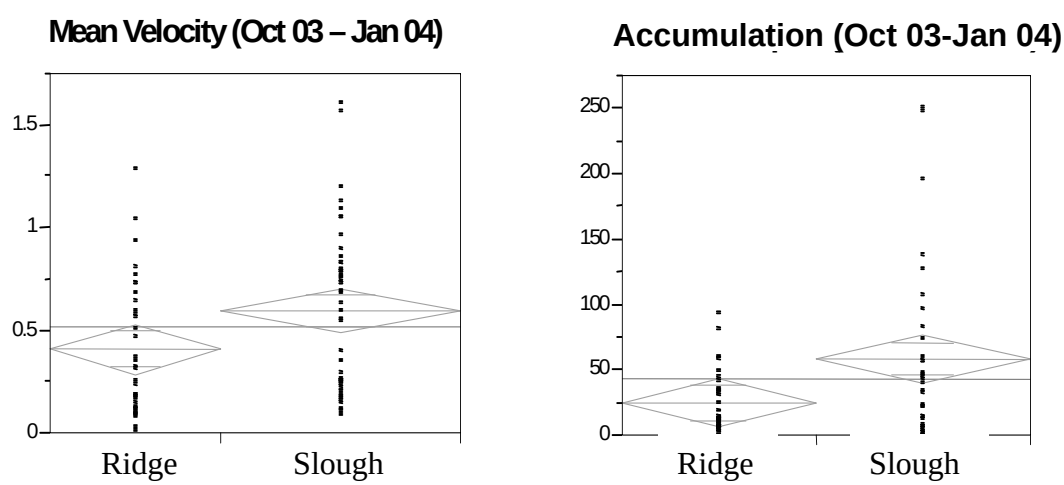

Figure 20. Mean flow velocity (left panel) and mean rate of floc production (right panel) along the experimental transect.

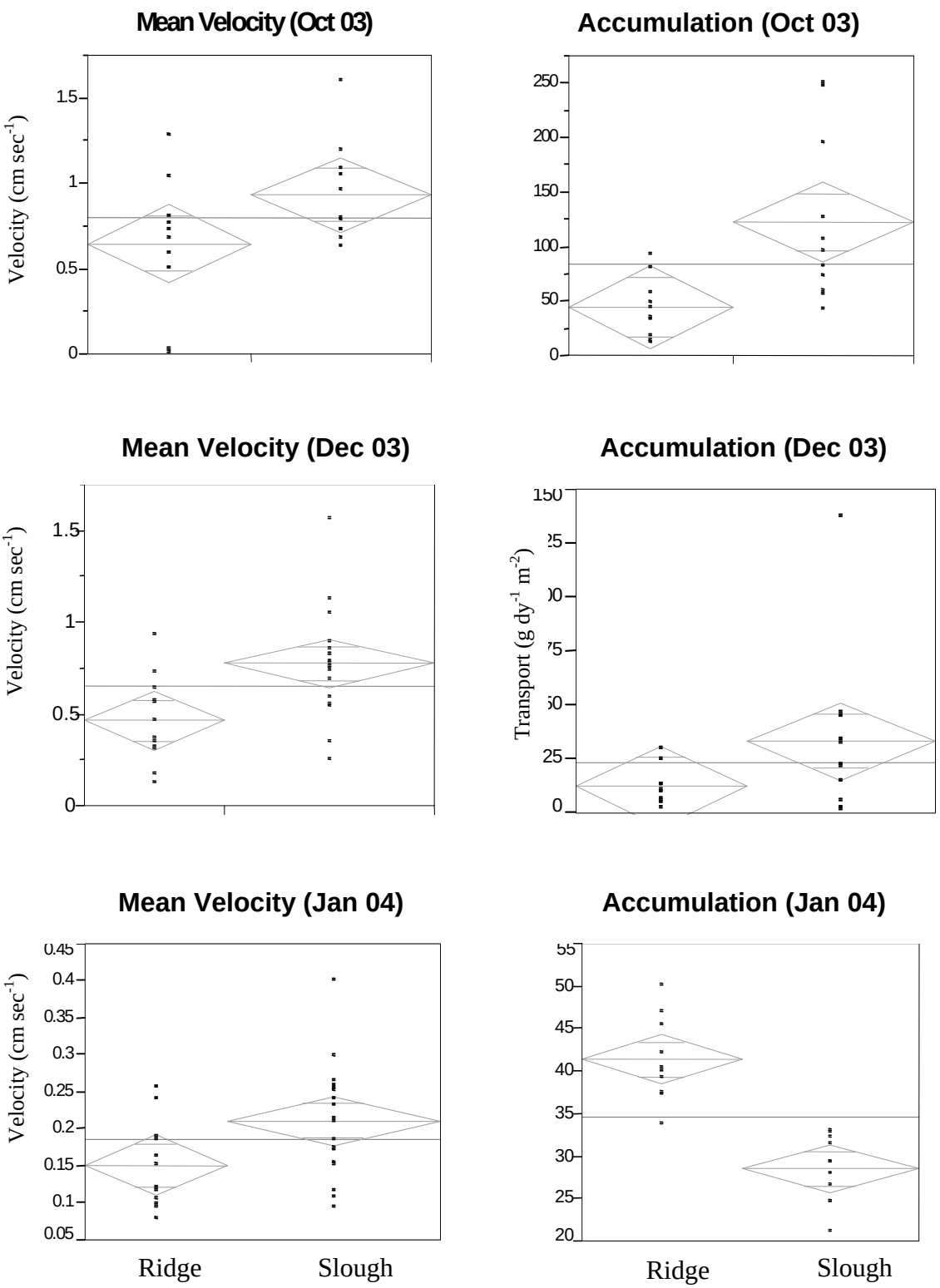

Figure 21. Mean monthly flow velocities (left panels) and floc production rates (right panels) for ridge and slough sites along the Gumbo Limbo transect.

Canopy characteristics (vegetation type, stem density, and presence or absence of periphyton and *Utricularia* sp.) were monitored, as well, to determine their influence on flow velocities in Everglades sloughs. These measures were coupled with the collection of vertical flow profiles to gain a better understanding of flow variability in three dimensions (Table 2). Based on the well-established relationship between flow speed and stem density in tidal wetland systems (Leonard and Luther 1995), we first investigated correlations between stem density and velocity. This preliminary analysis, however, showed no relationship between the standing biomass of spikerush and flow velocity for data collected in sloughs along and near our experimental transect. Nonetheless, observations of dye-tracer releases suggested that the presence of biomass locally impeded flow and that these impediments were not distributed uniformly over either vertically or horizontally.

Table 2. Vertical flow profile data collected in flume enhancement treatments and control areas. Flow data include only x and y components of velocity in cm/s. Each height was sampled for 3 consecutive bursts and these were then averaged to determine mean velocity at each position in the water column.

Date	Site	Water Depth (cm)	Sampling Depth (cm)	Burst #	Station #	Burst-averaged Velocity (cm/s)	Mean Velocity (cm/s)	Burst-Standard Deviation	Velocity Standard Deviation	NOTES/COMMENTS
6/25/03	PCC2	57.5	8.5	3	1	0.85		0.48		Sawgrass
6/25/03	PCC2	57.5	8.5	4	2	1.18		0.36		control site 2
6/25/03	PCC2	57.5	8.5	5	3	0.74	0.92	1.48	0.77	
6/25/03	PCC2	57.5	19	10	5	0.81		0.24		
6/25/03	PCC2	57.5	19	11	6	0.74		0.19		
6/25/03	PCC2	57.5	19	12	7	0.72	0.76	0.21	0.21	
6/25/03	PCC2	57.5	29	13	8	0.44		0.13		
6/25/03	PCC2	57.5	29	14	9	0.45		0.14		
6/25/03	PCC2	57.5	29	15	10	0.20	0.36	0.41	0.23	
6/25/03	PCC2	57.5	38.5	18	13	0.18		0.13		
6/25/03	PCC2	57.5	38.5	19	14	0.18		0.09		
6/25/03	PCC2	57.5	38.5	20	15	0.12	0.16	0.09	0.11	
6/25/03	PFHPA	64	8.5	1	1	1.08		0.67		Flume enhancement-
6/25/03	PFHPA	64	8.5	2	2	0.73		0.26		Half-plant treatment
6/25/03	PFHPA	64	8.5	3	3	1.02	0.95	0.66	0.53	
6/25/03	PFHPA	64	22.5	4	4	0.54		0.72		
6/25/03	PFHPA	64	22.5	5	5	0.91		0.45		
6/25/03	PFHPA	64	22.5	7	6	0.66	0.71	0.52	0.56	
6/25/03	PFHPA	64	37	8	7	0.47		0.59		
6/25/03	PFHPA	64	37	9	8	0.59		0.34		
6/25/03	PFHPA	64	37	10	9	0.43	0.50	0.12	0.35	
6/25/03	PFHPA	64	53.5	11	10	0.18		0.14		
6/25/03	PFHPA	64	53.5	12	11	0.06		0.11		
6/25/03	PFHPA	64	53.5	13	12	0.06	0.10	0.15	0.13	
6/25/03	CC1	40.5	8.5	1	1	0.32		0.31		Sawgrass control

6/25/03	CC1	40.5	8.5	2	2	0.04		0.10		site 1
6/25/03	CC1	40.5	8.5	3	3	0.03	0.13	0.10	0.17	
6/25/03	CC1	40.5	17	4	4					
6/25/03	CC1	40.5	17	6	5	0.43		0.36		
6/25/03	CC1	40.5	17	8	6	0.23	0.33	0.45	0.41	
6/25/03	CC1	40.5	23	9	7	0.39		0.66		
6/25/03	CC1	40.5	23	10	8	0.38		0.31		
6/25/03	CC1	40.5	23	11	9	0.44	0.40	0.16	0.38	
6/25/03	CC1	40.5	30	12	10	0.19		0.27		
6/25/03	CC1	40.5	30	13	11	0.07		0.13		
6/25/03	CC1	40.5	30	14	12	0.12	0.13	0.04	0.15	
6/25/03	HEAD	63	7.5	2	1	1.51		0.53		Flume head (control)
6/25/03	HEAD	63	7.5	4	2	1.32		0.31		site
6/25/03	HEAD	63	7.5	5	3	1.10	1.31	0.33	0.39	
6/25/03	HEAD	63	22	6	4	0.83		0.68		
6/25/03	HEAD	63	22	8	5	0.37		0.27		
6/25/03	HEAD	63	22	9	6	0.73	0.64	0.23	0.39	
6/25/03	HEAD	63	37	10	7	0.15		0.16		
6/25/03	HEAD	63	37	11	8	0.25		0.13		
6/25/03	HEAD	63	37	12	9	0.21	0.21	0.09	0.13	
6/25/03	HEAD	63	46	19	11	0.04		0.20		
6/25/03	HEAD	63	46	20	12	0.17		0.14		
6/25/03	HEAD	63	46	21	13	0.05	0.09	0.14	0.16	
6/25/03	PNFA	57	9	1	1	0.14		0.22		Flume enhancement-
6/25/03	PNFA	57	9	2	2	0.02		0.10		No flow site A
6/25/03	PNFA	57	9	3	3	0.01	0.06	0.12	0.14	
6/25/03	PNFA	57	22	4	4	0.08		0.37		
6/25/03	PNFA	57	22	6	5	0.20		0.19		
6/25/03	PNFA	57	22	7	6	0.27	0.19	0.48	0.35	
6/25/03	PNFA	57	34	8	7	0.14		0.57		
6/25/03	PNFA	57	34	9	8	0.08		0.25		
6/25/03	PNFA	57	34	11	9	0.30	0.18	0.37	0.40	
6/25/03	PNFA	57	47	13	11	0.30		0.22		
6/25/03	PNFA	57	47	14	12	0.07		0.08		
6/25/03	PNFA	57	47	15	13	0.11	0.16	0.10	0.13	
6/25/03	SC1	53	7.5	2	1	1.00		0.35		Spike rush (slough)
6/25/03	SC1	53	7.5	3	2	0.92		0.20		control
6/25/03	SC1	53	7.5	6	3	0.88	0.93	0.73	0.43	
6/25/03	SC1	53	18	12	4	0.65		0.35		
6/25/03	SC1	53	18	13	5	0.63		0.15		
6/25/03	SC1	53	18	14	6	0.46	0.58	0.20	0.24	
6/25/03	SC1	53	29	16	7	0.31		0.06		
6/25/03	SC1	53	29	17	8	0.38		0.10		
6/25/03	SC1	53	29	18	9	0.38	0.36	0.09	0.08	
6/25/03	SC1	53	37	19	10	0.06		0.14		
6/25/03	SC1	53	37	20	11	0.11		0.10		
6/25/03	SC1	53	37	21	12	0.11	0.10	0.05	0.10	
6/25/03	PFFPA	62	8.5	1	1	1.28		0.40		Flume enhancement
6/25/03	PFFPA	62	8.5	3	2	0.69		2.71		Full plant density
6/25/03	PFFPA	62	8.5	4	3	1.15	1.04	1.21	1.44	treatment
6/25/03	PFFPA	62	24	5	4	0.85		1.20		
6/25/03	PFFPA	62	24	6	5	1.03		0.42		
6/25/03	PFFPA	62	24	7	6	0.72	0.87	0.32	0.65	

6/25/03	PFFPA	62	38	8	7	1.03		0.68		
6/25/03	PFFPA	62	38	10	8	0.25		0.60		
6/25/03	PFFPA	62	38	12	9	0.74	0.67	0.41	0.57	
6/25/03	PFFPA	62	52	13	10	0.32		0.17		
6/25/03	PFFPA	62	52	14	11	0.31		0.18		
6/25/03	PFFPA	62	52	15	12	0.09	0.24	0.13	0.16	
6/25/03	PNFB	61	7	4	2	0.21		0.15		Flume enhancement
6/25/03	PNFB	61	7	5	3	0.22		0.21		No Flow site B
6/25/03	PNFB	61	7	6	4	0.24	0.23	0.49	0.28	
6/25/03	PNFB	61	16	11	5	0.83		0.44		
6/25/03	PNFB	61	16	12	6	0.70		0.15		
6/25/03	PNFB	61	16	14	7	0.83	0.79	0.17	0.25	
6/25/03	PNFB	61	30	15	8	0.12		0.28		
6/25/03	PNFB	61	30	17	9	0.10		0.21		
6/25/03	PNFB	61	30	19	10	0.34	0.19	0.12	0.20	
6/25/03	PNFB	61	45	20	11	0.33		0.09		
6/25/03	PNFB	61	45	21	12	0.09		0.26		
6/25/03	PNFB	61	45	22	13	0.18	0.20	0.09	0.15	
1/23/03	CC1	14	6	8	5	0.06		0.26		Sawgrass control
1/23/03	CC1	14	6	10	6	0.20		0.24		site 1
1/23/03	CC1	14	6	12	7	0.25	0.17	0.13	0.21	
1/23/03	CC1	14	10	4	1	0.09		0.14		
1/23/03	CC1	14	10	6	3	0.02		0.13		
1/23/03	CC1	14	10	7	4	0.01	0.04	0.14	0.13	
1/23/03	SC1	25	5	7	5	0.17		0.14		Slough control
1/23/03	SC1	25	5	8	6	0.15		0.18		site 1
1/23/03	SC1	25	5	12	7	0.31	0.21	0.23	0.18	
1/23/03	SC1	25	12	15	8	0.29		0.14		
1/23/03	SC1	25	12	16	9	0.39		0.40		
1/23/03	SC1	25	12	17	10	0.24	0.31	0.22	0.25	
1/23/03	SC1	25	16	18	11	0.14		0.17		
1/23/03	SC1	25	16	19	12	0.04		0.17		
1/23/03	SC1	25	16	20	13	0.04	0.08	0.14	0.16	
1/23/03	FFP	34	5	1	1	0.28		0.33		Flume enhancement
1/23/03	FFP	34	5	2	2	0.36		0.26		Full plant density
1/23/03	FFP	34	5	3	3	0.46	0.37	0.20	0.26	treatment
1/23/03	FFP	34	11	28	10	0.30		0.14		
1/23/03	FFP	34	11	30	11	0.31		0.13		
1/23/03	FFP	34	11	32	12	0.37	0.33	0.16	0.15	
1/23/03	FFP	34	18	12	7	0.50		0.18		
1/23/03	FFP	34	18	13	8	0.44		0.16		
1/23/03	FFP	34	18	22	9	0.56	0.50	0.21	0.18	
1/23/03	FFP	34	24.5	5	4	0.20		0.11		
1/23/03	FFP	34	24.5	6	5	0.28		0.11		
1/23/03	FFP	34	24.5	7	6	0.32	0.27	0.15	0.12	
1/23/03	FHP	37	4	3	1	0.38		0.19		Flume enhancement
1/23/03	FHP	37	4	5	2	0.41		0.24		Half plant density
1/23/03	FHP	37	4	7	3	0.53	0.44	0.14	0.19	treatment
1/23/03	FHP	37	10	17	10	0.71		0.22		
1/23/03	FHP	37	10	22	11	0.72		0.19		
1/23/03	FHP	37	10	23	12	0.56	0.66	0.16	0.19	
1/23/03	FHP	37	15	14	7	0.85		0.13		
1/23/03	FHP	37	15	15	8	0.67		0.27		

1/23/03	FHP	37	15	16	9	0.90	0.81	0.20	0.20	
1/23/03	FHP	37	20	9	4	0.07		0.08		
1/23/03	FHP	37	20	10	5	0.01		0.04		
1/23/03	FHP	37	20	11	6	0.01	0.03	0.07	0.06	
1/23/03	FNP	36	4	2	1	0.77		0.48		Flume enhancement
1/23/03	FNP	36	4	5	2	0.67		0.38		no plants
1/23/03	FNP	36	4	6	3	0.60	0.68	0.29	0.38	treatment
1/23/03	FNP	36	13	8	4	0.53		0.18		
1/23/03	FNP	36	13	9	5	0.75		0.36		
1/23/03	FNP	36	13	11	6	0.59	0.62	0.36	0.30	
1/23/03	FNP	36	22	12	7	0.46		0.43		
1/23/03	FNP	36	22	13	8	0.53		0.13		
1/23/03	FNP	36	22	15	9	0.25	0.42	0.10	0.22	
1/23/03	FNP	36	30	1	1	0.18		0.18		
1/23/03	FNP	36	30	2	2	0.06		0.09		
1/23/03	FNP	36	30	3	3	0.05	0.10	0.08	0.12	
1/23/03	NF	31	5	1	1	0.13		0.19		Flume enhancement
1/23/03	NF	31	5	3	2	0.35		0.13		no flow
1/23/03	NF	31	5	4	3	0.24	0.24	0.14	0.15	
1/23/03	NF	31	10	13	10	0.08		0.09		
1/23/03	NF	31	10	14	11	0.07		0.13		
1/23/03	NF	31	10	15	12	0.11	0.09	0.14	0.12	
1/23/03	NF	31	15	10	7	0.22		0.14		
1/23/03	NF	31	15	11	8	0.10		0.13		
1/23/03	NF	31	15	12	9	0.18	0.17	0.06	0.11	
1/23/03	NF	31	20.5	5	4	0.11		0.13		
1/23/03	NF	31	20.5	7	5	0.19		0.44		
1/23/03	NF	31	20.5	8	6	0.01	0.10	0.18	0.25	
1/23/03	CC1-2	24	6	5	4	0.35		0.21		Sawgrass
1/23/03	CC1-2	24	6	7	5	0.14		0.18		control site 1
1/23/03	CC1-2	24	6	10	7	0.36	0.29	0.12	0.17	
1/23/03	CC1-2	24	10	1	1	0.11		0.08		
1/23/03	CC1-2	24	10	2	2	0.07		0.04		
1/23/03	CC1-2	24	10	3	3	0.04	0.07	0.04	0.05	
1/23/03	PSC1-2	24	6	13	8	0.40		0.09		Slough
1/23/03	PSC1-2	24	6	14	9	0.42		0.08		control site 1
1/23/03	PSC1-2	24	6	15	10	0.39	0.40	0.09	0.09	
1/23/03	PSC1-2	24	10	10	5	0.23		0.24		
1/23/03	PSC1-2	24	10	11	6	0.37		0.14		
1/23/03	PSC1-2	24	10	12	7	0.51	0.37	0.12	0.16	
1/23/03	PSC1-2	24	15.5	1	1	0.04		0.53		
1/23/03	PSC1-2	24	15.5	3	2	0.37		0.18		
1/23/03	PSC1-2	24	15.5	4	3	0.46	0.29	0.26	0.32	
1/23/03	FFP-2	36.5	7	1	1	0.35		0.38		Flume enhancement
1/23/03	FFP-2	36.5	7	2	2	0.19		0.26		Full plant density
1/23/03	FFP-2	36.5	7	3	3	0.59	0.38	0.38	0.34	treatment
1/23/03	FFP-2	36.5	12	16	10	0.24		0.18		
1/23/03	FFP-2	36.5	12	17	11	0.27		0.23		
1/23/03	FFP-2	36.5	12	18	12	0.18	0.23	0.25	0.22	
1/23/03	FFP-2	36.5	15	11	7	0.27		0.12		
1/23/03	FFP-2	36.5	15	12	8	0.19		0.14		
1/23/03	FFP-2	36.5	15	13	9	0.14	0.20	0.33	0.20	
1/23/03	FFP-2	36.5	21	4	4	0.17		0.20		

1/23/03	FFP-2	36.5	21	5	5	0.15		0.17		
1/23/03	FFP-2	36.5	21	8	6	0.24	0.19	0.16	0.18	
1/23/03	FHP-2	36	7	5	1	0.67		0.32		Flume enhancement
1/23/03	FHP-2	36	7	7	2	0.69		0.59		Half plant density
1/23/03	FHP-2	36	7	8	3	0.56	0.64	0.27	0.39	treatment
1/23/03	FHP-2	36	12	17	10	0.91		0.33		
1/23/03	FHP-2	36	12	18	11	0.89		0.36		
1/23/03	FHP-2	36	12	22	12	0.58	0.79	0.30	0.33	
1/23/03	FHP-2	36	17	13	7	0.74		0.30		
1/23/03	FHP-2	36	17	14	8	0.55		0.30		
1/23/03	FHP-2	36	17	15	9	0.62	0.63	0.26	0.29	
1/23/03	FHP-2	36	23.5	9	4	0.07		0.23		
1/23/03	FHP-2	36	23.5	10	5	0.03		0.09		
1/23/03	FHP-2	36	23.5	11	6	0.01	0.04	0.10	0.14	
1/23/03	FNP-2	36	6	13	10					Flume enhancement
1/23/03	FNP-2	36	6	15	11	0.67		0.51		no plants
1/23/03	FNP-2	36	6	17	12	0.46	0.57	0.24	0.37	treatment
1/23/03	FNP-2	36	13.5	9	7	0.25		0.35		
1/23/03	FNP-2	36	13.5	10	8	0.18		0.22		
1/23/03	FNP-2	36	13.5	11	9	0.05	0.16	0.29	0.29	
1/23/03	FNP-2	36	22	4	4	0.53		0.21		
1/23/03	FNP-2	36	22	5	5	0.42		0.21		
1/23/03	FNP-2	36	22	6	6	0.30	0.42	0.20	0.21	
1/23/03	FNP-2	36	28	1	1	0.27		0.21		
1/23/03	FNP-2	36	28	2	2	0.37		0.49		
1/23/03	FNP-2	36	28	3	3	0.06	0.24	0.15	0.28	
1/23/03	NF-2	31	6	17	12	0.02		0.25		Flume enhancement
1/23/03	NF-2	31	6	18	13	0.11		0.21		no flow
1/23/03	NF-2	31	6	20	14	0.08	0.07	0.21	0.22	
1/23/03	NF-2	31	11.5	14	9	0.12		0.10		
1/23/03	NF-2	31	11.5	15	10	0.09		0.13		
1/23/03	NF-2	31	11.5	16	11	0.09	0.10	0.10	0.11	
1/23/03	NF-2	31	17	6	6	0.26		0.14		
1/23/03	NF-2	31	17	7	7	0.01		0.15		
1/23/03	NF-2	31	17	8	8	0.18	0.15	0.11	0.13	
1/23/03	NF-2	31	24.5	3	3	0.07		0.10		
1/23/03	NF-2	31	24.5	4	4	0.06		0.11		
1/23/03	NF-2	31	24.5	5	5	0.05	0.06	0.07	0.10	

Our vertical flow profiles, collected in the presence of vegetation, unexpectedly deviated from a logarithmic shape (e.g. Leonard and Luther 1995; Leonard and Reed 2002). Unlike observations made in other wetlands characterized by monospecific stands of vegetation (Leonard and Luther 1995), we found that profiles collected at our sawgrass ridge sites and at our slough sites varied in non-systematic ways in response to the canopy architecture of the dominant vascular plant (Figures 22 and 23). Where vertical changes were observed, the differences in magnitude were very subtle (given the very low velocities in the system) and not statistically significant. However, by measuring other canopy attributes (e.g. presence or absence

of periphyton and *Utricularia*), we determined that the shape of the velocity profile was, in fact, affected by the distribution of all plant biomass in the water column, not simply by the architecture of the dominant emergent plant canopy.

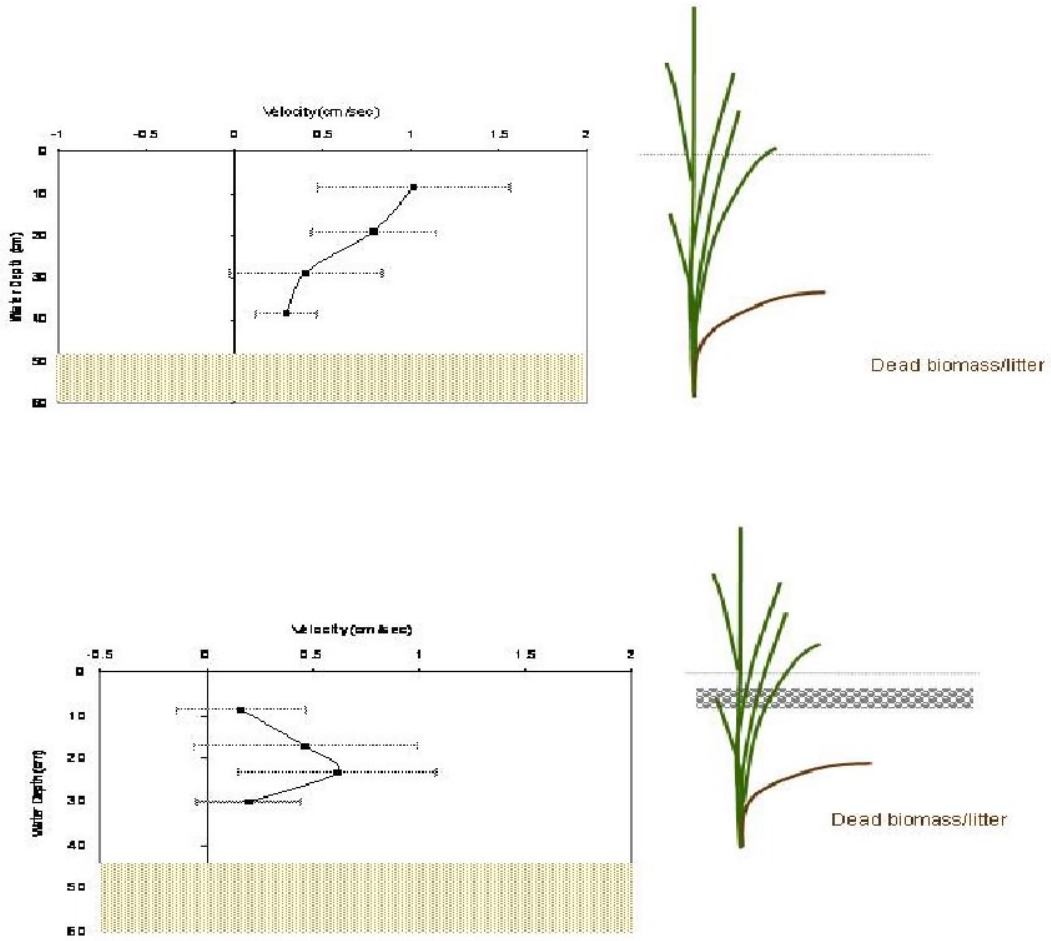

Figure 22. Representative vertical velocity profiles collected in sawgrass areas in June 2003. Error bars denote standard deviation of velocity sampled over a 40 second sampling burst. The stippled region indicates the position of the soil surface at the time of sampling. Panel A shows profile collected in absence of surface periphyton. Panel B shows profile collected in presence of surface periphyton.

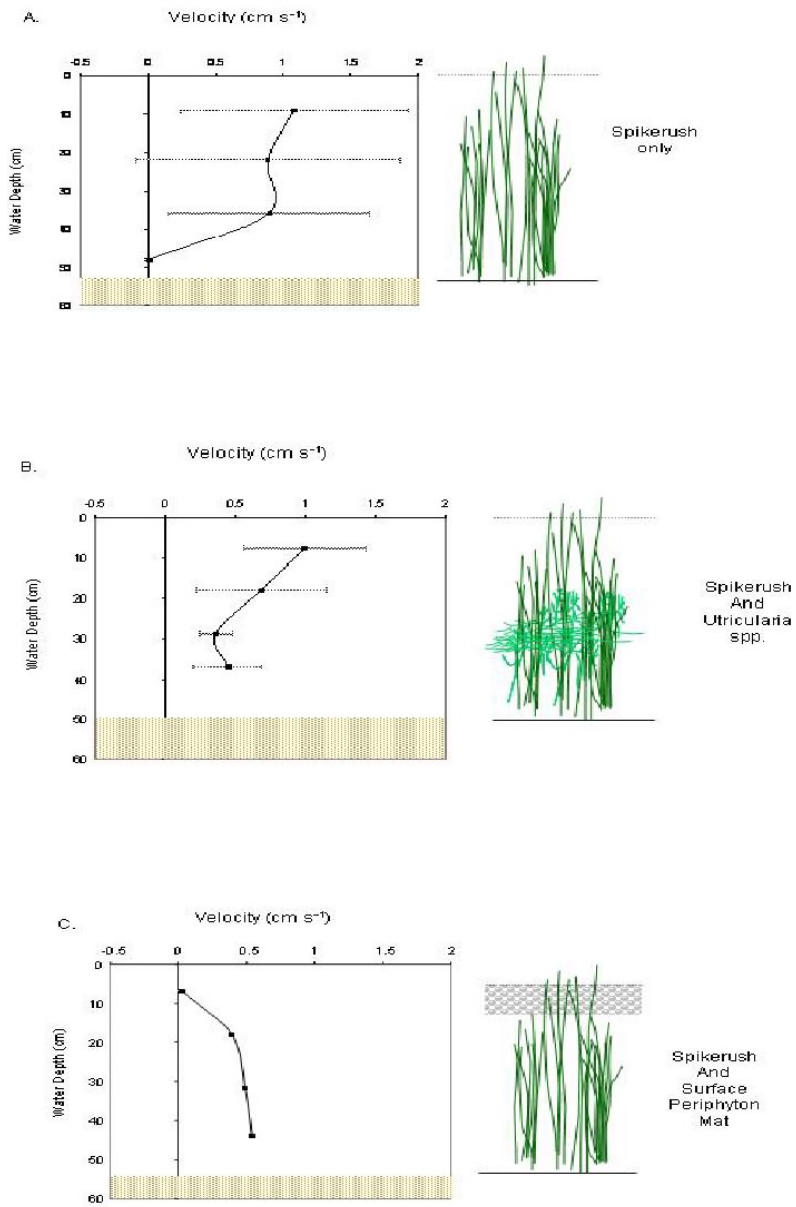

Figure 23. Vertical flow profiles collected in spikerush sloughs in the presence and absence of floating *Utricularia* and well-developed periphyton mats. Panel A shows a typical flow profile collected in an area with no periphyton mat and devoid of *Utricularia*. Panel B shows a flow profile collected in an area where *Utricularia* was present in the canopy but no periphyton mat existed. Panel C shows a flow profile collected in an area with a well established periphyton mat, but no *Utricularia*.

Profiles collected within stands of sawgrass varied in shape due to presence or absence of litter and/or periphyton (Figure 22). Flow velocities were generally lower than expected in areas of the profile coincident with the presence of extensive litter even if stem densities were low. Similarly, flow velocities were reduced at heights on the profile where surfical periphyton mats existed or where periphyton was abundant on other living or dead biomass. The presence of periphyton, especially well-developed surface mats, also exhibited control over the shape of vertical profiles collected in the spikerush sloughs (Figure 23C). Where surface mats were extensive, very low velocities (often below the resolution of the current meter) were observed. Higher flow velocities, however, usually were measured at depths below the mat as long as flows were unimpeded by the presence of *Utricularia*. *Utricularia*, which rarely occurred on sawgrass ridges, was pervasive in the spikerush sloughs and adds another factor that appears to affect flow velocity (Figure 23B). Velocities in regions of the flow profile coincident with *Utricularia* tended to be reduced with higher velocities usually observed above and below this height.

Our observations of the effects of periphyton and *Utricularia* led us to further vegetative manipulations. In these, we followed a three-tiered process to investigate the relative control of standing and submerged biomass on flow velocity within a slough. Figure 24 illustrates the effects of three levels of vegetative biomass manipulations on a flow profile. With all floating and standing biomass in place, the profile exhibited an irregularly shaped profile with the highest velocity of 0.36 cm sec^{-1} occurring at $6/10^{th}$ depth in the water column (Figure 24A). The velocity near the top of this profile was lower (0.11 cm sec^{-1}). When the floating biomass (*Utricularia* and periphyton) was removed, thus removing some of the baffling elements in the canopy, velocities increased to 0.94 and 0.42 cm sec^{-1} for the near-surface and $6/10^{th}$ depths, respectively (Figure 24B). When the spikerush and other emergent biomass was removed, the profile did not change its relative shape and depth-averaged velocity did not significantly increase. After we removed all vegetation, flow velocities of 1.11 and 0.42 cm sec^{-1} were observed for the near-surface and $6/10^{th}$ depths, respectively (Figure 24C).

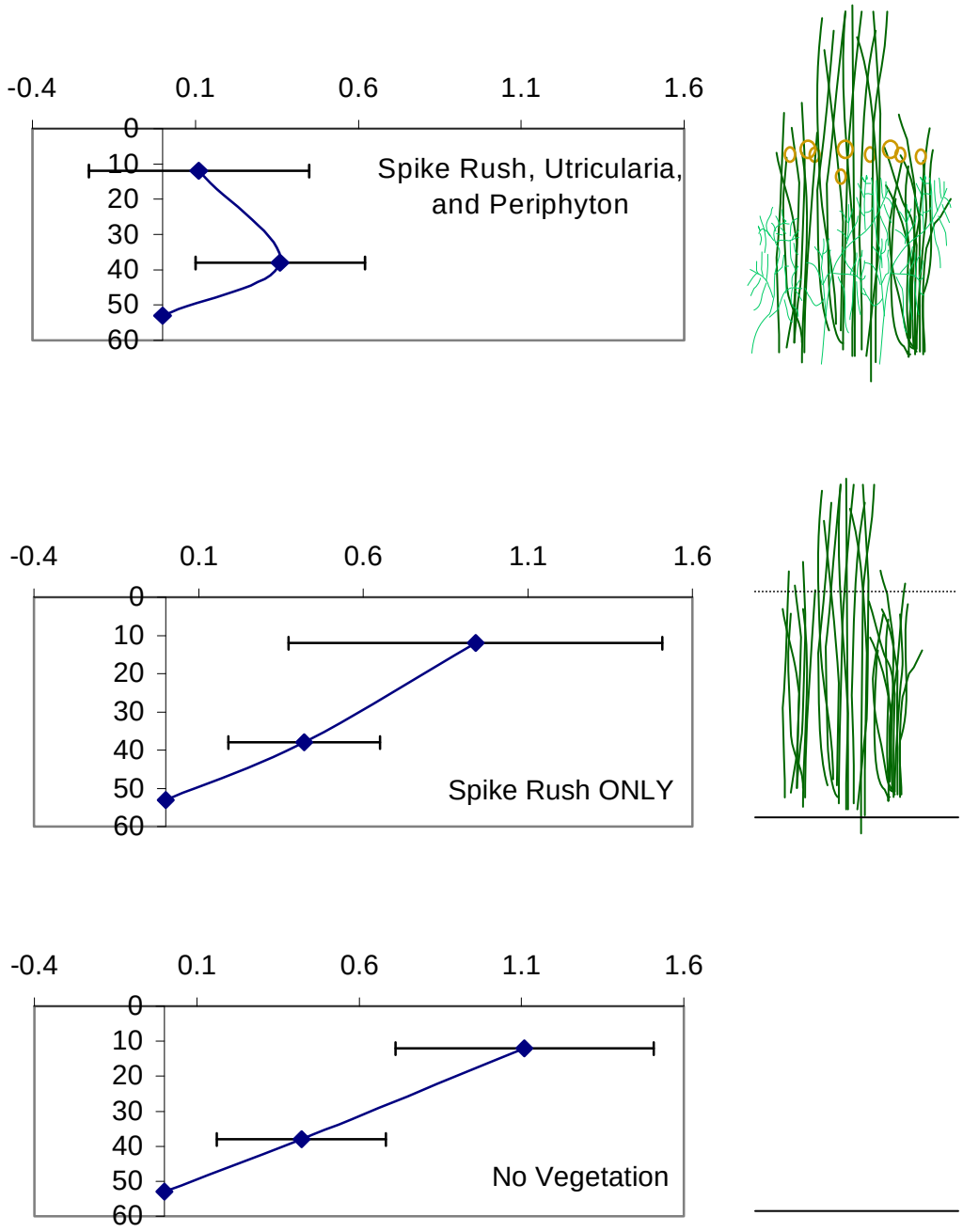

Figure 24. Vertical velocity profiles associated with plant clearing experiments. Uppermost panel shows conditions with no biomass removed from the plot. Middle panel shows profile after *Utricularia* and other floating material was removed from plot. Lower panel shows profile with all biomass cleared. Error bars indicate ± standard deviation of the mean velocity for a 30 second sampling burst.

4. Experimentally Enhancing Flow

We used an ecosystem-scale field manipulation to enhance ambient flow rates through an experimental area of marsh (Figure 7). Our objectives for this manipulation were to investigate key processes in our floc conceptual model (Figure 3) under conditions of increased water flow. We did not replicate this large, complex setup because of uncertainty about the efficacy of the design to actually increase ambient flow rates. The experimental sites included a 1.5 m X 3 m area in the enhanced flow flume that had ambient stem density (FFPB = flow, full plant biomass); 50% stem density (FHPB = flow, half plant biomass), and 0% stem density (FNPB = flow, no plant biomass), a 3 m X 5 m area where flow rates were reduced below ambient (NFB = no flow, full plant biomass), and two control sites that each had a slough (SC1, SC2) and a sawgrass (CC1, CC2) sampling location.

Over the duration of this study, mean flow speeds in the enhanced flow flume usually exceeded mean flow speeds measured at the control sites (Figure 25). The single exception was the mean speed measured in the no plant treatment (FNPB), which was generally lower than the other flume sites and comparable to the control sites. This may have been an artifact of locating the no plant treatment immediately downstream of the full and half-plant treatments. This might have caused velocities, that were accelerated in the upper reaches of the flume, to decelerate when water reached the (no plant) open area. The loss of plant biomass effectively increased the available volume within the flume in this area, and by the law of conservation of mass this additional volume would have to be occupied by water flowing in from upstream. To conserve momentum, then, velocities would slow as volume increased. Interestingly, though, we did not observe the expected relationship between plant density and water velocity—we found no difference in mean velocities between the full plant and half plant treatment (Figure 25). However, this relationship assumed that all volume displacement and flow obstruction phenomena were represented by emergent plant vegetation. In fact, as much as a third of the water column was occupied (even blocked) by the dense periphyton-*Utricularia* complex. There was no real difference in periphyton-*Utricularia* coverage between the FFPB and FHPB treatments, but the FNPB zone contained neither emergent plant stems nor periphyton-*Utricularia*. This suggests to us that much of the velocity-volume relationship is driven by the biomass of the latter, not the former.

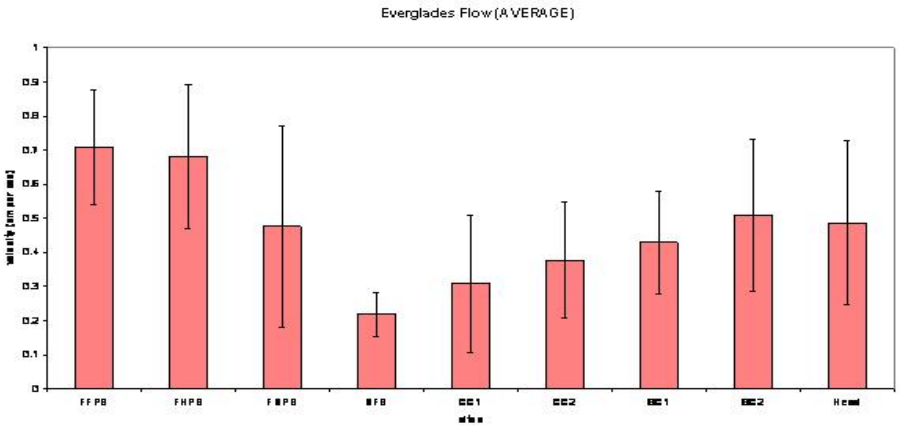

Figure 25. Mean flow speeds measured in the enhanced flow flume and in ridge and slough control sites over the entire study. Error bars show ± one standard deviation of the mean flow. See text for abbreviations. "Head" is a reference site just upstream of the flume venturi (Figure 7).

The large standard deviations reflect considerable variation in flow speed over the duration of this study (Table 3). Within the flume, mean speeds varied with season, water depth, and presence of plant biomass. In particular, increased growth of the periphyton-*Utricularia* complex in the wet season was often associated with lower flow velocities. When this material was cleared from the flume, flow speeds increased, suggesting that at some times the periphyton-Utricularia complex acts as a barrier to water flow while at other times its biovolume may enhance flow by reducing water column volume available for water movement. Notably, the latter phenomenon is likely an artifact of our restricted experimental flume: The walls prevented flow from moving around obstacles, and conservation of momentum thus required increased velocities where unobstructed volumes were greater. Mean flow rates in the sawgrass marsh (CC1, CC2) were lower than velocities measured in either the enhanced flow flume or in the control slough marshes. These results are consistent with ridge and slough patterns measured along the Gumbo Limbo transect (above).

The production of new floc, as collected in sediment traps deployed within the flume treatments, was typically less than 20 g m^{-2} d^{-1} and was nearly always less than 50 g m^{-2} d^{-1}

(Figure 26; Table 3). The only exception to these values was a mean of approximately 193 $g/m^2/day$ measured in June 2003 in the no-plant flow enhanced flume (Figure 26). This unusually high value was associated with sunfish nesting activity in this open area. We observed several fish nesting at this time, and their activity caused a great deal of bioturbation of floc (Figure 27). Floc production was generally lowest at the beginning and the end of the wet season, when water levels were changing most rapidly. Maximum production rates occurred in the middle of the wet season, and were usually associated with higher water levels and flow speeds. The increased floc production at this time may also reflect the greater turnover rates of biomass from periphyton, *Utricularia*, and emergent plants during this warmest time of the year. We also found lower floc production rates in the enhanced flow flume treatments compared with those at the slough control sites, but slightly higher rates compared with those at the sawgrass controls(Figure 26; Table 1 and Table 3). These results were also consistent with floc production in ridges versus sloughs, from our Gumbo Limbo transect (see above). There was little difference in production rates among the different flume treatments, or through time. The P content of this new floc tended to be lower in the enhanced flow flume treatments, and this difference was more pronounced later in the wet season (Figure 26B).

Floc metabolism is an important process because it largely determines the balance between new floc production, floc transport, and floc deposition to the soil. In the long term, all of these processes should largely balance out into a near steady state condition. Short-term (seasonal or episodic) imbalances are likely, though. The oxygen change (BOD) method we used to quantify floc metabolism generates values for aerobic respiration (R; dark bottles) and net primary production (NEP; light bottles). Gross primary production (GPP) is the difference between NEP and R, with R typically presented as a negative value (=negative oxygen change). If there is no autotrophic activity (i.e. no GPP), then R = -NEP. When NEP is positive (i.e. when GPP > R), the system is net autotrophic; when NEP is negative, the system is net heterotrophic. Our metabolism data showed that floc respiration (Figure 28B) always exceeds NEP (Figure 28A), although in most cases some photosynthetic activity was occurring. In October 2003 and January 2004, NEP and R were nearly equal, meaning very little autotrophic activity was occurring. This contrasts with August 2004, however, when NEP was roughly half of R, and photosynthetic activity in the floc was relatively high. The P component of floc metabolism was based on a simple C:P conversion of the C metabolism values (Figure 28), using the P content of

floc in each treatment during that sampling month (Figure 29). The patterns are very similar for C and P metabolism.

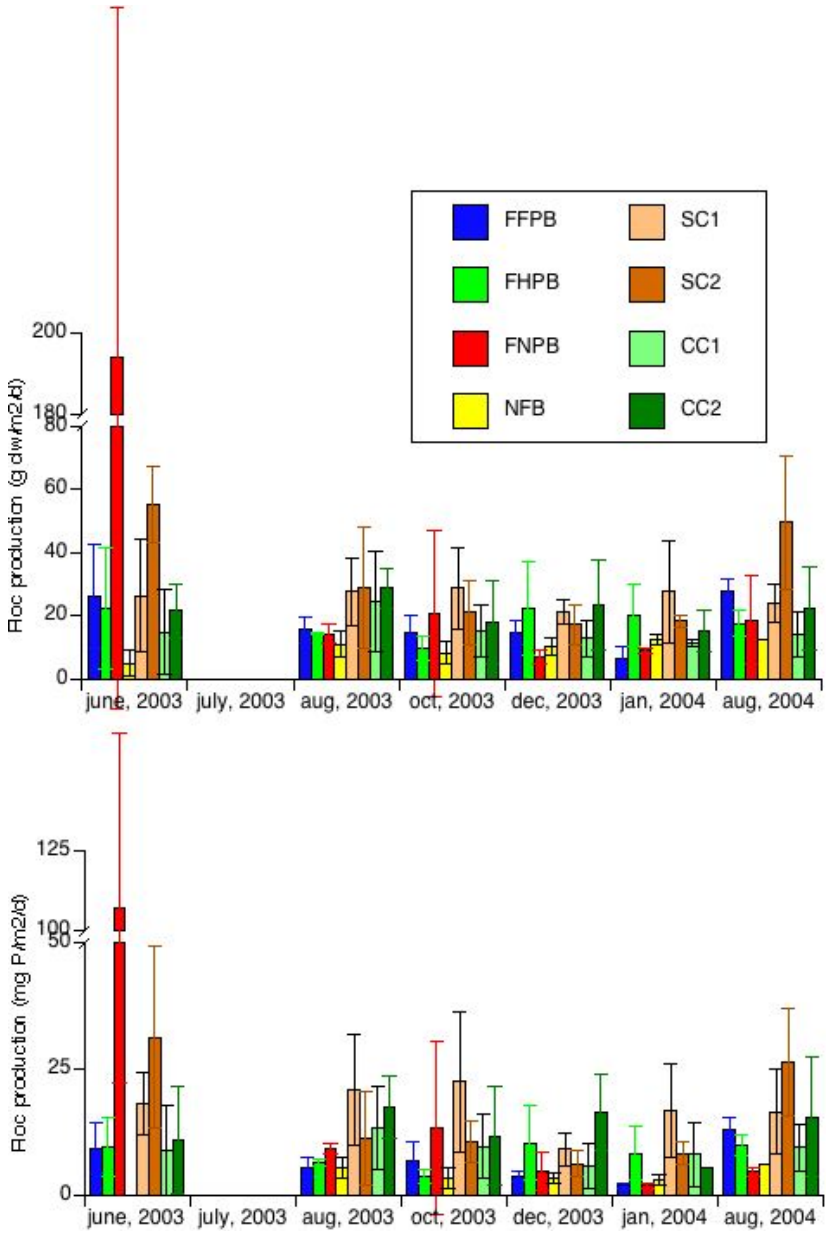

Figure 26. Floc production as measured with sediment traps, in g dw (A) and mg P (B). FFPB = flow enhanced flume, full plant stem density; FHPB = flow enhanced flume, half plant stem density; FNPB = flow enhanced flume, all plants removed; NFB = no flow treatment, ambient plant stem density; SC = slough control, ambient plant density; CC = *Cladium* control, ambient plant density.

Figure 27. Photographs of the sunfish nesting activities that took place in the no vegetation sampling zone of the enhanced flow flume in June 2003, including pictures of a sunfish bioturbating the floc layer at the opening of a flocculator (upper left, lower right), making a nest between a sediment trap and a soil elevation pin (lower left), and a nest without the fish (upper right).

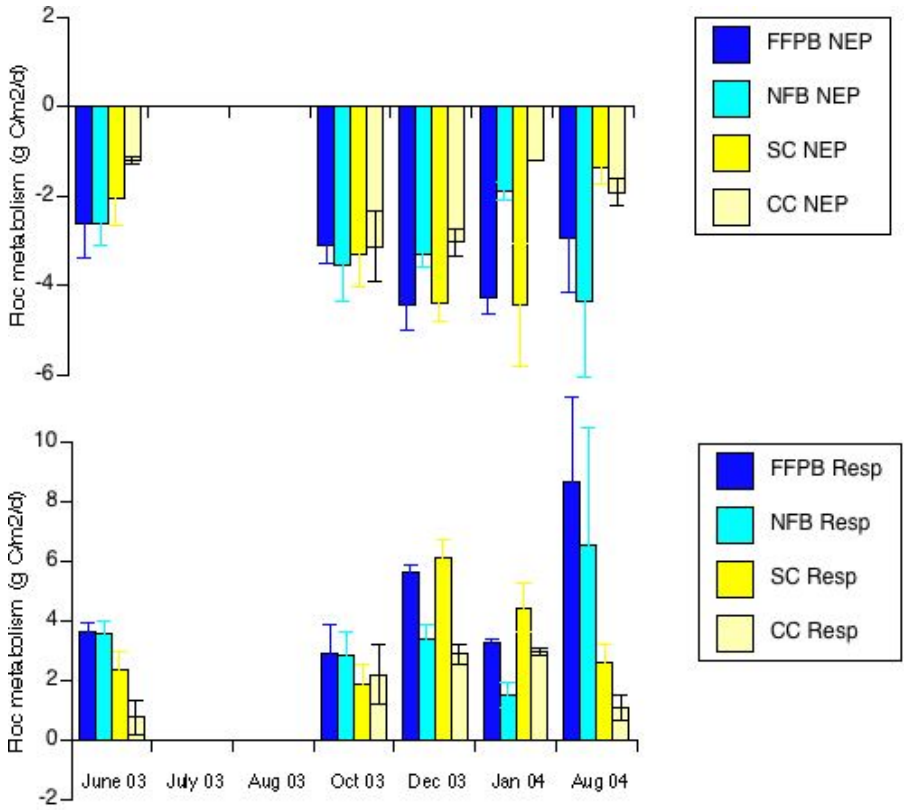

Figure 28. Floc carbon metabolism as measured with BOD incubations and oxygen concentration change. (A) net primary/ecosystem production and (B) respiration. FFPB = flow enhanced flume, full plant stem density; NFB = no flow treatment, ambient plant stem density; SC = slough control, ambient plant density; CC = *Cladium* control, ambient plant density.

We initially hypothesized that the process by which floc is permanently incorporated into the soil layer would be episodic, and associated with drydown events. During these events, the floc layer should dewater, compact, perhaps decompose to some extent, and become a permanent surficial layer on the soil. The marsh in central SRS experiences drydown events on roughly a decadal interval, though, so we expected soil elevation change via floc incorporation to not be measurable during our 2 year experimental flow manipulation experiment. In fact, the soil elevation pin data show no consistent spatial or temporal patterns (Figure 30). The only consistent pattern is that soil elevations decreased in the enhanced flow site that had no

vegetation. Under increased flow conditions, it should be possible to gradually erode away surficial soil, ultimately deepening the slough. This erosive process should be more rapid where emergent plants are at low density or are absent, because plant roots stabilize the organic soil matrix and inhibit erosion. As such, our finding of decreasing soil elevation where we experimentally increased flow velocities and removed all emergent plants makes sense. However, these elevation changes are not significant, and the time period of the experiment (less than 2 years) is too short to determine whether this is a slough scouring process, or merely a spurious finding.

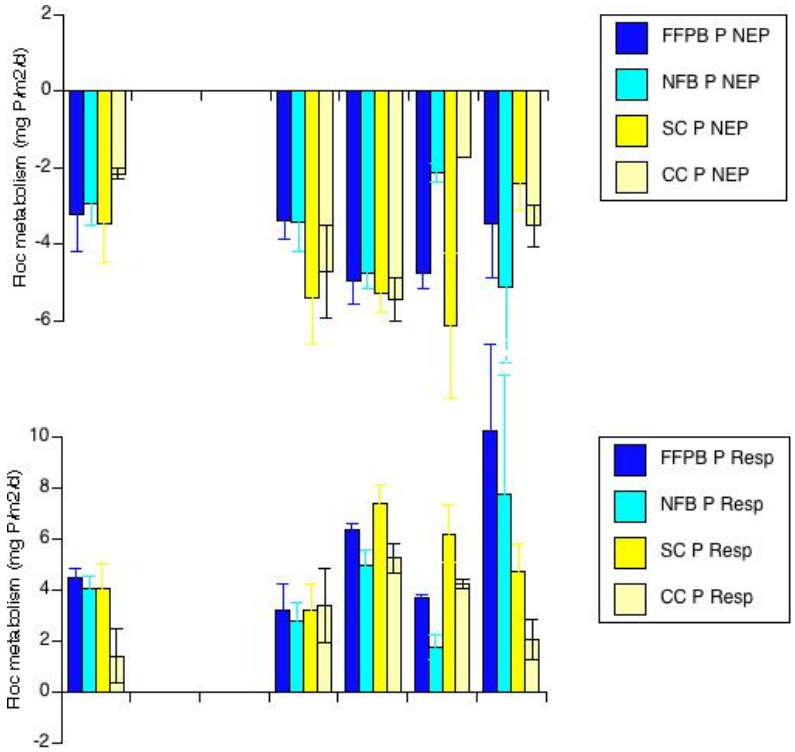

Figure 29. Floc phosphorus metabolism as measured with BOD incubations and oxygen concentration change. (A) net primary/ecosystem production and (B) respiration. FFPB = flow enhanced flume, full plant stem density; NFB = no flow treatment, ambient plant stem density; SC = slough control, ambient plant density; CC = *Cladium* control, ambient plant density.

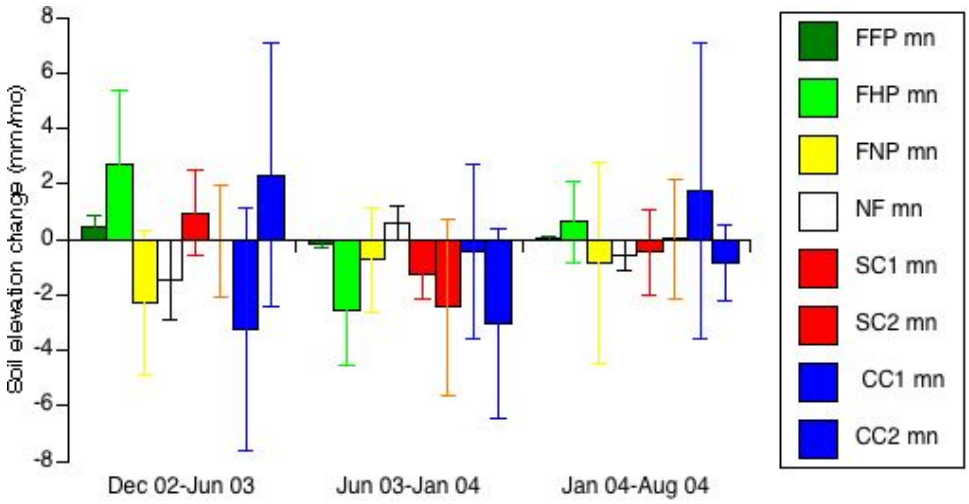

Figure 30. Change in soil elevations as measured with soil pins. Positive change represents accretion and negative change represents erosion. FFPB = flow enhanced flume, full plant stem density; FHPB = flow enhanced flume, half plant stem density; FNPB = flow enhanced flume, all plants removed; NFB = no flow treatment, ambient plant stem density; SC = slough control, ambient plant density; CC = *Cladium* control, ambient plant density.

Flow velocities measured in sawgrass ridges were significantly less than flow speeds measured in adjacent sloughs and this difference was usually significant. Given that stem densities were usually lower on the ridges and that extensive periphyton or *Utricularia* were not present within the sawgrass, the most likely explanation for the lower velocities at the ridge sites was that some of the flow was diverted around the topographically higher ridges into adjacent sloughs and other depressions. While we did not attempt to measure flow diversion at the landscape scale for this study, a similar process was observed qualitatively using dye tracers near patches of very dense vegetation. When dye was deployed upstream of a vegetation patch, some of the dye was observed to divert around the vegetation and this dye moved at a higher speed than the dye moving through the vegetation. Lastly, flow data collected along slough cross-sections (Figure 6) suggest that slightly higher flow speeds occur near the center of the sloughs or where topographic lows occur. Additional flow data collected at the sawgrass (CC) and slough (SC) control pairs also indicated an appreciable reduction in flow speed at the

ridge/slough interface. These results were consistent with the concept of channelization and support Aumen (2003) who hypothesized that the formation of ridges might be due to slower velocities in the sides of the sloughs which result in sediment accumulation. While some of the sediment trap data along the Gumbo Limbo transect suggest that accumulation may, in fact, be enhanced near the edges of the sloughs, the data at this time are inconclusive.

The observed differences in flow speed and water level between ridge and slough sites were consistent with sediment cup measurements. The rate of material accumulated in traps deployed on sawgrass ridges was significantly less than the rate measured in sloughs. These data suggest that, at present, more material is moving through the sloughs than across the ridges. Further, given the very low concentrations of suspended material observed, we believe that this material consists mostly of floc and other detritus that is transported very close to the bed. Given the low flow speeds, presence of litter in the sawgrass, and change in elevation, it may be very difficult to transport this “bedload” material out of the deeper sloughs up and on to the ridges. This mechanism, coupled with reducted periphyton and less flow on the ridges, largely explains the lack of material accumulation reported here. The enhanced material availability in the sloughs relative to the ridges-- combined with the low flow conditions in the sloughs--suggests that sloughs are infilling more and ridges are accumulating less than might be the case if flow rates were increased.

For this study, emergent vegetative densities were shown to have no correlation when compared to flow within our slough system. This is in contrast to other research from a west-central Florida marsh, which demonstrated flow speed and turbulence to be very dependent on stem densities (Leonard and Luther 1995 and Leonard et al. 1995). For this marsh, flow rates

were greatly reduced when stem densities increased from 100 to 300 stems m^{-2}. Within the Everglades marsh, the rate of flow was basically shown to have no change as stems m^{-2} increased. However, a clear relationship was seen between floating vegetative biomass and flow speeds. A three-fold increase was seen in mean flow of the velocity profiles from 0.23 to 0.68 cm sec^{-1} when the floating vegetation was removed from our experimental plot. Conversely, only a small increase in mean flow from 0.68 to 0.76 cm sec^{-1} was observed when the remaining emergent stems were removed. The velocity profiles measured within the no vegetation and the spikerush only vegetative stage for the manipulation experiment were both generally exponentially increasing. These profiles did; however, appear to be more linearly increasing as opposed to truly exponentially increasing. This was likely a result of a low number of measured heights along the profile and especially the lack of measurements taken across the sediment boundary layer. Nonetheless, the profiles seen in the cleared (no vegetation) and spikerush only (no bladderwort or periphyton) flows were comparable to vertical velocity profiles observed in other work where the flow is unobstructed. Leonard and Luther (1995) documented a similar exponentially increasing profile in an unvegetated area of *Spartina alterniflora* marsh.

Table 3. Flow speeds (A), water depths (B) and material collected in sediment cups (C) in the flow enhanced flume treatments and the flume "head" control.

A. Flow speeds. All measurements collected at 6/10 total water depth.

	Full Plants	Half Plants	No Plants	No Flow	Head
12/18/2002	0.434	0.385	0.565	No Data	No Data
1/10/2003	0.750	0.622	0.498	No Data	No Data
1/23/2003	0.680	0.868	0.392	0.262	0.198
2/15/2003	0.495	0.520	0.297	0.281	No Data
6/24/2003	0.461	0.566	0.607	0.255	0.259
8/22/2003	0.854	0.696	0.569	0.243	0.973
10/15/2003	1.242	1.183	0.723	0.203	0.576
12/10/2003	0.806	0.885	0.450	0.545	0.722
1/29/2004	0.657	0.410	0.182	0.178	0.195
8/30/2004	0.285	0.511	0.448	0.349	1.067

B. Water depth (cm) measured where flow readings were collected.

	Full Plants	Half Plants	No Plants	No Flow	Head
12/18/2002	47	47	48	No Data	No Data
1/10/2003	39.5	40.5	42.5	36.5	No Data
1/23/2003	36.5	35.5	38	31.5	31
2/15/2003	32.5	31.5	34	27	No Data
6/24/2003	65	63	65.5	58.5	60
8/22/2003	67.5	65.5	70.5	64	67
10/15/2003	74	77.5	80	72	72
12/10/2003	67	40.5	42	37.5	63
1/29/2004	51	50	55	47	45
8/30/2004	51	51	53	46.5	45

C. Sediment cup ($g/m^2/day$). Values are means of 3 replicates.

	Full Plants	Half Plants	No Plants	No Flow	Head
1/23/2003	5.890	5.152	3.035	3.234	
2/7/2003	4.348	4.158	2.720	2.044	
6/23/2003	1.297	1.420	2.497	1.280	
6/27/2003	26.114	22.347	193.996	5.045	40.319
8/18/2003	4.446	4.222	7.901	2.541	2.883

8/21/2003	15.498	14.265	14.354	11.011	11.996
10/14/2003	14.764	9.685	20.594	8.191	12.020
12/10/2003	14.432	22.442	7.098	10.314	31.792
1/29/2004	6.157	19.982	8.981	12.629	27.857
8/26/2004	23.439	14.940	15.937	10.535	36.038

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