

Predicting bed shear stress and its role in sediment dynamics and restoration potential of the Everglades and other vegetated flow systems

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ABSTRACT

Entrainment of sediment by flowing water affects topography, habitat suitability, and nutrient cycling in vegetated floodplains and wetlands, impacting ecosystem evolution and the success of restoration projects. Nonetheless, restoration managers lack simple decision-support tools for predicting shear stresses and sediment redistribution potential in different vegetation communities. Using a field-validated numerical model, we developed state-space diagrams that provide these predictions over a range of water-surface slopes, depths, and associated velocities in Everglades ridge and slough vegetation communities. Diminished bed shear stresses and a consequent decrease in bed sediment redistribution are hypothesized causes of a recent reduction in the topographic and vegetation heterogeneity of this ecosystem. Results confirmed the inability of present-day flows to entrain bed sediment. Further, our diagrams showed bed shear stresses to be highly sensitive to emergent vegetation density and water-surface slope but less sensitive to water depth and periphyton or floating vegetation abundance. These findings suggested that instituting a pulsing flow regime could be the most effective means to restore sediment redistribution to the Everglades. However, pulsing flows will not be sufficient to erode sediment from sloughs with abundant spikerush, unless spikerush density first decreases by natural or managed processes. Our methods provide a novel tool for identifying restoration parameters and performance measures in many types of vegetated aquatic environments where sediment erosion and deposition are involved.

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1. Introduction

Riparian and wetland vegetation influences erosional and depositional processes in aquatic environments through its effects on flow (Nepf et al., 1997; Millar, 2000; Thompson et al., 2004), with consequences for floodplain and wetland geomorphology (Huang and Nanson, 1997; Smith, 2004; D'Alpaos et al., 2007). However, effects of vegetation on local processes of sediment erosion and deposition are nonlinear, and under different circumstances, vegetation can either increase or decrease erosion (Nepf, 1999). While the partitioning of shear between stems and the bed can reduce bed shear stress (Lopez and Garcia, 1998; Thompson et al., 2004), the production of turbulence in stem wakes can enhance near-bed momentum transfer and increase the rate of sediment entrainment (Nezu and Onitsuka, 2001). Within a certain range of stem spacing and stem geometry, vegetative drag is the dominant effect (Smith, 2004), and sediment erosion is decreased relative to unvegetated

flow (Elliott, 2000; Leonard and Reed, 2002; Jordanova and James, 2003; James et al., 2004). Outside this range turbulence enhancement by stem wakes is the dominant effect, and erosion is enhanced (Nepf, 1999).

Though several studies have examined the effects of vegetation on flow velocities (Leonard and Luther, 1995; Neumeier and Ciavola, 2004; Lightbody and Nepf, 2006b), few studies have demonstrated the influence of different natural vegetation community architectures on bed shear stress and sediment erosion and deposition. Understanding the feedback between the structure of vegetation canopies in different plant communities, the distribution of those communities across the landscape, flow velocity, bed shear stress, and sediment transport can aid in restoration design and the engineering of constructed wetlands. Such an understanding could also guide species selection and initial planting design for wastewater treatment wetlands or floodplains in order to maximize particle settling and system throughput. In the Florida Everglades, predictions of the effect of vegetation density and architecture on bed shear stress could guide management decisions intended to restore sediment transport to the ridge and slough landscape (RSL).

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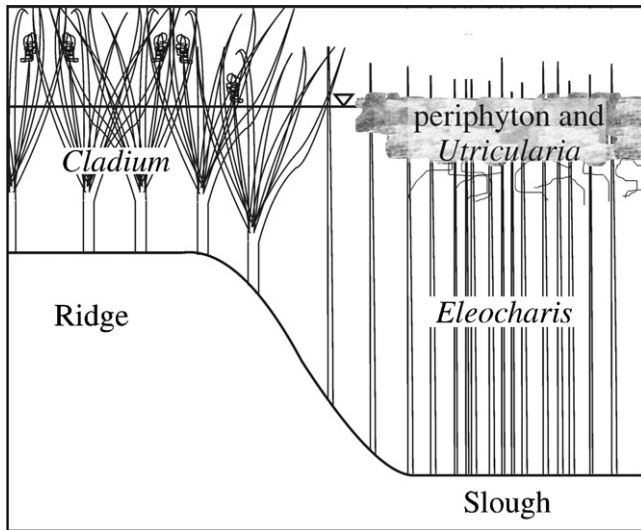


Fig. 1. Schematic of idealized ridge-slough cross-section. The dominant vegetation class considered in the ridge is *Cladium jamaicense*, whereas the dominant classes considered in the slough are emergent *Eleocharis* spp. and floating mats of periphyton and *Utricularia* spp.

The RSL exhibits distinctive patterning in peat topography and vegetation distribution (Fig. 1). Ridges that presently rise 15–20 cm above sloughs (Givnish et al., 2008; Harvey et al., 2009) are predominantly colonized by emergent *Cladium jamaicense* (sawgrass) and are typically 300–1000 m long. The north-south axis of ridge/slough elongation coincides with the historic flow direction. Sloughs, which occupy the lower portions of the peat microtopography, are interconnected and are typically 140–360 m wide (Wu et al., 2006). Slough vegetation, which is less abundant than ridge vegetation, is characterized by emergent *Eleocharis* spp. (spikerush), which tolerates a longer hydroperiod than *Cladium* (Childers et al., 2006) and by floating macrophytes such as *Nymphaea odorata* (fragrant water lily), *Nymphoides aquatica* (bleeding heart), and *Utricularia* spp. (bladderwort). Highly microbial floating mats of periphyton are also typically found in association with *Utricularia purpurea* in sloughs (Gunderson and Loftus, 1993; Gunderson, 1994; Lodge, 1994).

The RSL has been rapidly degrading since the drainage and compartmentalization of the Everglades through the construction of levees beginning in the early 1900s (SCT, 2003). Widespread topographic flattening has been accompanied by the encroachment of *Cladium* into sloughs, eliminating open-water habitats, forming barriers to fish migration, and diminishing biodiversity (Ogden, 2005). This degradation is thought to have resulted, in part, from diminished flow velocities (SCT, 2003), which have been reduced from approximately 4 cm s^{-1} to 1.2 cm s^{-1} in Everglades National Park (Riscassi and Schaffranek, 2003) and even less (0.3 cm s^{-1}) in the Water Conservation Areas (WCAs) that now comprise the central part of the Everglades (Harvey et al., 2009).

Geomorphic patterning within the RSL is thought to have been maintained historically by a combination of feedback mechanisms (SCT, 2003): (1) a differential peat accretion feedback, in which peat accumulates at different rates under different vegetation assemblages, in response to hydrology and nutrient dynamics (Givnish et al., 2008), and (2) feedback between drag effects on flow through vegetation stems and sediment transport (Larsen et al., 2007). Larsen et al. hypothesized that while the differential peat accretion feedback leads to stability in the vertical dimension, only the sediment transport feedback can produce lateral stability by preventing the spreading of ridges into sloughs. Since the depth and

duration of surface-water inundation within sloughs is unfavorable for *Cladium* growth, *Cladium* will not expand into sloughs if the topographic gradient between the ridge and the slough remains static despite ongoing below-ground biomass production and gravitational transport of sediment down topographic gradients. Lateral stability of the ridge/slough transition zone can be achieved when flow is sufficient to entrain loosely consolidated particulate organic bed sediment (“floc”) from sloughs and transition zones. The entrained material is re-deposited when flow streamlines cross from slough to ridge, where suspended particles settle to the bed or are filtered onto *Cladium* stems, resulting in a net redistribution of material from slough to ridge.

The objective of this paper was to determine the bed shear stress differential in ridge and slough vegetation communities over a range of water-surface slopes and surface-water depths and infer implications for ecosystem degradation and restoration. To this end, we applied a field-validated numerical model (Larsen, 2008) of bed shear stress in emergent and floating vegetation communities to ridges and sloughs. As we describe here, we determined model parameters through field measurements. Then, based on the results of laboratory experiments that related bed shear stress to the entrainment flux of Everglades bed floc (Larsen et al., 2009), we related the computed bed shear stresses to the occurrence of sediment erosion or deposition. The result was a series of state-space diagrams for the vegetation communities examined that show the state of sediment transport (ubiquitous erosion, redistribution, ubiquitous deposition) over a two-space of water depth and energy slope. These state-space diagrams can be used as a tool to explore the sensitivity of the state of sediment transport to system drivers and to support informed decisions between restoration alternatives under the Congressionally authorized Comprehensive Everglades Restoration Plan (US Army Corps of Engineers, 1999). Similar diagrams in other vegetation communities will likewise provide a valuable tool for the ecological engineering of other wetlands and floodplains.

2. Methods

2.1. Numerical model

We employed the computational fluid dynamics model of Larsen (2008), which calculates vertical velocity profiles, total depth-averaged vegetative drag, and bed shear stresses in steady, uniform flow using a turbulent eddy viscosity formulation of the Reynolds-averaged Navier-Stokes equations. First, velocity profiles were calculated from the 1D momentum equation in steady, uniform flow:

$$\sum_i \frac{1}{2} C_{D_i} a_i u^2 = gS \left(1 - \frac{\pi}{4} \hat{a} \hat{d} \right) + \frac{\partial}{\partial z} \left(\varepsilon \frac{\partial u}{\partial z} \right) \left(1 - \frac{\pi}{4} \hat{a} \hat{d} \right), \quad (1)$$

where C_{D_i} is the drag coefficient for vegetation class i , a_i is the local (i.e., vertically variable) frontal area per unit volume for vegetation class i [L^{-1}], u is the local velocity [L T^{-1}], g is gravitational acceleration [L T^{-2}], S is the slope of the water surface, \hat{a} is total (i.e., depth-averaged) vegetation frontal area per unit volume [L^{-1}], \hat{d} is area-weighted mean stem diameter [L], $(\pi/4)\hat{a}\hat{d}$ is the solid volume fraction of vegetation (Nepf, 2004), z is the vertical coordinate [L], and ε is the vertical eddy viscosity [$\text{L}^2 \text{T}^{-1}$]. The vertically variable eddy viscosity was based on profiles of vegetation architecture (frontal areas per unit volume and mean stem diameters) and theory of flow through arrays of cylinders (Nepf, 1999; White and Nepf, 2003; Lightbody and Nepf, 2006a). Relationships for vegetation drag coefficients were formulated through dimensional analysis and laboratory experimentation (Schutten and Davy, 2000; Lee et

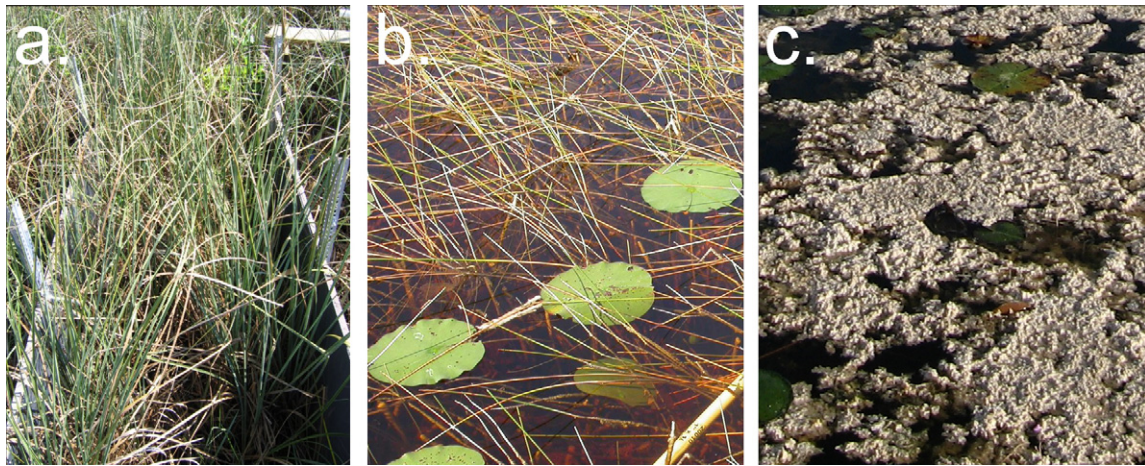


Fig. 2. Dominant vegetation classes in the RSL: (a) emergent *Cladium jamaicense* (sawgrass), the dominant ridge vegetation class; (b) emergent *Eleocharis cellulosa* (spikerush), part of the emergent slough vegetation class (also depicted in the photograph is *Nymphaea odorata* (water lily)), and (c) calcareous floating periphyton mat. The *Utricularia* (bladderwort) that forms associations with floating periphyton is typically located just beneath the water surface and is not visible in this image.

al., 2004; Harvey et al., 2009) and needed to be calibrated uniquely to each vegetation class (Section 2.3). Boundary conditions were zero velocity at the bed (i.e., no-slip) and zero velocity gradient at the water surface (i.e., no wind shear).

Next, using the computed velocity profiles, Eq. (1) was integrated over the vertical dimension to solve for the bed shear stress τ_0 ($\text{ML}^{-1}\text{T}^{-2}$) corresponding to a given combination of water-surface slope and water depth H (L) (Larsen, 2008):

$$\tau_0 = \rho g H S - \left(1 - \frac{\pi}{4} \hat{a} \hat{d}\right)^{-1} \sum_i 0.5 \rho H C_{D_i} \overline{a_i u^2}, \quad (2)$$

where the overbar denotes a depth-averaged quantity and ρ is the density of water (ML^{-3}).

2.2. Vegetation architecture

We considered three dominant vegetation classes in our analysis. In the ridge, the dominant class is *Cladium*, which is simulated as rigid emergent vegetation (Fig. 2a). Within the sloughs, *Eleocharis* is the dominant rigid emergent vegetation class (Fig. 2b), which co-occurs with the floating vegetation class encompassing periphyton mats and *Utricularia* (Fig. 2c). Sometimes the emergent vegetation class within sloughs is coated with epiphyton “sweaters”. Whether these sweaters significantly change flow hydrodynamics in sloughs is of interest for restoration planning, so we performed an additional modeling analysis that compared bed shear stresses in a slough vegetation community with and without epiphyton. Though we did not have the data to determine the effect of epiphyton on the drag coefficient of emergent vegetation, we examined the effect of epiphyton through its addition to vegetation frontal areas and mean stem diameter.

The vegetation architecture parameters used in our model were based on statistical analyses of clip plots acquired within relatively well-preserved portions of the RSL in central Water Conservation Area 3A (Fig. 3; Harvey et al., 2009) and Shark River Slough in Everglades National Park (Carter et al., 1999a,b), as well as within Taylor Slough (Rybicki et al., 2001), also part of Everglades National Park. Plots were collected synoptically during the months of April, September, and November. As described in the cited references, clip plot measurements were obtained within 0.25 m^2 quadrats randomly oriented within the landscape. At 20-cm vertical increments (central WCA-3A, Harvey et al., 2009) or 10-cm vertical increments in Shark River Slough (Carter et al., 1999a,b) and Taylor Slough

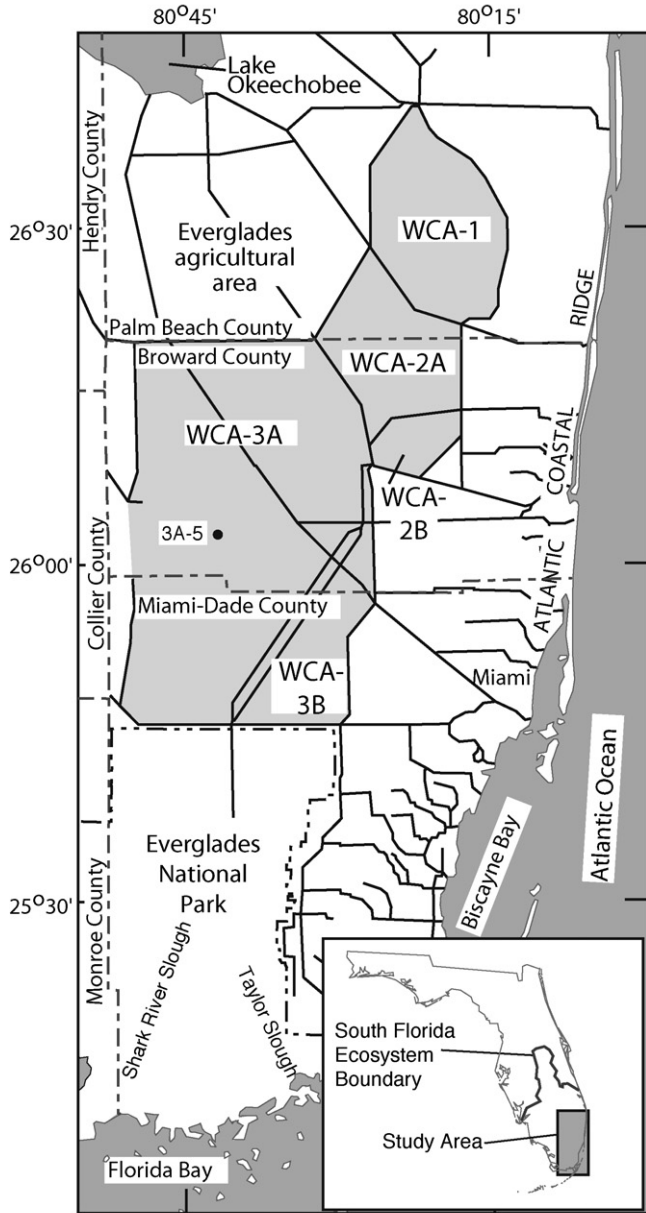
(Rybicki et al., 2001), all vegetation within the quadrats was harvested, grouped by species, and bagged for later measurements in the laboratory. From laboratory measurements (Harvey et al., 2009) the average frontal area per unit volume and stem diameter for each species within each clip plot were computed.

For statistical analysis of the clip plot dataset, we grouped the clip plots into the following categories according to the qualitative vegetation description: ridge (plots dominated by *Cladium*, with little to no *Eleocharis*, $N=35$ plots), *Eleocharis* slough (plots characterized by relatively dense *Eleocharis*, $N=7$ plots), and deep-water slough (plots characterized by relatively sparse *Eleocharis* and abundant floating species, $N=9$ plots).

2.2.1. Emergent vegetation

Because clip plots were collected during different times of year and because the plots from Taylor Slough may not have been representative of well-preserved RSL, we needed to determine whether season or site significantly affected emergent vegetation architecture, and if so, how to interpret those differences in the selection of representative frontal area and stem diameter profiles. To this end, we performed three-way ANOVAs on the log-transformed frontal area per unit volume (a [L^{-1}]) for each clip plot category using the statistical software package JMP (SAS Institute, Cary, NC). Month and region were the main effects, and the vertical coordinate corresponding to each measurement of a was treated as a repeated measure. Individual sites within regions were treated as replicates. We also performed the same ANOVA analyses on the log-transformed stem diameter (d [L]). Due to a lack of replicates, we did not include WCA-3A in the ANOVA analyses, nor did we perform an ANOVA for the *Eleocharis* slough dataset.

All testable effects and interactions were associated with significant variance in the response variable a on the ridge at the $\alpha < 0.05$ level, but in the deepwater slough category, no effects were significant (Table 1). Within the ridge, the only significant effect on profiles of stem diameter was the vertical coordinate. In contrast, within the deepwater slough, no effects on stem diameter profiles were significant (Larsen, 2008). Based on the ANOVA results and the relatively well-preserved nature of the RSL in Shark River Slough and WCA-3A but not in Taylor Slough, we excluded the Taylor Slough clip plots in determining representative emergent frontal area and stem diameter profiles for the ridge. Also, because depths and flow velocities are low in April compared to September and November (Harvey et al., 2009), and because frontal area profiles



EXPLANATION

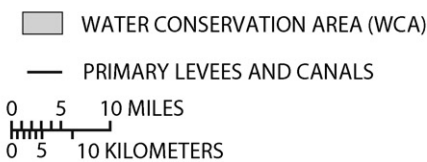


Fig. 3. Map of the greater Everglades, showing the locations of Water Conservation Areas (WCAs), site 3A-5, Everglades National Park, Shark River Slough, and Taylor Slough.

were significantly different in April and September within Shark River Slough, we excluded April clip plots from our determination of representative frontal area and stem diameter profiles on the ridge. Due to the more limited clip plot dataset for deepwater and *Eleocharis* sloughs and to the lack of significant effects on profiles of frontal area and stem diameter in deepwater sloughs, we retained all slough clip plots in our analysis.

Table 1

Significance of main effects and interaction terms from repeated-measures ANOVAs of frontal areas in Everglades ridges and deepwater sloughs. All testable effects and interactions are shown, and asterisks denote significant results at the $\alpha < 0.05$ level.

Response variable	Effect	DF	F ratio	p
a_{ridge}	Month	2	3.2086	0.0450*
a_{ridge}	Region	1	6.8965	0.0103*
a_{ridge}	Vertical coordinate	8	13.2450	<0.0001*
a_{ridge}	Month \times vertical coordinate	12	2.0431	0.0234*
a_{ridge}	Region \times vertical coordinate	7	2.7615	0.0094*
$a_{deepwater\ slough}$	Month	3	1.1815	0.4437
$a_{deepwater\ slough}$	Region	1	3.6370	0.2103
$a_{deepwater\ slough}$	Vertical coordinate	6	0.5357	0.7745
$a_{deepwater\ slough}$	Month \times vertical coordinate	15	0.7612	0.7011
$a_{deepwater\ slough}$	Region \times vertical coordinate	6	0.7570	0.6121

Using the non-excluded clip plots (ridge $N=9$, *Eleocharis* slough $N=7$, deepwater slough $N=9$), we calculated mean frontal area and stem diameter profiles for ridge, *Eleocharis* slough, and deepwater slough emergent vegetation, along with the 95% confidence intervals around the mean profiles and minimum and maximum values at each profile location (Fig. 4a–c). Mean profiles were calculated at a vertical increment of 1 cm, linearly interpolating between available data points from the clip plots (at 10 or 20 cm vertical increments). We considered these mean profiles representative of well-preserved RSL and employed them in the remainder of our analysis.

2.2.2. Floating mats of periphyton and *Utricularia*

Data for the frontal area of *Utricularia* throughout the Everglades are available in Harvey et al. (2005, 2009), Rybicki et al. (2001), and Carter et al. (1999a,b). Since *Utricularia* floats, we used the water surface as the datum and averaged all available data to obtain mean, minimum, and maximum frontal area profiles of *Utricularia*. Because the diameter of *Utricularia* stems does not vary greatly, we used a uniform *Utricularia* diameter of 0.4 mm, obtained as a weighted average of *Utricularia purpurea* stems and fronds measured from a scaled botanical drawing (Britton and Brown, 1913).

The clip plot datasets of Carter et al. (1999a,b) and Rybicki et al. (2001) also include periphyton biomass. Using our measured periphyton density of 18.3 mg mL^{-1} (Larsen, 2008), we converted the periphyton biomass to a total volume, $V\text{ [L}^3\text{]}$. Assuming that periphyton and *Utricularia* occur in association, with periphyton growing exclusively on *Utricularia* stems, we calculated new effective stem diameter ($d_{\text{effective}}\text{ [L]}$) at each profile point by partitioning the periphyton volume as annuli of constant thickness around all *Utricularia* stems:

$$\frac{V_{\text{periphyton}}}{n\Delta z} = \frac{\pi d_{\text{effective}}^2}{4} - \frac{\pi d_{\text{Utricularia}}^2}{4}, \tag{3}$$

where Δz is the thickness of the vertical increment in the calculation (1 cm) and n is the number of stems present per within the clip plot, equal to

$$n = \frac{a_{\text{Utricularia}} \times 0.25\text{ m}^2}{d_{\text{Utricularia}}}, \tag{4}$$

where 0.25 m^2 is the area of the clip plot quadrat. Total effective frontal area per unit volume [L^{-1}] for floating vegetation can then be calculated as

$$a_{\text{effective}} = \frac{d_{\text{effective}}n}{0.25\text{ m}^2}. \tag{5}$$

To obtain representative profiles of effective stem diameter and effective frontal area of the floating mats vegetation class (Fig. 4d), we averaged Eqs. (3)–(5) over all permutations of the available *Utricularia* and periphyton data.

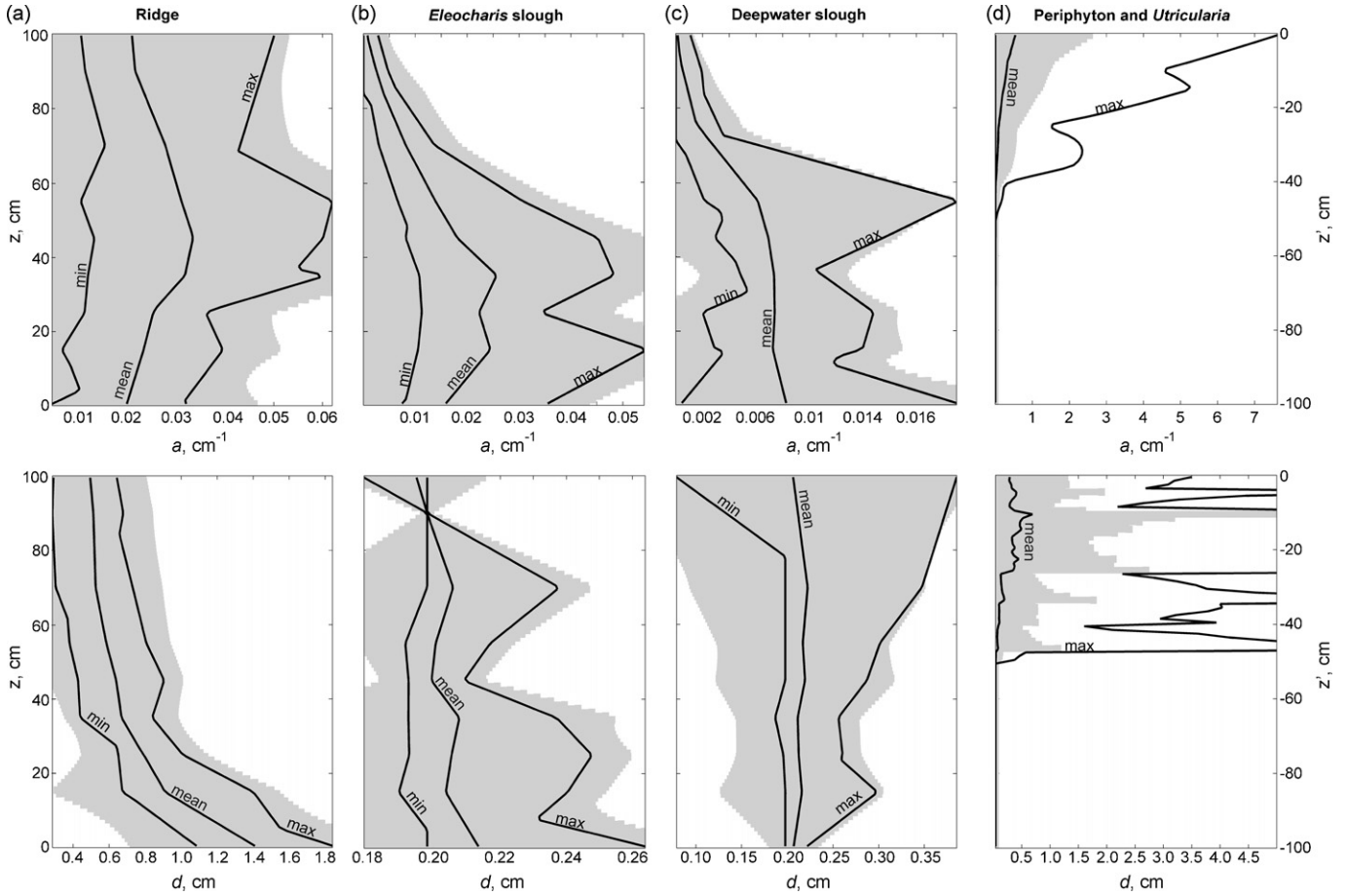


Fig. 4. Frontal area and stem diameter vertical profiles for vegetation categories of interest within the Everglades clip-plot database: (a) ridge, (b) *Eleocharis* slough (emergent vegetation only), (c) deepwater slough (emergent vegetation only), and (d) periphyton and *Utricularia*. Mean, minimum observed, and maximum observed frontal areas and stem diameters at each vertical increment are depicted, as well as 95% confidence intervals surrounding the mean profiles (shaded gray). Note z is the vertical coordinate relative to the soil surface but that a different datum pertains to the periphyton and *Utricularia* vegetation class, which float at the water surface. For this vegetation class, the vertical coordinate is specified by z' , which is zero at the water surface and negative beneath the water surface. Coordinate z' is related to z by $z = z' + H$, where H is water depth.

2.2.3. Epiphyton

For our comparison between the flow hydrodynamics in slough vegetation communities with and without epiphyton sweaters, we used data from a clip plot collected at USGS site WCA-3A-5 (Fig. 3), located in the best-preserved portion of the RSL. The clip plot was harvested as described in Harvey et al. (2009). Thick epiphyton sweaters surrounding emergent stems were minimally disturbed by sampling. After initial measurements of frontal area and mean stem diameter in the laboratory, we repeated the measurements with the epiphyton sweaters removed. Since epiphyton sweaters were confined to the 30 cm water depth at the time of harvest, we assumed for modeling purposes that the total diameter (stem + epiphyton) measured in the 20–30 cm increment could be extrapolated higher in the water column under deep-water conditions with epiphyton. This assumption is supported by statistical analyses indicating that the depth effect on stem diameters was insignificant in sloughs (Section 2.2.1).

2.3. Drag coefficients for vegetation classes

We followed the method of Harvey et al. (2009) in calibrating the drag coefficient for emergent vegetation. Drag coefficient is given by

$$C_D = 2K_0 Re_d^{-k} (ad)^{-0.5}, \quad (6)$$

where Re_d is a stem diameter-based Reynolds number and K_0 and k are empirical coefficients. Vegetative drag is the dominant term in the generic force balance of flow through vegetation (Nepf, 2004), which simplifies to

$$gS \left(1 - \frac{\pi}{4} \hat{a} \hat{d} \right) \approx \sum_i \frac{1}{2} C_{D,i} a_i u^2. \quad (7)$$

When the contribution of the floating class to vegetation architecture profiles is negligible, substitution of Eq. (6) into (7) and rearrangement yields

$$\frac{gS}{\bar{u}^2} \left(1 - \frac{\pi}{4} \hat{a} \hat{d} \right) \left(\frac{d}{a} \right)^{0.5} \approx K_0 Re_d^{-k}. \quad (8)$$

In Eq. (8), $-k$ and $\log(K_0)$ can be determined as the slope and intercept, respectively, of linear regression through a log-transformed dataset of the product on the left-hand side of the equation plotted against $\log(Re_d)$ (Fig. 5a). The data required for this procedure consist of measurements of vegetation architecture and time-series of S , \bar{u} , and water depth H (which also affects the depth-averaged values of vegetation architecture parameters). We performed the regression using a two-year time-series (Harvey et al., 2009) of measured water depth, depth-averaged velocity, and water-surface slope in the well-preserved ridge and slough vegetation communities of site WCA-3A-5 and the representative mean

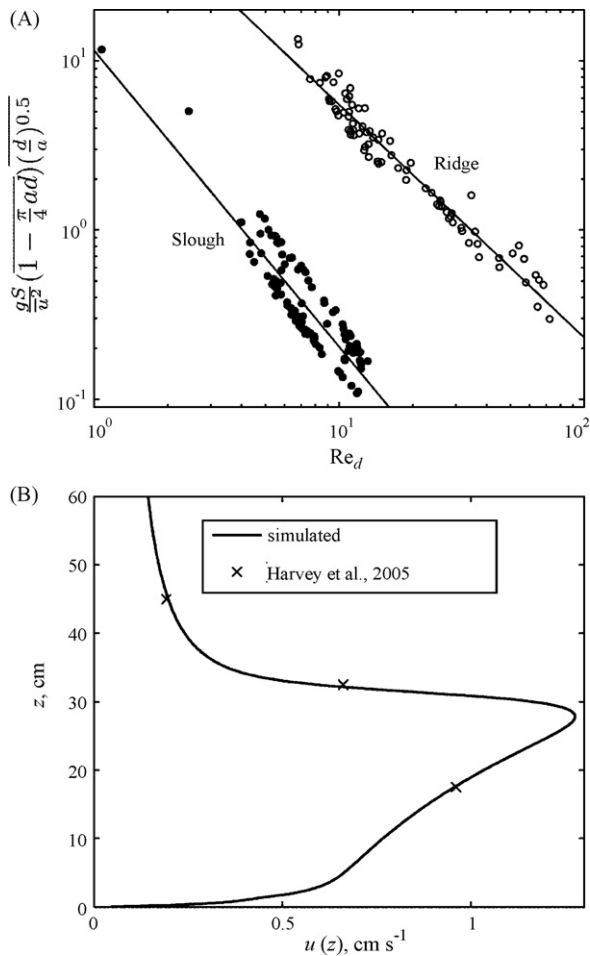


Fig. 5. Calibration of drag coefficients for *Cladium*, *Eleocharis* and floating mats of periphyton and *Utricularia*. In (a), empirical coefficients $-k$ and $\log(K_0)$ (Eq. (8)) for *Eleocharis* (slough) and *Cladium* (ridge) are determined as the slope and intercept, respectively, of the linear regression (solid lines) through the depicted log-transformed field dataset. In (b), a velocity profile simulated using the model of Larsen (2008) is fit to an observed velocity profile (Harvey et al., 2005) by adjusting the empirical term, ζ , within the expression for the drag coefficient of periphyton and *Utricularia* (Eq. (9)) to minimize the sum of squared error in the simulated velocities.

vegetation architectures from ridges and *Eleocharis* sloughs without periphyton or *Utricularia*. The time-series spanned a period (August 2005–February 2008) when the contribution of floating periphyton and *Utricularia* to vegetative drag at the site was negligible, due to their removal by hurricane Wilma in October 2005. Coefficients calibrated using this method are reported in Table 2. The coefficients differed from those calculated by Harvey et al. (2009) (ridge $K_0 = 10^{2.37}$, slough $K_0 = 10^{0.29}$; ridge $k = 1.54$, slough $k = 1.73$), who used the same time-series of flow data but local measurements frontal areas and stem diameters. Since our objectives focused on simulating flow in the ridge and slough landscape as a whole, we instead used our landscape-averaged representative *Cladium* and *Eleocharis* profiles.

The relationship for the floating vegetation drag coefficient was based on Schutten and Davy (2000) and Vogel (1994):

$$C_D = \zeta u^{-0.5}, \quad (9)$$

where ζ is an empirical coefficient. The inverse relationship between drag coefficient and flow velocity is due to the reconfiguration of floating mats at high flows in a way that minimizes drag (Dodds and Biggs, 2002; Sand-Jensen, 2003).

Table 2

Calibrated parameters for solution of drag coefficients for ridge and slough vegetation classes.

Vegetation class	K_0	k	ζ
<i>Cladium</i>	$10^{2.12}$	1.38	
<i>Eleocharis</i>	$10^{1.06}$	1.75	
<i>Utricularia</i> + periphyton			0.60

To calibrate ζ , we compared velocity profiles simulated with our model to a velocity profile measured during a tracer test in an *in situ* slough flume within Everglades National Park (Harvey et al., 2005), adjusting ζ until the best match was produced (Fig. 5b; Table 2). The flume contained both emergent *Eleocharis* and a thick layer of floating vegetation, and clip plots representative of the flume vegetation community provided the required vegetation architecture input parameters.

2.4. Model execution

We combined the measured vegetation architecture categories into eight unique communities for comparison (Table 3). Within each vegetation community of interest, we ran the model 200 times over a range of input S and H values that may have occurred in the historic RSL (SCT, 2003). Outputs were the predicted values of \bar{u} and τ_0 under steady, uniform conditions. To compare the differential in bed shear stress between slough and ridge, we assumed a 20-cm elevation difference (i.e., 20-cm difference in surface-water depth at any given time), which is consistent with the present-day topography in the best-preserved portion of the RSL (Harvey et al., 2009).

3. Results and discussion

3.1. Ridge/slough bed shear differentials across vegetation communities

Over most of the two-space of water-surface slopes and surface-water depths tested, the differential in bed shear stress from slough to ridge was positive (Fig. 6). Because the entrainment of bed sediment is a positive function of bed shear stress, the ridge/slough bed shear differential indicates that the erosion of floc from sloughs is greater than the erosion of floc from ridges when shear stresses are above the floc entrainment threshold. When erosion of floc occurs within sloughs but not ridges, a greater bed shear differential corresponds to a greater redistribution of sediment, both through advective and dispersive processes.

To delineate the three possible states of sediment transport (ubiquitous deposition, redistribution of sediment from slough to ridge, and ubiquitous erosion) within the two-space of surface-water depth and water-surface slope, we calculated the $\tau_0 = 1.0 \times 10^{-2}$ Pa contour for the ridge and slough vegetation communities compared in each state-space diagram (Fig. 6). This bed shear stress is the threshold for the initiation of erosion of Everglades floc, determined through simultaneous measurement of Reynolds stress profiles and concentrations of suspended floc in a laboratory flume (Larsen et al., 2009). The zone between the threshold bed shear stress contours for the slough and ridge represents conditions under which sediment redistribution from sloughs to ridges occurs, which is the target for restoration of the RSL. The combination of water-surface slope and depth that produces the greatest slough/ridge bed shear differential within this zone maximizes the redistribution of sediment from slough to ridge and has the greatest potential to reinforce landscape patterning.

Table 3

Composition of modeled Everglades vegetation communities. See Section 2.2 for a description of data sources.

Vegetation community nomenclature	Composition		
	Emergent <i>Cladium</i> vegetation class	Emergent <i>Eleocharis</i> vegetation class	Floating periphyton and <i>Utricularia</i> class
Ridge	Representative ridge (Fig. 4a)	None	None
<i>Eleocharis</i> sloughs, all vegetation present	None	Representative <i>Eleocharis</i> slough (Fig. 4b)	Representative periphyton and <i>Utricularia</i> (Fig. 4d)
Deepwater sloughs, all vegetation present	None	Representative deepwater slough (Fig. 4c)	Representative periphyton and <i>Utricularia</i> (Fig. 4d)
Deepwater sloughs, no emergent vegetation	None	None	Representative periphyton and <i>Utricularia</i> (Fig. 4d)
<i>Eleocharis</i> sloughs, no floating vegetation	None	Representative <i>Eleocharis</i> slough (Fig. 4b)	None
Deepwater sloughs, no floating vegetation	None	Representative deepwater slough (Fig. 4c)	None
WCA-3A-5 slough, with epiphyton	None	3A-5 profile, with epiphyton	3A-5 profile
WCA-3A-5 slough, epiphyton-free	None	3A-5 profile, epiphyton-free	3A-5 profile

Given that the present-day dimensionless bed slope averages 3×10^{-5} (Kushlan, 1990), with water-surface slopes that are often lower (1×10^{-5} – 3×10^{-5} for the 2006–2007 wet seasons, Harvey et al., 2009) due to impoundment, the present system is well within the zone of ubiquitous sediment deposition for the most common slough vegetation community (*Eleocharis* sloughs, see Fig. 6a). Since the critical bed shear stress contour for the slough is nearly invariant with water level at depths above approximately 45 cm, it will be necessary to increase water-surface slope to move the system within the zone of sediment redistribution if the slough vegetation community does not change. At the low water-surface slopes typical of the present system, increasing surface-water depths will not cause sediment redistribution. At higher water-surface slopes (6.0×10^{-5} – 1.0×10^{-4}), increasing the water depth may be sufficient to move the system within the zone of sediment redistribution, particularly if surface-water level crosses the 45 cm threshold, at which a break in the slope of the critical bed shear stress contour occurs. This breakpoint occurs only when slough vegetation communities include floating mats of *Utricularia* and periphyton. Because *Utricularia* and periphyton rise away from the bed with the water surface, the bottom portion of the floating mat just clears the peat surface at a surface-water level of approximately 45 cm (Fig. 4). Due to the high resistance and closely spaced stems of the *Utricularia* and periphyton, flow is preferentially routed to the near-bed *Utricularia*-free location at surface-water levels above this depth threshold, increasing bed shear stress and enabling the entrainment of sediment at lower water-surface slopes.

When the floating vegetation class is absent, as after hurricane Wilma, the breakpoint in the slope of the critical bed shear stress contour for the slough does not occur (Fig. 6d and e). Additionally, due to the decrease in vegetative resistance, mean velocities increase for particular combinations of depth and water-surface slope. However, at surface-water depths above 45 cm, the position of the zone of sediment redistribution within the two-space of surface-water depth and water-surface slope is not sensitive to the presence or absence of floating mats of periphyton and *Utricularia*.

When periphyton was not floating but instead coated the stems of emergent vegetation as epiphyton “sweaters,” effects on the state-space diagram were minimal (Fig. 7a compared to b). Frontal areas and stem diameters were 1.3–2.3 times larger for *Eleocharis* communities with attached epiphyton compared to *Eleocharis* communities without epiphyton (Harvey, Noe, and Larsen, unpublished data). Despite the added thickness of the periphyton, two opposing effects caused depth-averaged velocities and bed shear stresses to be approximately equivalent in the two vegetation communities. First, the increase in frontal area from epiphyton colonization was allocated disproportionately near the water surface (i.e., in the 10–20 cm vertical increment; G. Noe, pers. comm.), rout-

ing a greater proportion of the momentum flux to the 0–10 cm increment, just above the bed. Secondly, the greater diameter of colonized stems increased the eddy scale and the vertical transfer of momentum. Since Fig. 7 is based on data from only a single clip plot, it is possible that the opposing effects of shape of the vegetation profile, vegetative resistance, and turbulence would not balance so evenly in other vegetation communities. Still, the effects of periphyton colonization are likely small compared to the effects of a shift in vegetation community (Fig. 6).

Although floating vegetation and floating or attached periphyton had little effect on the sediment transport state-space diagram, removal of *Eleocharis* had a highly significant effect on the shape and location of the zone of sediment redistribution from slough to ridge. Progressive removal of *Eleocharis* (from Fig. 6a to b to c and from Fig. 6d to e) not only promoted higher mean flow velocities at lower water-surface slopes but also higher bed shear stresses within the sloughs. Higher bed shear stresses result primarily from decreased vegetative drag and secondarily from the increase in near-bed stem spacing, which increases eddy scale and eddy viscosity near the boundary layer, enabling more efficient transfer of momentum from locations higher in the water column. The effect is both a broadening of the zone of sediment redistribution and a shift of the zone to lower water-surface slopes, so that in the extreme scenario, when *Eleocharis* is absent (Fig. 6c), sediment redistribution can be induced simply by increasing water depth.

The zone of sediment redistribution broadens further at larger ridge/slough elevation differences. Figs. 6 and 7 assume that ridges are elevated 20 cm above sloughs. If the actual elevation difference is greater, the critical bed shear stress contour for entrainment of sediment from the ridge is translated along the vertical axis of the plot to larger slough depths, and vice-versa. Thus, as ridge elevations increase above sloughs, the set of conditions under which sediment redistribution from sloughs to ridges occurs enlarges, until the ridge is no longer submersed and cannot act as a sink for suspended sediment.

3.2. Use of velocity and bed shear stress modeling in restoration planning

There are many uncertainties associated with restoration planning in the Everglades, including uncertainties due to heterogeneity in vegetation communities, temporal variability in hydrologic forcing, and modeling simplifications. Consequently, Everglades restoration is enacted via adaptive management, in which pilot-scale restoration projects based on the best available information are implemented, results are evaluated, and engineering details are adjusted until the uncertainty in the outcome is reduced to a level acceptable for large-scale implementation (Walters, 1986). Our modeling and field experimentation will aid

in adaptive management planning for preservation and restoration of the RSL.

In particular, state-space diagrams delineating the state of sediment transport over a range of water-surface slopes and depths provide concrete guidance for the hydrologic and hydraulic drivers needed for restoration of sediment redistribution from sloughs to ridges, leading to more educated planning for initial adaptive management steps. Available measurements of flow velocities within Everglades sloughs averaged 0.3 cm s^{-1} in central WCA-3A (Harvey et al., 2009), $0.8\text{--}1.6 \text{ cm s}^{-1}$ in Everglades National Park in the vicinity of tree islands (Bazante et al., 2006), and 1.15 cm s^{-1} (Riscassi and Schaffranek, 2003) or lower (0.50 cm s^{-1} , Leonard et al., 2006) in Shark River Slough. Comparing these values and the measured water-surface slopes of the present system (ranging from 1×10^{-5} to 3×10^{-5} in WCA-3A and from 4×10^{-5} to 6.5×10^{-5} in Shark

River Slough Harvey et al., 2009) to the state-space diagrams of Fig. 6, it is apparent that sediment entrainment events are rare in the present system, primarily due to the low water-surface slopes. Indeed, Bazante et al. (2006) found that flow speeds of 4 cm s^{-1} were insufficient to entrain bed particles in the shaded, sparsely vegetated channels between tree trunks on Everglades National Park tree islands, which is consistent with the model predictions in Fig. 6d and e.

The low surface-water slopes of the present system are not representative of the historic Everglades. Over the past century, the regional bed slope and water-surface slope have decreased as a result of subsidence of peat in northern parts of the Everglades due to overdrainage (Snyder and Davidson, 1994) and surface-water ponding at the downstream levees of the WCAs. Under current vegetation assemblages, it will be necessary to increase water-surface

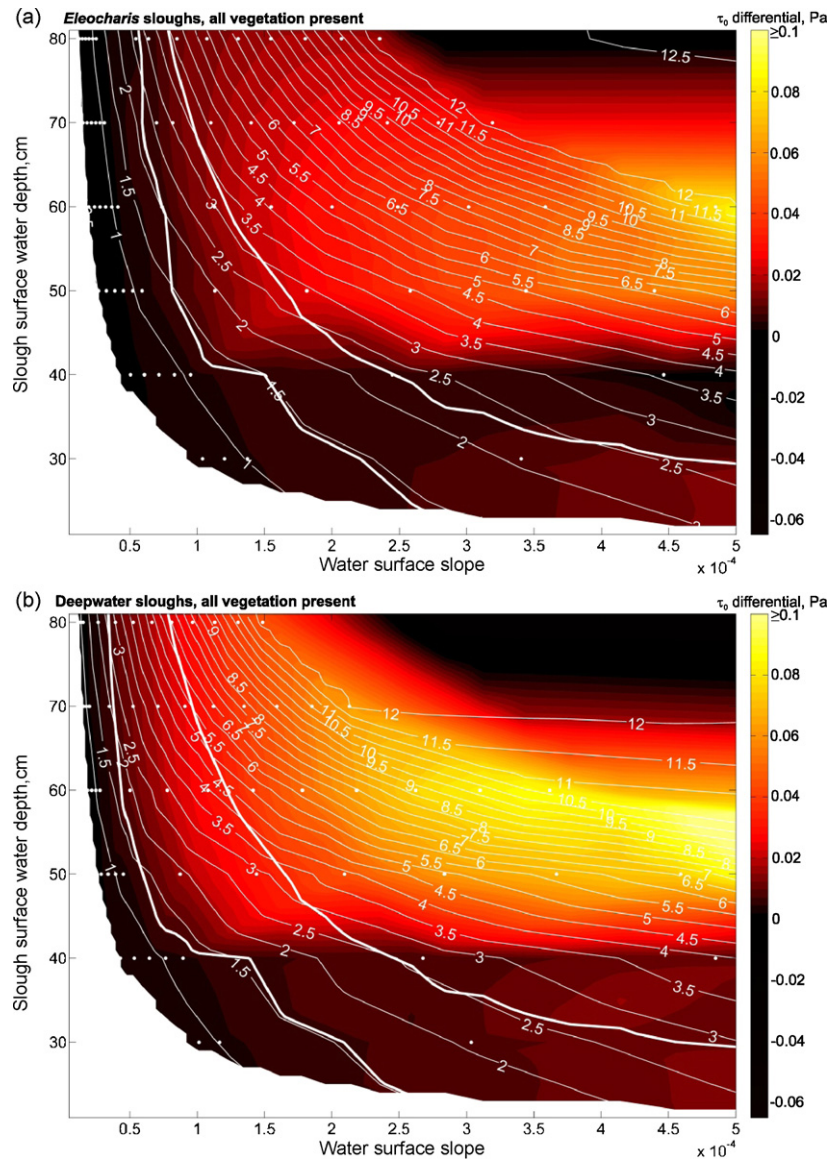


Fig. 6. The state-space for sediment redistribution from slough to ridge for different slough vegetation communities over a range of water-surface slopes and slough surface-water depths. Colors represent the differential in bed shear stress from slough to ridge, with positive values being bed shear stresses that are much higher in slough than in ridge. To compute the differential in bed shear stress, we have assumed that ridges are 20 cm higher than sloughs. Thin contours are depth-averaged velocity contours, and the two thick contours represent the threshold bed shear stress ($\tau_0 = 1.0 \times 10^{-2} \text{ Pa}$) for the slough (lower contour) and for the ridge (upper contour). The threshold bed shear stress contours divide the two-space into three states of sediment transport—from left to right: a zone of ubiquitous deposition, a zone of sediment erosion from sloughs and deposition on ridges (redistribution), and a zone of ubiquitous erosion. Within the zone of sediment redistribution, greater bed shear stress differentials are associated with a greater mass of sediment redistribution. Points show the locations of individual simulation results.

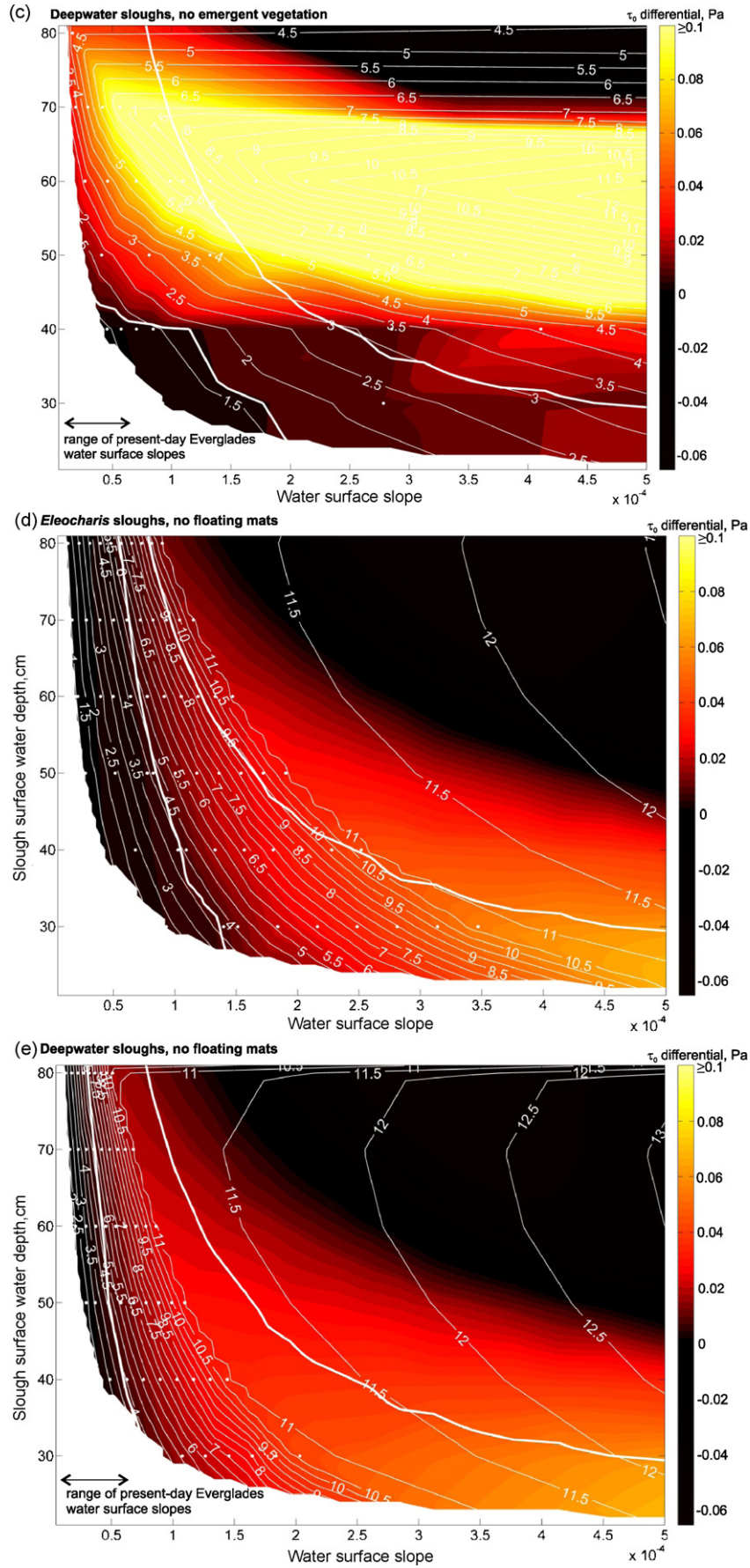


Fig. 6. (Continued)

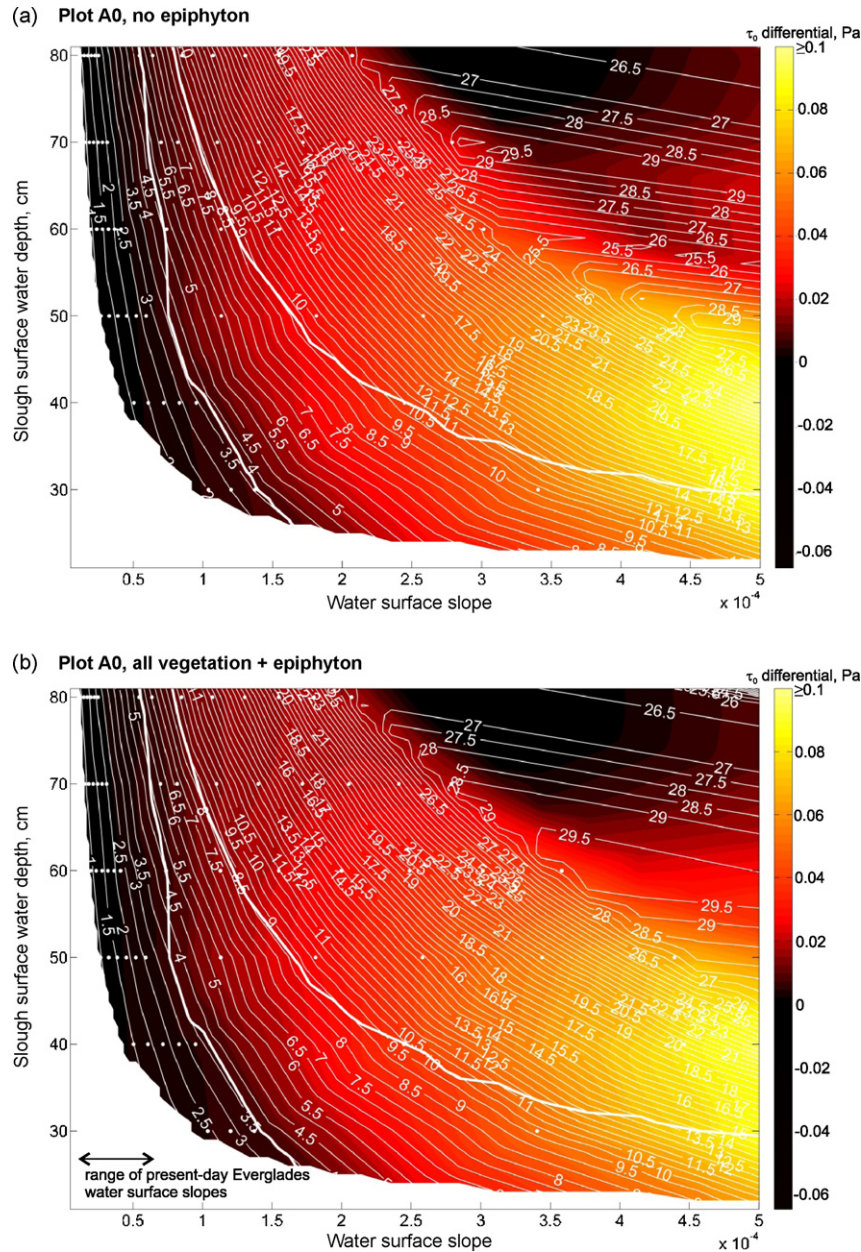


Fig. 7. The state-space for sediment redistribution from slough to ridge for the A0 clip plot vegetation community, with and without colonization of emergent stems by epiphyton “sweaters”. See Fig. 6 for an explanation of symbols and colors.

slope to restore sediment redistribution to the ridge and slough landscape, which can be accomplished through pulsed releases of water from impounded areas (Harvey et al., 2009). However, in sloughs where *Eleocharis* is highly abundant, it may not be practical to increase water-surface slope sufficiently to induce sediment redistribution.

When the abundance of *Eleocharis* is moderate to low, it will be possible to restore sediment redistribution through pulsed releases of water of moderate depth (>45 cm) that transiently bring water-surface slopes within the range of $\approx 5 \times 10^{-5}$ – 1×10^{-4} . Whereas WCA-3A most frequently has water-surface slopes less than 3×10^{-5} under typical flow conditions and would require pulsed discharge events to restore sediment redistribution, Shark River Slough regularly experiences water-surface slopes of 4×10^{-5} – 6.5×10^{-5} (Harvey et al., 2009), so additional pulsed releases to Everglades National Park would not be necessary, pro-

vided moderately high surface-water levels could be attained. Laboratory floc entrainment experiments show that if bed shear stress within sloughs is approximately 2.0×10^{-2} Pa (just above the threshold bed shear stress for floc entrainment of 1.0×10^{-2} Pa), the mass of floc equivalent to 0.3 mm of peat would be scoured in just one day (Larsen et al., 2009). Given that the historic average annual rate of peat aggradation is 0.1 – 1.4 mm yr⁻¹ (Bernhardt and Willard, 2009), bed sediment redistribution by flow has the potential to be a significant landscape-forming process even if high-flow conditions occur for only a small fraction of the year. Thus, the intermittent, short-term nature of pulsed discharge events would be suitable for restoration of sediment transport processes in the Everglades.

Hurricanes may have an even larger effect on the redistribution of sediment. Following Hurricane Wilma, 77 mm of sediment were deposited in the riverine mangrove forests flanking the Shark River in southern Florida (Cahoon, 2006). Additional studies of hurricane

effects on coastal marsh sedimentation show that a single hurricane can have a greater impact on sediment accretion than a year of high-frequency cold fronts (Cahoon et al., 1995) and that delivery of sediment to coastal marshes from a hurricane can exceed amounts delivered by typical overbank floods or channel diversions by several times (Turner et al., 2006).

Even pulsed flow events that do not entrain bed sediment have the potential to influence mass transfer of particles across the Everglades wetland. Fine particles that are produced within the water column and/or settle on vegetation stems and leaves are entrained and transported at mean flow velocities and bed shear stresses lower than the threshold for bed sediment (Larsen et al., 2009). However, transport of bed sediment by flow may have a greater impact on landscape evolution than transport of fine particles. First, the faster settling velocities of bed particles result in a more distinct separation between zones of net erosion and net deposition in the ridge/slough transition, which enhances topographic differentiation (Larsen et al., 2009). Second, fine particles are more enriched in the limiting nutrient phosphorus than bed particles (Noe et al., 2007), which may lead to rapid microbial utilization of fine particles (Noe et al., 2003) and mineralization of their constituent carbon to CO₂ rather than immobilization in the peat. For this reason, our study focused solely on the entrainment and deposition of bed sediment, but the role of fine particles remains an area of uncertainty in the restoration that should be addressed.

Up to this point, much of the literature on restoring the RSL has focused on increasing flow velocities, without mention of bed shear stress (SCT, 2003; Ogden, 2005; Leonard et al., 2006). The state-space diagrams presented here (Fig. 6) show that the shear stresses associated with the entrainment of sediment occur over a range in depth-averaged velocity that is sensitive to surface-water depth and vegetation community composition. For example, in *Eleocharis* sloughs with all vegetation present, sediment entrainment begins at a depth-averaged velocity of approximately 1.4 cm s⁻¹ when the surface-water depth is 30 cm but at a velocity of 2.2 cm s⁻¹ when the depth is 70 cm (Fig. 6a). Meanwhile, in *Eleocharis* sloughs without a floating mat of periphyton and *Utricularia*, sediment entrainment begins at 3.6 cm s⁻¹ and 5.5 cm s⁻¹ for depths of 30 cm and 70 cm, respectively (Fig. 6d). At the higher surface-water depths, faster mean velocities are needed to entrain sediment as a result of the larger form drag on vegetation stems. Therefore, a single depth-averaged velocity should not be targeted for restoration of sediment transport. However, because depth-averaged velocity is more readily measurable than surface-water slope or bed shear stress, target velocities for restoration can be designed for particular surface-water depths and vegetation assemblages using the state-space diagrams presented here. In this way, engineers managing water control structures will be able to make adjustments to operations using water velocities measured at downstream locations. Confidence in this strategy will be augmented by future experiments that further validate the details of these state-space diagrams.

3.3. The ratchet effect in streams and wetlands

In streams with multiple, dynamic channels (e.g., anastomosed streams such as the Platte River), the growth of emergent vegetation on the channel bed during relatively dry periods is often irreversible, due to increased drag and increased deposition of sediment during subsequent flow periods (Tal et al., 2004). This irreversibility of channel loss is known as the “ratchet effect.” Everglades sloughs, likewise, may be experiencing the ratchet effect. Palaeoecological studies show that historically, sloughs contained less *Eleocharis*, and vegetation assemblages were characteristic of

deeper water conditions (Willard et al., 2001; Willard and Cronin, 2007; Bernhardt and Willard, 2009). Additional studies show that *Eleocharis cellulosa* grown in deep-water conditions (54 cm depth) produces fewer shoots and lower biomass than *Eleocharis cellulosa* grown in shallower (7 cm depth) water (Edwards et al., 2003). *Eleocharis* that became more abundant in sloughs over the past century as a result of anthropogenically lowered water depths now prevents entrainment of floc within sloughs, except at exceedingly high water-surface slopes. Moreover, the relatively refractory nature of *Eleocharis* organic matter compared to floating vegetation likely increases the rate of *in situ* peat accumulation within sloughs, further diminishing the topographic differentiation between ridge and slough (Larsen et al., 2007). Thus, as with streams (Tal et al., 2004), vegetation within Everglades sloughs can amplify the effect of a decrease in discharge, making the effect of a temporary hydrologic change more permanent. However, if the loss of topographic differentiation is not too great, phenomena that decrease vegetation density, such as prolonged inundation (e.g., Edwards et al., 2003), may “reset” the system so that subsequent landscape evolution trajectories are more similar to those of the unperturbed system.

While the ratchet effect in streams permanently removes channels, the effect on stream sediment transport budgets is often small, since the affected side channels typically account for only small fluxes of sediment (Tal et al., 2004). In contrast, in the Everglades the flux of suspended sediment through sloughs is approximately twice as great as the flux of material through ridges (Noe et al., *in press*). Unlike streams, the RSL lacks dominant channels, so processes (such as surface-water level declines) that promote emergent vegetation growth in sloughs and slough infilling tend to affect sloughs across the system, thereby having an adverse impact on sediment transport and redistribution that is highly significant.

4. Summary

Implementation of our field-validated model facilitates the creation of state-space diagrams that provide a new tool for predicting sediment transport over a range of water-surface slopes and depths. In the Everglades RSL, these state-space diagrams can aid adaptive management programs that aim to restore the redistribution of sediment from sloughs to ridges. Over the range of vegetation architectures and hydraulic/hydrologic conditions found in the Everglades, the state-space diagrams indicated that presence of vegetation had the dominant effect of reducing bed shear stresses, which in turn reduced sediment entrainment. Though bed shear stresses were not sensitive to minor variations in stem characteristics due to epiphyton coatings or, in relatively deep flows, to the presence or absence of floating mats of periphyton and *Utricularia*, they were highly sensitive to changes in vegetation community that increased the abundance of emergent *Eleocharis* within sloughs. Except for shallow sloughs with floating vegetation mats, bed shear stresses were more sensitive to water-surface slope than surface-water depth. These sensitivities suggested that restoration of the RSL will be more effectively achieved by increasing water-surface slope through pulsed releases of water from impounded areas than by increasing surface-water level. However, in sloughs where *Eleocharis* is highly abundant, it may not be practical to restore sediment redistribution through these measures, unless *Eleocharis* abundance first decreases, which may occur through natural or managed processes. Landscape-scale adaptive management projects that provide a range of elevated bed shear stresses in different vegetation communities will provide a valuable opportunity to further test and

refine the model and restoration engineering strategies in tandem.

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