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Project: Landscape Model of Ridge and Slough Topography: Integration of Hydrology and Biological Processes

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Following are results and discussion of the project entitled: "Landscape Model of Ridge and Slough Topography: Integration of Hydrology and Biological Processes." The project was funded by the Critical Ecosystem Studies Initiative and the scope of the project was to address the potential of flow in determining the self-assembly of the strikingly patterned landscape in the Central Everglades. In this Final Report, we focus on the changes in landscape patterning in the Central Everglades. We have used a four-tiered approach to investigate surface patterning in three large areas of the Everglades ecosystem that have experienced different water management regimes over the past half-century (Fig. 1). These four approaches were to: 1) map the current vegetation cover by physiognomic class, 2) quantify current landscape pattern metrics and abiotic environmental variables, 3) examine changes in landscape pattern from 1940 to the present using historic and current aerial photographs, and 4) develop a quantitative model that relates abiotic variables and landscape metrics, with the overall objective of predicting how landscape patterns are likely to respond to different water management scenarios.

Potential mechanisms that explain the distribution of vegetation communities along environmental gradients in the central Everglades, based on detailed analyses of the relationship between vegetation composition and abiotic variables, are presented in a companion final report submitted by Givnish *et al.* Finally, a third companion final report that provides crucial stratigraphic evidence bearing on several positive feedback mechanisms that form the backbone of our landscape model presented in Givnish *et al.* will be submitted in September 2007, by Glaser *et al.* A summary of previous progress for this third project entitled: "Everglades Soil Analysis: landscape model of ridge and slough topography," is presented in this report. Also presented in this report are results from two decomposition studies which were reported on earlier. Finally, a hardcopy of this report and electronic copies of the data and geo-rectified aerial photography will be sent by mail.

Summary

Aim To describe the landscape pattern of the tree island-ridge-slough ecosystem of the Central Florida Everglades, to test for changes in the pattern over the last 64 years and to model the relationship between the landscape pattern and associated environmental parameters.

Location Our study site consisted of three large areas of the Central Everglades in southern Florida, USA; specifically central Water Conservation Area (WCA)-3A, southern WCA-3A and WCA-3B. As a result of water management over the last half century, these three regions differ dramatically in flow regimes and hydrology.

Methods Using high-resolution infrared aerial photographs, we first conducted a supervised classification into slough, ridges and tree islands that was then ground-truthed using 564 quadrats. Next, we used a fast Fourier transform and morphological measurements to quantify the landscape pattern and identify changes in that pattern that may have resulted from changes in water management. Finally, we modeled the relationship between environmental measurements and landscape patterns to identify predictors of landscape pattern. Vertical relief of the soil surface, hydroperiods, water depths and water surface slopes were calculated from data gathered through intensive field sampling and from 1999-2006 data obtained from the Everglades Depth Estimation Network.

Results We found significant differences in the percentages of slough, ridges and tree islands across the three study areas, with ridge communities dominating the region most isolated from historic flow regimes. From 1940 through 2004 the landscape pattern was highly conserved in all three study areas; in WCA-3B the historic pattern was already substantially altered by 1940. Water surface slope, soil thickness, and the divergence of the direction of water flow from the historic orientation of the landscape were negatively correlated with vertical relief, slough width, and the characteristic wavelength of the landscape pattern perpendicular to the direction of water flow. Multiple regression models showed that these three environmental variables were significant predictors of current landscape pattern.

Main conclusions This study, in conjunction with our companion paper (see Givnish *et al.* 2007, submitted), supports our hypothesis that spatially coupled positive and negative feedbacks among vegetation, peat accumulation and hydrology, including water flow, drive the self-assembly of the tree island-ridge-slough patterning within the Central Everglades of southern Florida. In addition, historic changes in these feedbacks have resulted in a severe degradation of the tree island-ridge-slough pattern in WCA-3B. Given the slow response of landscape patterns to shifts in these parameters, it is likely that the effects of proposed changes in Everglades water management will take decades to become apparent. Recognition of such delayed system responses must be an

important consideration in monitoring and adaptive management of restoration efforts.

Following is a manuscript that has been submitted for consideration for publication to “*Global Ecology and Biogeography*,” which provides detailed analysis on what was found regarding landscape patterns in the Central Everglades. Following the manuscript are results and discussion of other associated research that have yet to be put into manuscript format.

Changes in landscape patterning in the Central Everglades: importance of surface water flow and soil thickness

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ABSTRACT

Aim We describe tree island-ridge-slough patterning in the Central Everglades, quantify changes over the past 64 years, and relate landscape pattern to local and regional parameters.

Location Our study sites consisted of central Water Conservation Area (WCA)-3A, southern WCA-3A and WCA-3B, which have diverged dramatically in flow regime as a result of water management over the last half century.

Methods We used high-precision infrared photography to map sloughs, ridges, and tree islands over an area of 400 km²; employed fast-Fourier transforms and visual measurements to quantify landscape pattern; and then analyzed landscape pattern in relation to hydroperiod, water depth, soil relief, historic flow direction, and regional water-surface slope.

Results Sloughs, sawgrass ridges, and tree islands occupied significantly different areas in the three study regions, with ridges dominating the region most isolated from historic flow regimes. From 1940 through 2004, landscape pattern was highly conserved in each region; in WCA-3B the historic pattern was already substantially altered by 1940. Water-surface slope, soil thickness, and divergence of water flow from historic orientation were significant inverse predictors of vertical relief, slough width, and characteristic wavelength of landscape pattern perpendicular to water flow.

Main conclusions This study, in conjunction with our companion paper (see Givnish *et al.*, submitted), supports our hypothesis that spatially coupled positive and negative feedbacks among vegetation, topography, biogeochemistry, and hydrology drive self-assembly of tree island-ridge-slough patterning in the Central Everglades of southern Florida. Historic changes in these feedbacks have resulted in a severe degradation of the tree island-ridge-slough pattern in WCA-3B. Given the slow response of landscape patterns to shifts in environmental parameters, the effects of proposed changes in Everglades water management will probably require decades to become apparent. Recognition of such delayed system responses must be an important consideration in monitoring and adaptive management of restoration efforts.

Keywords landscape change, restoration, Fourier, tree islands, peatland, hydrology

INTRODUCTION

The Everglades of southern Florida are one of the most extensive and intensively managed wetland systems in the world. Before the vast networks of canals and levees crisscrossed the Everglades ecosystem, surface water flowed southward from the expansive pond apple forest at the southern edge of Lake Okeechobee into the Gulf of Mexico over an area of more than a million hectares (Davis *et al.*, 1994). The pre-drainage marsh showed a striking pattern of teardrop-shaped tree islands embedded in a regular, linear background pattern of ridges and sloughs oriented in the direction of water flow (Browder & Ogden, 1999). Sawgrass-dominated ridges and slough bottoms may have differed by up to 0.45 m in elevation (Wright, 1912; Baldwin & Hawker 1915). This surface microtopography was largely independent of fluctuations in the elevation of the underlying calcareous substrate (Sklar *et al.*, 2003). In addition to the well-documented changes in tree-islands (Loveless, 1959; McPherson, 1973; Brandt *et al.*, 2000; Sklar & van der Valk, 2003), it is widely held that much of the patterned ridge and slough landscape of the historic Everglades has been severely disrupted by drainage during the past century. These changes appear to be particularly evident in the regions converted to compartmentalized, rain-fed systems with minimal flow across the landscape.

The three major physiognomic land classes in the central Everglades, sloughs, ridges and tree islands, form characteristic patterns at different spatial scales. The size and spacing of tree islands are an order of magnitude greater than the background pattern of ridges and sloughs and, although they comprise less than 5% of the overall landscape, tree islands play a disproportionately critical role in the Everglades ecosystem (*e.g.* Sklar and van der Valk, 2003). Consequently, many previously published studies have focused on the system drivers and processes that govern the formation and maintenance of tear-drop shaped tree islands (Orem *et al.*, 2002; Bazante *et al.*, 2006, Wetzel *et al.* 2005). On the other hand, relatively

little is known about the factors that have formed and maintained the smaller-scale, linear patterning of ridges and sloughs that dominates the Everglades landscape.

The linkage between hydrology and linear landscape patterns oriented *perpendicular* to the direction of water flow has been well characterized for systems such as the patterned boreal peatlands (Glaser *et al.*, 1981; Foster, 1983; Glaser *et al.*, 1987a, b; Glaser, 1999; Glaser *et al.*, 2004) and the striped "tiger bush" of semi-arid regions (Lefever & Lejeune, 1997; Klausmeier, 1999; Couteron, 2002). Several hypotheses have been advanced to explain the development and persistence of the ridge and slough pattern in the Everglades, including the downstream transport of floc or periphyton, differential rates of peat accumulation and decomposition along hydrologic gradients, and the development of microhabitat differences in water chemistry along the water flow path (Givnish & Volin, 2003; SCT, 2003; Ross *et al.*, 2006). While each of these hypotheses invokes processes that are known to operate in systems where water flow has shaped landscape patterns, they do not explicitly address the properties peculiar to the Everglades landscape, e.g., linear ridges and sloughs oriented *parallel* to the direction of surface water flow, average surface flow velocities of only 2 cm sec⁻¹, and spatial patterns on a scale of hundreds of meters.

As a first step toward understanding the processes that mediate the linkage between hydrology and the ridge and slough landscape, we have used a four-tiered approach to investigate surface patterning in three large areas of the Everglades ecosystem that have experienced different water management regimes over the past half-century (Fig. 1). These four approaches were to: 1) map the current vegetation cover by physiognomic class, 2) quantify current landscape pattern metrics and abiotic environmental variables, 3) examine changes in landscape pattern from 1940 to the present using historic and current aerial photographs, and 4) develop a quantitative model that relates abiotic variables and landscape

metrics, with the overall objective of predicting how landscape patterns are likely to respond to different water management scenarios.

We hypothesized that landscape evolution parallel to water flow in the Central Everglades is of the result of facilitative processes that lead to the self-similar, downstream propagation of plant communities and that these processes are driven primarily by water flow velocity and direction. One implication of these hypotheses is that sustained alterations of the direction of water flow relative to the historic orientation would disrupt the historic tree island-ridge-slough pattern.

Potential mechanisms that explain the distribution of vegetation communities along environmental gradients in the central Everglades, based on detailed analyses of the relationship between vegetation composition and abiotic variables, are presented in a companion paper (Givnish *et al.*, submitted).

METHODS AND STUDY SITES

Study sites

The study area consisted of three distinct areas of the managed Everglades ecosystem: the central and southern portions of Water Conservation Area (WCA)-3A, and WCA-3B. Together, they occupy roughly 400 km². Central WCA-3A is bounded by Interstate 75 to the north and the Miami Canal to the east. Sheetflow enters this area from the Big Cypress region to the west and through water control structures that connect it with compartments to the north and east (Fig. 1). Comparisons of the output from models of water flow in the pre-drainage system with recent hydrologic data indicate that surface water flows in central WCA-3A, although diminished, are similar to historic conditions (SCT, 2003). As surface water moves into southern WCA-3A, which is bounded to the south by the Tamiami Trail (State Highway 41), there is a tendency for water to pool north of the roadway levee that restricts the flow of surface water entering the southern portion of the Everglades. Water

Conservation Area 3B is bounded on the west by levees and by the L-67 canal, which separate it hydrologically from central and southern WCA-3A to the west and northwest. This completely compartmentalized area receives very little surface water flow and has become primarily a rain-fed system (SCT, 2003) (Fig. 1).

Physiognomic Landscape Classification

To map the landscape by physiognomic class we used false-colored infrared (CIR) aerial photography, with a resolution of 1 ft per pixel, flown in March 2002 for southern WCA-3A and WCA-3B and in April 2003 for central WCA-3A. The digital CIR images were registered to State Plane NAD 83 Florida East coordinates by image-to-image georectification using 1995 CIR Digital Ortho Quarter Quads (DOQQs) obtained from the United States Geological Survey (USGS). Image classification as slough, ridge or tree island within each of the three study areas was carried out by a two-step process. In an initial unsupervised step, imagery was resampled at a resolution of $15 \text{ m}^2 \text{ pixel}^{-1}$ and classified into 12 categories by ISODATA clustering using ArcGIS (Version 9.1, 2005). These classes were then regrouped by visual interpretation in a supervised step into slough, ridge or tree island classes. Ground-truth data from 562 quadrats stratified by physiognomic class and located on 38 separate transects oriented either parallel or perpendicular to water flow ($> 39 \text{ km}$ in total length) were used to assess the accuracy of the classified image. Error matrices, associated κ values (Rosenfield & Fitzpatrick-Lins, 1986), and mean patch fractal dimension (MPFD) (Frohn, 1998) were generated for the overall classification and for each study area.

Landscape metrics and abiotic variables

In order to capture the variation in the vertical relief and abiotic environment that occurs on the same spatial scale as the alternating ridges and sloughs, we collected field data along multiple transects within each study area, averaging 1.5 km in length. High-resolution aerial

photographs were analyzed within 2.5 km x 2.5 km image subsets encompassing individual transects to detect the characteristic landscape wavelength (the regular spacing of ridges and sloughs perpendicular to the direction of water flow) at the appropriate scale.

Within each of the three study areas, five to six transects were oriented perpendicular to flow, comprising a total of 75 sloughs and 88 ridges (Fig. 1). Based on field measurements of species coverage, two slough community types and two ridge community types were identified: flooded slough, emergent slough, short sawgrass ridge and tall sawgrass ridge. Measurements of water depth, percent cover of herbaceous, shrub and canopy vegetation species and soil thickness were measured at each ecotone and at the midpoint of each ridge and slough along a transect. A detailed description of field methods and an extensive analysis of the vegetation data are presented in a companion paper (Givnish *et al.*, submitted).

To determine daily water depths and hydroperiods, water depth measured at transect points were benchmarked to water depths measured at digital monitoring wells that recorded water levels every twelve hours within each study area (Fig. 1). Water surface slopes across the three study areas were calculated using daily water elevation data from the Everglades Depth Estimation Network (EDEN) (Telis *et al.* 2006). The direction of the slope of the water surface for the period of peak flow during the study period was determined from the daily EDEN grid using ArcGIS Spatial Analyst. The daily EDEN data, which were provided by the USGS as a time series of surface grids composed of 400 m x 400 m cells, cover the entire Everglades watershed from January 1999 through May 2006. Water velocity, V , was estimated using the Manning relation, $V=(R^{2/3} S^{1/2}) n^{-1}$, where S is the water surface slope, R is the hydraulic radius (approximated by water depth for wide, shallow channels), and n was assigned a value of 0.05 for open sloughs, as calculated by Kadlec & Knight (1996). Maximum water velocity within the area of each transect was estimated using the water

depth in the deepest open slough at the time of maximum surface water slope during the 2002-2003 study period. The annualized number of days during the wet seasons for which estimated maximum water velocity exceeded the lower threshold of 7 cm sec⁻¹ calculated for Everglades sediments (Ross *et al.*, 2006) was also determined for each transect area.

The width and length of ridges and sloughs was determined by on-screen digitization using the 2002 or 2003 CIR imagery. Average width and length values were calculated from measurements of individual ridges and sloughs intersected by a single transect oriented perpendicular to the visible orientation of the landscape pattern within the area of each image subset. In addition, we used spectral analysis of RGB DOQQs with a resolution of 1 m per pixel, flown in January 2004, to detect the characteristic wavelength of the landscape within each image subset area. For this analysis, the Matlab fast Fourier transform (fft) procedure was first used to calculate the normalized autocorrelation function for each image subset (Fig. 2). The fft was then used to generate the power spectrum of the autocorrelation matrix. The inverse of the dominant frequency of the power spectrum corresponds to λ , the characteristic wavelength of the landscape (Fig. 2). The significance of the spectral signature derived from each image was evaluated by Bartlett's Kolmogorov-Smirnov white-noise test statistic as implemented in SAS (2006).

Changes in landscape pattern over time

The methodology described above for the 2002 and 2003 CIR imagery was also used to measure the historic width and length of ridges and sloughs and to determine the characteristic wavelength of the historic landscape, using 2.5 km x 2.5 km image subsets of USGS black and white aerial photographs taken in 1940, scanned at a resolution of 600 dpi, and registered to UTM Zone 17 coordinates by image-to-image georectification. The historic orientation of ridges and slough within the area of each transect was estimated visually from the georectified 1940 aerials. The divergence between the historic orientation of the

landscape and the current direction of the water surface slope (described above) was determined for each transect area.

Model of environmental variables as related to landscape pattern

Correlations of pattern metrics (vertical relief, landscape wavelength, width and length of ridges and sloughs) and hydrologic and environmental variables (maximum water depth, water surface slope, flow direction, annual period of inundation, soil thickness) corrected for spatial correlation were calculated using SAM v1.1 software (Rangel *et al.*, 2006). The SAM v1.1 spatial autocorrelation procedure was used to verify the spatial independence of transect pattern metrics and the environmental variables measured for the image subsets areas within each study area. ANOVA comparisons between areas were done using the SPSS (Version 14.0, 2006) ANOVA procedure. The SPSS paired t-test procedure was used to analyze changes in landscape wavelengths between 1940 and 2004. Multiple regression models to predict landscape metrics from environmental variables were developed using SPSS backward linear regression procedures. Model coefficients were generated with data from central WCA-3A and WCA-3B and the model was validated using spatially independent data from southern WCA-3A.

RESULTS

Physiognomic Landscape classification

Our high-resolution false-color infrared photography from 2002 and 2003 was used for an initial classification of the study area physiognomy. Table 1 shows the classification error matrices and associated κ values for the combined and individual study areas. Within central WCA-3A, where current water level and surface flow are most similar to historic conditions, the percent of the landscape covered by sloughs, ridges and tree islands was 38, 48, and 14, respectively (Table 2). In the southern portion of WCA-3A, where water tends to

pool north of the roadway that forms the southern boundary of this area, the proportion of sloughs was higher, representing 50% of the landscape, while tree island cover was lower at 3%, and ridge cover was essentially the same as in central WCA-3A. The average size of contiguous areas of all community types was greater in southern WCA-3A than in central WCA-3A, with sloughs more than three times larger, again reflecting the ponding that occurs north of the roadway. In WCA-3B, an impounded and essentially rain-fed system with little surface water flow, the landscape was dramatically different from either area in WCA-3A. Ridge communities dominate the landscape (94%), while sloughs comprised only 3.5% and tree islands only 2.5%. The agglomeration of the landscape in WCA-3B was also reflected in the lower mean patch fractal dimension compared to the two areas in WCA-3A (Table 2).

Landscape metrics and abiotic variables

During the 2002-2003 study period, which spanned two wet seasons and two dry seasons, water surface elevations within the study area followed the seasonal pattern of wet and dry periods characteristic of the Everglades ecosystem (Fig. 3). Most of the difference in water elevations among areas was a reflection of the underlying topographic gradient, but, as summarized in Table 3, water depths in both sloughs and ridges were significantly higher in southern WCA-3A than in central WCA-3A, while water depths in WCA-3B were significantly shallower for both communities than in either area of WCA-3A. Maximum water surface slope, a unitless measure of the unit change in vertical height per unit of horizontal distance, was not significantly different between the two areas of WCA-3A. Although maximum surface water slopes were significantly higher in WCA-3B than in WCA-3A, these maximum slopes were not sustained over long periods and appeared to reflect localized rain events or intermittent water management activities. The number of days per year for which estimated maximum surface-flow velocities exceeded the lower threshold for re-suspension of typical Everglades sediments estimated at 7 cm s^{-1} by Ross *et al.* (2006)

was significantly lower in WCA-3B (10.7 ± 1.2) than in southern WCA-3A (20.8 ± 4.8) or central WCA-3A (47.8 ± 1.6).

When compared among the study areas, both average slough and average ridge soil thickness were significantly greater in WCA-3B than in central or southern WCA-3A (Table 3). Examination of the variation in soil thickness and bedrock elevation across the study areas from north to south and east to west shows that the central axis of north to south flow through the Everglades, where bedrock elevations are lowest, was overlain by the deepest soils (Fig. 4). Elevational differences in the underlying bedrock were not generally reflected in differences in soil elevation between ridges and adjacent sloughs (data not shown), but the average depth of slough soils was consistently shallower than ridge soils in all three areas (Table 3).

As expected, landscape wavelengths, determined from fft analyses, tended to be greater than the sum of the average width of a ridge and slough unit as measured by manual digitization from aerial photographs, since manual measurements included small, irregular patches of ridge and slough that could not have been excluded without introducing a significant bias (Table 3). ANOVA comparison among study areas showed that the average width of ridges in WCA-3B was significantly higher ($p < 0.05$) than in central or southern WCA-3A. This was accompanied by an overall reduction in the size of sloughs, with the result that landscape wavelengths were generally not significantly different among areas, except between central WCA-3A and WCA-3B in 2004. As tested by the Bartlett's Kolmogorov-Smirnov statistic, the spectral pattern of each of the images was significantly ($p < 0.001$) different from random white-noise.

The average length of ridges and sloughs parallel to the direction of water flow was too big to be detected by fft analysis at an appropriate spatial scale. On the other hand, manual measurements of lengths showed that average length of ridges were not significantly

different between central and southern WCA-3A (Table 3). Because of the general absence of a visible pattern in WCA-3B, the length of ridges and sloughs could not be determined manually in this area.

Changes in landscape patterns over time

Comparisons of landscape patterns showed that there was no significant change in the average landscape wavelength within each study area between 1940 and 2004 (Table 3). In 1940 the landscape wavelength was essentially the same among study regions, but as a result of the overall shifts that occurred between 1940 and 2007, the landscape wavelength in central WCA-3A was significantly greater than in WCA-3B by 2004, and a similar, though not significant trend, was seen in the difference between southern WCA-3A and WCA-3B. The highly conserved pattern of the ridge and slough landscape between 1940 and 2004 was evident in the paired images shown in Fig. 5(a) for a typical transect in central WCA-3A. By contrast, Fig. 5(b) illustrates an area in northern WCA-3B, near the L-67 canal and outside the range encompassed by the study transects, where striking changes in the landscape occurred between 1940 and 2004. The orientation of the water surface slope during recent periods of peak flow velocity did not deviate appreciably from the presumed historic direction of water surface flow in central or southern WCA-3A ($7.3^{\circ} \pm 2.1^{\circ}$ and $18.2^{\circ} \pm 6.2^{\circ}$, respectively) but the divergence from historic orientation was striking in WCA-3B ($70.8^{\circ} \pm 18.1^{\circ}$) (Table 3).

Model of environmental variables as related to landscape pattern

As shown in the correlation matrix (Table 4), several environmental variables were strongly correlated with two or more landscape pattern metrics that varied among study areas, e.g. vertical relief, width of ridges and sloughs, and landscape wavelength. Of the eleven environmental variables measured, three were strongly correlated with three or more

landscape metrics. For example, soil thickness was significantly negatively correlated with the width of sloughs ($r = -0.71$, $p < 0.01$) and with landscape wavelength ($r = 0.56$, $p < 0.05$), and positively correlated with ridge width ($r = 0.59$, $p < 0.05$). The divergence in the direction of the peak water flows from the historic orientation of the landscape pattern was significantly negatively correlated with vertical relief ($r = -0.61$, $p < 0.05$), slough width ($r = -0.65$, $p < 0.01$), and landscape wavelength ($r = -0.52$, $p < 0.01$). Maximum water surface slope during peak flow was significantly positively correlated ($p < 0.05$) with ridge width, and was negatively correlated with the remaining three landscape metrics.

Environmental variable data from transects in central WCA-3A and WCA-3B were used in backward regression models of vertical relief, slough width, and landscape wavelength. The backward elimination procedure retained soil thickness, maximum water surface slope, and divergence between the direction of peak water flows and the historic orientation of the landscape pattern as independent variables in all of the calibrated regression models (data not shown). The models of slough width and landscape wavelength included maximum slough water depth and the model of vertical relief included maximum ridge water depth. Spatially independent transect data and measurements of landscape metrics in southern WCA-3A were used to validate the regression models, using the variable coefficients specified by the calibrated model. Estimates of vertical relief showed the best fit with the validation data ($r = 0.96$, $p < 0.01$) (Fig. 6), while estimates of slough width were less well correlated with actual values ($r = 0.77$), but still significant ($p < 0.01$) (Fig. 6). Estimates of landscape wavelength were not significantly correlated with actual validation values ($r = 0.54$, $p = 0.23$). The divergence between the direction of peak water flows and the historic orientation of the landscape pattern had the greatest explanatory power, yielding significant r^2 values of 0.42 and 0.56 when used alone to predict the values of vertical relief and slough width, respectively, for the validation data.

DISCUSSION

In the present study we used extensive field data and remote sensing to relate vegetation patterning in the Central Everglades to environmental and hydrological variables such as soil thickness and the rate, duration, and direction of regional water flow. Further, we demonstrated that quantitative models based on environmental and hydrological conditions can be used to predict landscape patterns. Our findings are consistent with several hypotheses proposed to explain the genesis and maintenance of the ridge and slough pattern (e.g. Givnish & Volin, 2003, Ross *et al.*, 2006). From these findings, together with recently published results from other researchers, a picture of the environmental and hydrological conditions that are required to ensure the persistence of the Everglades ridge and slough landscape begins to emerge.

A role for the differential decomposition and accretion of organic substrates, controlled by feedback mechanisms involving the interaction of vegetation, hydrology, and topography, was first proposed by Givnish & Volin (2003). Other potential feedback mechanisms and environmental drivers that could play an important role in maintaining the microtopography of the Everglades landscape are discussed in a companion paper (Givnish *et al.*, submitted). In the current study we have quantified several aspects of the ridge and slough landscape pattern in areas that have experienced different hydrologic conditions in past decades and we have identified the landscape metrics that have a predictable relationship with measurable abiotic variables.

We have found that quantitatively significant differences in several measures of regional hydrology are associated with significant differences in ridge and slough landscape metrics, even in hydrologically connected areas such as central and southern WCA-3A. In central WCA-3A, current hydrology most resembles the conditions that are believed to have prevailed historically (SCT 2003). In our study of this area, water depths in sloughs averaged

slightly less than one meter; sloughs were inundated year-round; maximum water surface slope averaged $2.3 \pm 0.27 \text{ cm km}^{-1}$; and flow velocities in excess of the lower critical velocity for re-suspension of Everglades sediments, estimated to be 7 cm sec^{-1} by Ross *et al.* (2006), occurred for 48 days or more during the wet season. In southern WCA-3A, where water tends to pond north of the roadway levee, maximum water depths were higher than in central WCA-3A. Even though the average maximum water surface slopes were not significantly different ($2.8 \pm 0.23 \text{ cm km}^{-1}$), the duration of flows that exceeded critical velocity averaged only 21 days annually, less than half as much as central WCA-3A. These regional differences in hydrology are reflected in some, but not all, aspects of the landscape pattern. Ridges were generally longer and sloughs comprised a significantly smaller portion of the landscape in central WCA-3A than in southern WCA-3A, but there was no difference in the length of sloughs or the average elevation difference between adjacent ridges and sloughs. The higher water levels in southern WCA-3A were also associated with a much smaller representation of tree islands than in central WCA-3A, 3.4% compared to 13.5%, respectively.

The lowest water depths and shortest hydroperiods were found in WCA-3B, a completely compartmentalized area where the ridge and slough landscape is so degraded that there was no measurable orientation of the pattern. Estimates of maximum flow rates in this area were unexpectedly higher than in either area of WCA-3A, possibly as a result of localized rainfall events or sporadic water management activities. However, the annual duration of flows that exceed critical velocity was less than 11 days, and average surface water depths were significantly less than in either central or southern WCA-3A. In WCA-3B, every aspect of the current landscape pattern assessed in this study differed significantly from central and southern WCA-3A. Here ridges dominate the landscape (94%), with sloughs comprising less than 4% , and the average vertical relief between ridges and sloughs

was significantly smaller than in WCA-3A (0.098 m compared to 0.15 m). In addition, sloughs were highly fragmented, with an average width of only 31m, and there was no detectable landscape wavelength.

It is important to note that the landscape metrics that vary significantly among study areas (vertical relief, width of ridges and slough, wavelength) may reflect related, sequential aspects of landscape evolution. The first detectable change in landscape patterns produced by changes in regional hydrology would be a flattening or accentuation of the vertical relief; changes in vertical relief could ultimately lead to a change in landscape wavelength, but this would not be apparent until after spatial shifts in plant community composition have occurred along the new topographic gradient. This sequence of events is consistent with our finding that the landscape pattern was highly conserved over decadal time periods, with little detectable change in the width, length or location of ridges and sloughs. Over longer time spans, as loss of vertical relief continues, the landscape becomes an increasingly homogeneous sawgrass marsh or expanse of open water, and the ridge and slough pattern is eventually lost. Positive feedback processes, such as the decrease in decomposition associated with sawgrass invasion of sloughs, would also be associated with loss of vertical relief as soil thickness increases in sloughs. Such a mechanism could have contributed to the loss of patterning in WCA-3B, where soil thickness is significantly higher than in either central or southern WCA-3A and sloughs have been invaded by sawgrass.

In view of the strong correlation between vertical relief and the divergence in the current direction of water flow from the historic orientation of the surface patterns, it appears likely that both the rate and direction of water flow are important factors in maintaining the ridge and slough landscape. This view is further supported by comparison of aerial photographs from 1940 and 2004 that show the most striking changes in landscape patterns

have occurred in close proximity to canals and water control structures, where changes in flow velocities and direction are more extreme than in the surrounding marsh.

The potential importance of flow velocity and direction in determining landscape patterns is supported by the process model first developed by Lefever & Lejeune (1997) for the evolution of striped landscape patterns. This model shows that, when the predominant effects of water flow are mediated by competitive transport processes, such as reduced nutrient levels downstream as a result of upstream absorption, or reduced downstream sedimentation as a result of upstream sediment deposition, landscape evolution progresses to a striped configuration oriented perpendicular to the direction of flow. Such patterns are found in boreal peatlands (Glaser *et al.*, 1987) and the striped tiger bush of semi-arid regions (Barbier, 2006), where competitive transport processes have been shown to operate. By contrast, when the predominant effects of water flow are mediated by facilitative transport processes, such as the downstream transport of nutrients or seeds from upstream plant communities, the landscape evolves toward a striped configuration oriented parallel to the direction of flow. Evidence for our hypothesis that the self-similar, downstream propagation of plant communities through such facilitative processes may be shaping the formation of Everglades ridges and sloughs has been reported by Saunders *et al.* (2006), who found that the presence of sawgrass seeds in soil cores was strongly correlated with the vegetation 0-20 m upstream. In addition, consistent with our prediction that self-propagation perpendicular to flow would be constrained, they found that the boundary between the sawgrass ridges and adjacent sloughs was marked by a distinct boundary in the presence or absence of sawgrass seeds in soil cores. Data from soil cores within our study area also show little evidence of seed redistribution between ridges and sloughs (Glaser, unpublished data). Another significant distinction between competitive versus facilitative processes in the model simulations described by Lefever & Lejeune (1997) is the fact that, when competitive

processes dominate and stripes therefore develop perpendicular to flow, the stripes tend to migrate upstream with time. This phenomenon has been observed for striped tiger bush in some areas (Worrall, 1959; Montana, 1992). However, stripes oriented parallel to flow remain stable in model simulations, consistent with the surprisingly stationary pattern of ridges and sloughs that we have found.

The results we have presented here fit into a coherent view of Everglades landscape evolution that is driven by the interplay of decomposition versus accretion and facilitation versus competition. The higher decomposition rates that have been found for slough vegetation compared to the sawgrass on ridges (Volin *et al.*, unpublished data) points to differential decomposition and accretion, which are dependent on water levels, as an important mechanism for generating and maintaining differences in soil surface elevations. The importance of water velocity and the divergence of water flow from historic orientation in predicting landscape patterns, particularly vertical relief, argue for the importance of both the velocity and direction of water flow and the associated transport processes. Thus, water management strategies that set water level and hydroperiod targets without determining appropriate targets for the direction, duration and velocity of water flow, and vice versa, may create conditions that will ultimately alter landscape patterns and ecological functions.

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BIOSKETCHES

John Volin is Professor of Biological Sciences at Florida Atlantic University. He has led many studies on the ecology of the Everglades and nearby Big Cypress Swamp, and investigated the factors that permit *Lygodium microphyllum* and *L. japonicum* to become highly invasive weeds in these wetlands of global significance.

Thomas Givnish is Henry Allan Gleason Professor of Botany at the University of Wisconsin-Madison. His research involves various aspects of plant ecology, evolution, and biogeography, especially the interface between physiological and community ecology and the reconstruction of adaptive radiations.

Table 1. Error matrices and associated κ values for landscape classification by physiognomic class (slough, ridge, tree island) for three study areas in the central Florida Everglades

All Study Areas		Predicted Class		
		<i>Slough</i>	<i>Ridge</i>	<i>Tree Island</i>
Transect	<i>Slough</i>	138	16	0
Plot	<i>Ridge</i>	1	207	1
Class	<i>Tree Island</i>	10	41	135
$\kappa = 0.81$				

Central WCA-3A		Predicted Class		
		<i>Slough</i>	<i>Ridge</i>	<i>Tree Island</i>
Transect	<i>Slough</i>	41	0	0
Plot	<i>Ridge</i>	0	48	1
Class	<i>Tree Island</i>	5	1	32
$\kappa = 0.92$				

Southern WCA-3A		Predicted Class		
		<i>Slough</i>	<i>Ridge</i>	<i>Tree Island</i>
Transect	<i>Slough</i>	76	1	0
Plot	<i>Ridge</i>	0	67	0
Class	<i>Tree Island</i>	5	13	50
$\kappa = 0.87$				

WCA-3B		Predicted Class		
		<i>Slough</i>	<i>Ridge</i>	<i>Tree Island</i>
Transect	Slough	21	15	0
Plot	Ridge	1	92	0
Class	Tree Island	0	27	53
$\kappa = 0.66$				

Table 2. Results of landscape mapping (% cover, mean patch size, mean patch fractal dimension [MPFD]) of physiognomic classes (slough, ridge, tree island) for three study areas in the Florida Everglades, using high-resolution CIR aerial photography flown in 2002 and 2003.

	Landscape Cover (%)	Mean Patch Size (m ²)
Central WCA-3A		
Slough	38.3	2983
Ridge	48.2	3721
Tree Island	13.5	890
<i>MPFD=1.028</i>		
Southern WCA-3A		
Slough	49.8	9638
Ridge	46.8	6067
Tree Island	3.4	1469
<i>MPFD=1.040</i>		
WCA-3B		
Slough	3.6	784
Ridge	93.9	156319
Tree Island	2.5	1387
<i>MPFD=1.017</i>		

Table 3. Mean values $\pm$ standard error for environmental variables and landscape pattern metrics in three study areas in the Florida Everglades.

	Central WCA-3A		Southern WCA-3A		WCA-3B	
	Ridge	Slough	Ridge	Slough	Ridge	Slough
Soil Depth (cm)	75.5 $\pm$ 3.16 ^{bc}	55.9 $\pm$ 3.1 ^c	89.7 $\pm$ 6.0 ^b	73.1 $\pm$ 5.3 ^{bc}	137.9 $\pm$ 4.0 ^a	121.0 $\pm$ 6.2 ^a
Maximum water depth (m)	80.7 $\pm$ 1.6 ^d	91.9 $\pm$ 1.2 ^c	98.7 $\pm$ 1.9 ^b	114.4 $\pm$ 1.6 ^a	69.6 $\pm$ 0.9 ^e	80.7 $\pm$ 1.2 ^d
Annual hydroperiod (days)	358 $\pm$ 1.3 ^b	364 $\pm$ 0.2 ^a	364 $\pm$ 1.6 ^a	365 $\pm$ 1.3 ^a	352 $\pm$ 0.9 ^c	358 $\pm$ 1.1 ^b
¹ Width (m)	73 $\pm$ 5 ^b	102 $\pm$ 4 ^{ab}	67 $\pm$ 17 ^b	105 $\pm$ 22 ^{ab}	170 $\pm$ 36 ^a	31 $\pm$ 8 ^c
Average vertical relief (cm)	15.0 $\pm$ 0.7 ^a		15.3 $\pm$ 2.7 ^a		9.8 $\pm$ 2 ^b	
Annual days of water velocity > 7cm sec ⁻¹	47.8 $\pm$ 1.6 ^a		20.8 $\pm$ 4.8 ^b		10.7 $\pm$ 1.2 ^c	
Maximum water slope (%)	0.0023 $\pm$ 0.00027 ^b		0.0028 $\pm$ 0.00023 ^b		0.0058 $\pm$ 0.00064 ^a	
Change in flow direction (degrees)	7.3 $\pm$ 2.1 ^b		18.2 $\pm$ 6.2 ^b		70.8 $\pm$ 18.1 ^a	
	1940	2004	1940	2004	1940	2004
² Landscape wavelength (m)	276 $\pm$ 34 ^{ab}	341 $\pm$ 23 ^a	244 $\pm$ 27 ^{ab}	272 $\pm$ 19 ^{ab}	236 $\pm$ 64 ^{ab}	218 $\pm$ 23 ^b
¹ Length of ridges (m)	954 $\pm$ 12 ^a	916 $\pm$ 94 ^a	1050 $\pm$ 105 ^a	954 $\pm$ 94 ^a	NA	NA

Different letters denote significant differences in mean value by row ($p < 0.05$).

¹Width and length of ridges and sloughs were measured by on-screen digitization of CIR imagery flown in 2002 (Southern WCA3A and WCA3B) or 2003 (Central WCA3A).

²Landscape wavelength was determined by Fourier analysis of RGB DOQQs (2004) and black and white aerial photographs (1940).

Table 4. Pearson correlations of landscape metrics with environmental variables in the central Florida Everglades.

Landscape metrics:	Environmental variables:										
	Maximum Water Depth		Minimum Water Depth		Average Water Depth		Average Hydroperiod		Soil Thickness	Change in flow direction	Maximum water slope
	<u>Ridge</u>	<u>Slough</u>	<u>Ridge</u>	<u>Slough</u>	<u>Ridge</u>	<u>Slough</u>	<u>Ridge</u>	<u>Slough</u>			
Vertical Relief	-0.44	0.09	-0.54	-0.05	-0.52	-0.01	0.02	0.32	-0.46	-0.61*	-0.60*
Ridge Width	0.28	-0.60*	0.62*	-0.27	0.44	-0.49	-0.08	-0.30	0.59*	0.30	0.55*
Slough Width	0.13	0.33	-0.09	0.13	0.01	0.24	0.54*	0.71**	-0.71**	-0.65**	-0.57*
Landscape wavelength	0.09	0.15	-0.10	-0.10	-0.03	0.02	0.37	0.57*	-0.56*	-0.52*	-0.50*

* Significant at $p < 0.05$ (2-tailed). ** Significant at $p < 0.01$ level (2-tailed)

Figure Legends

Figure 1

Aerial view from 2004 DOQQ imagery showing the three different study regions, central Water Conservation Area (WCA) 3A, southern WCA-3A, and WCA-3B, the location of field transects (—), 2.5 x 2.5 km frames used for image analysis in the area of each transect (□) and water level monitoring wells (•).

Figure 2

Surface plot of spatial autocorrelation of 2.5 x 2.5 km image of the landscape in central WCA-3A, showing the characteristic wavelength λ , which corresponds to the spacing of adjacent ridges and sloughs perpendicular to the direction of water flow.

Figure 3

Average water surface elevations in central WCA-3A (—), southern WCA-3A (—) and WCA-3B (—).

Figure 4

Elevation of soil surface (•) and underlying bedrock (+) at transect points aligned east to west (left) and north to south (right) in central WCA-3A (top), southern WCA-3A (middle) and WCA-3B (bottom).

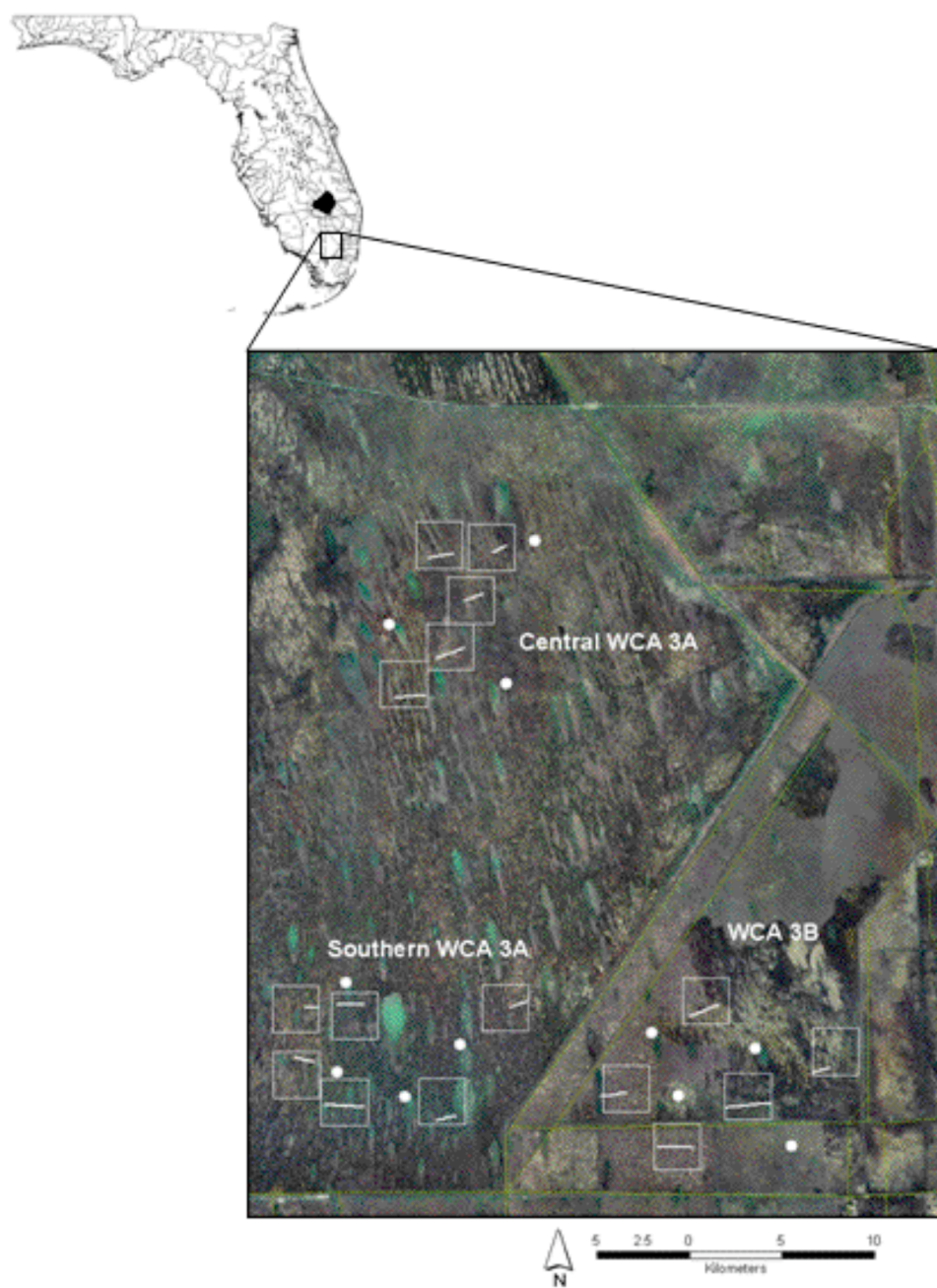
Figure 5

(a) Aerial photographs taken in 1940 (left) and 2004 (right) of the 2.5 x 2.5 km region encompassing a study transect in central WCA-3A. (b) Aerial photographs taken in 1940 (left) and 2004 (right) in northern WCA-3B.

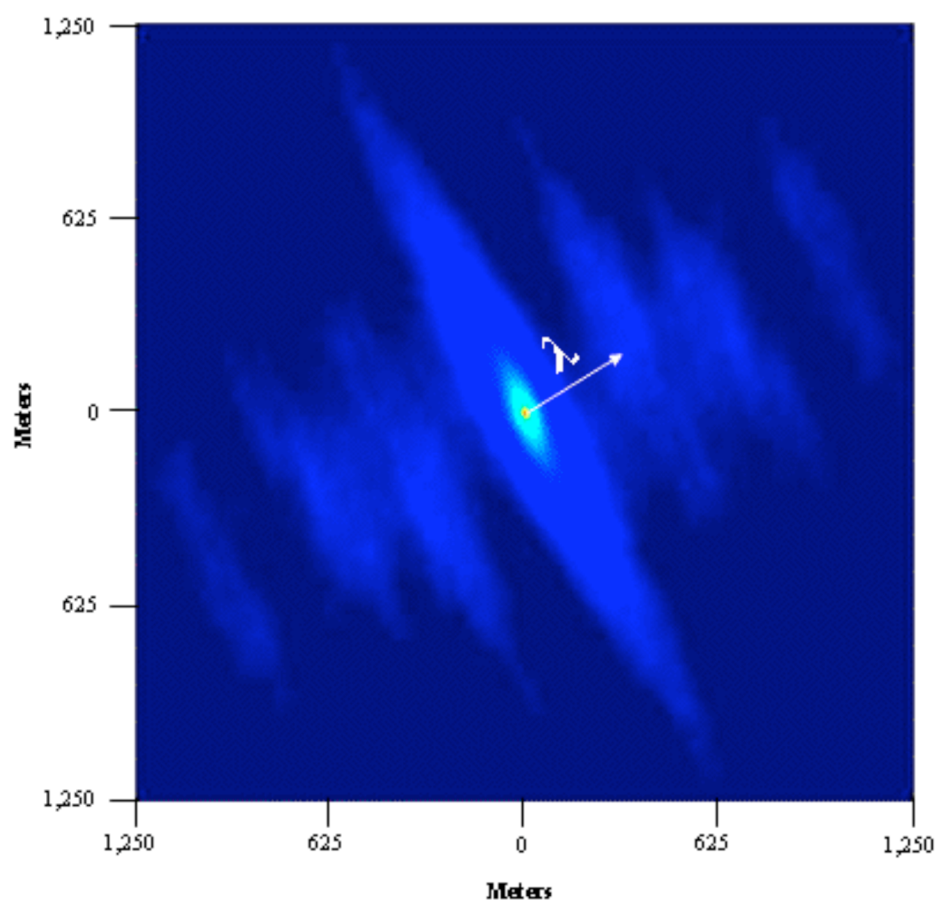
Figure 6

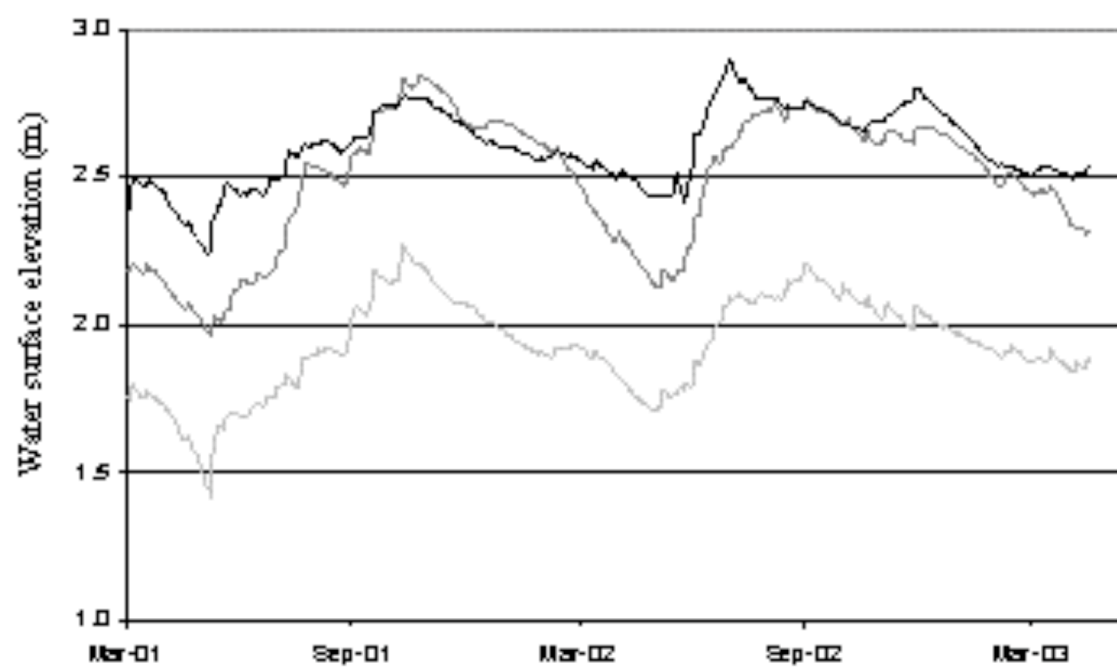
Comparison of predicted and actual vertical relief (a) and slough width (b) for study areas in southern WCA-3A. Predicted values were calculated using coefficients determined by regression models developed with data from central WCA-3A and WCA-3B. The independent variables used for prediction were soil depth, maximum water surface slope, difference in direction of current water slope from historic landscape orientation, and either maximum ridge water depth (to predict vertical relief) or maximum slough water depth (to predict slough width).

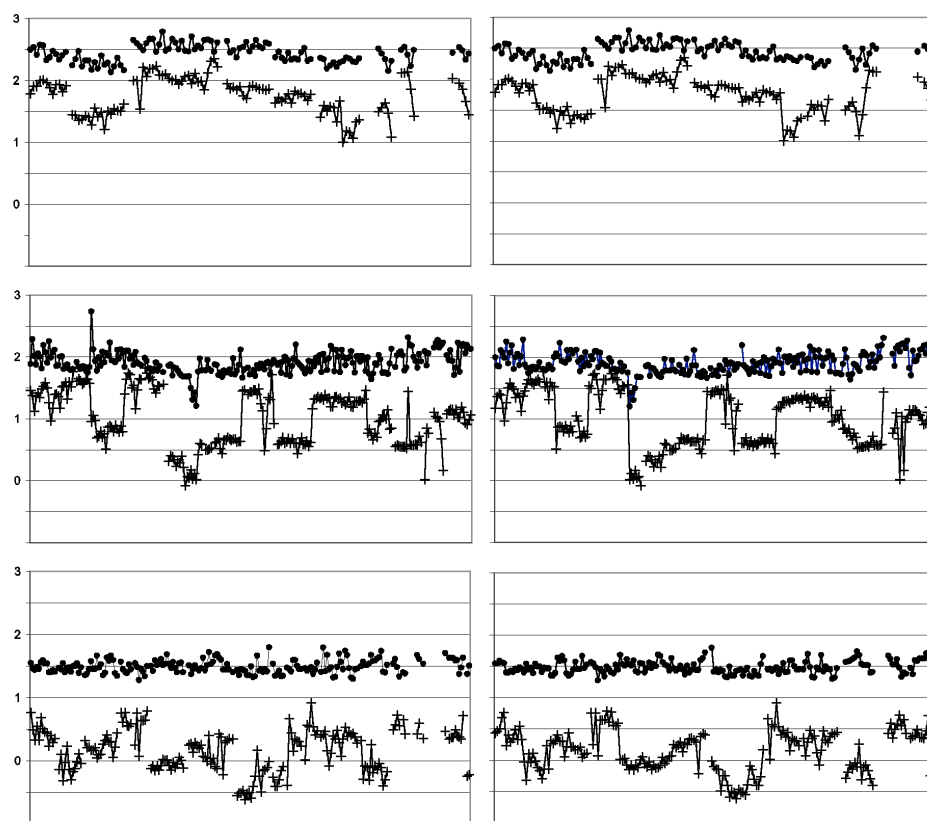
Volin et al.
Figure 1



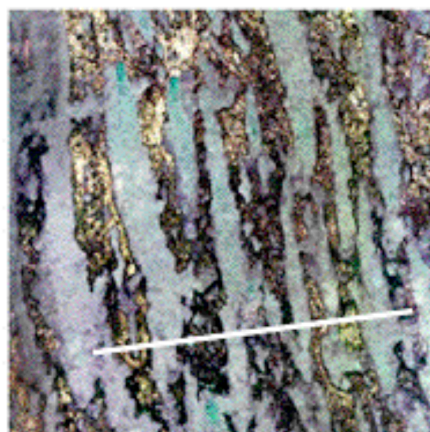
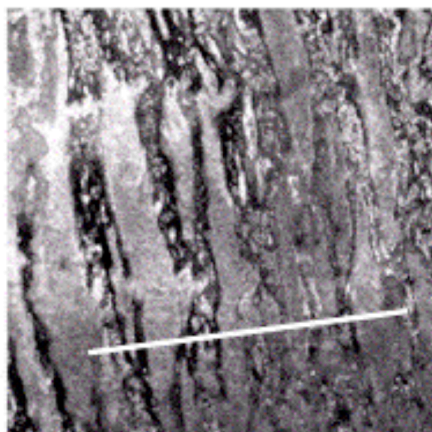
Volin et al.
Figure 2





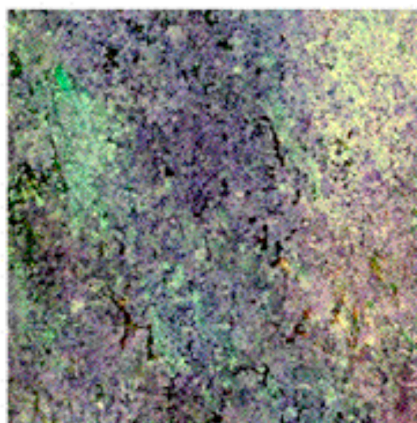
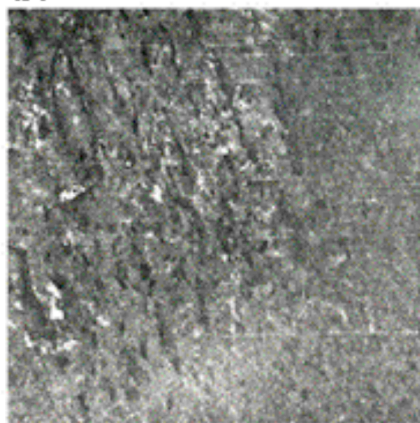


a.

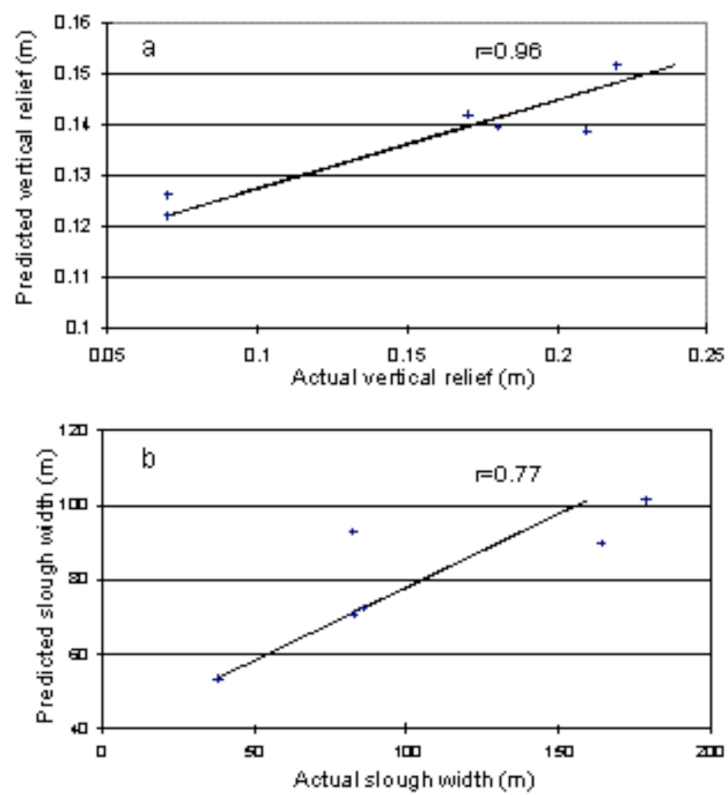


0 0.5 1 Kilometers
N

b.



0 0.5 1 Kilometers
N



Other work related to this project:

In this project:

- 1) we created a detailed GIS database of current vegetation within the four study areas through extensive field sampling and photointerpretation of high-resolution aerial photography, and image classification by a two-step procedure;
- 2) we sampled vegetation on 41 transects and 653 total plots, with measurements at each plot including soil depth to bedrock, water depth and vegetation coverage for each species in 1m² and 4m² plots for herbaceous and woody vegetation, respectively. Transects were oriented parallel and perpendicular to flow;
- 3) we also sampled vegetation in the same manner on twelve permanent transects (three per region) with 181 plots across the study site. Each of these twelve transects originated on a tree island and were established perpendicular to flow across the ridge-slough system. In total, 53 transects with 834 plots were used to sample vegetation and the associated abiotic variables;
- 4) we measured water flow in each of four vegetation types along the twelve permanent transects on 47 platforms that we constructed (four per transect except for one transect where we installed three platforms);
- 5) we measured water level by using twelve digital recording wells that we positioned across the study areas and we continue to maintain and monitor;
- 6) we constructed four meteorological stations, one per study region, that have also continuously been maintained and monitored;
- 7) we made morphometric measurements across the ridge and slough gradients within each region using our aerial photographs in combination with our transect data;
- 8) we developed a new soil corer and extruder that allows for soft near-surface sediment collection;
- 9) we collected 50 soil cores and measured their major characteristics and analyzed them creating RGB images, point magnetic susceptibility curves, Troels-Smith sediment descriptions, etc.;
- 10) we initially proposed to use relative plot elevations calibrated with the USGS 400 m² grid. Since we found that these elevations were not accurate enough for our study, we have obtained funding from a different source to gather an accurate measurement of elevations in the four regions. The results obtained are being used on this project as well;
- 11) we linked accurate elevation data to our abiotic data to determine regional hydrology, soil elevation, soil slopes and water surface slopes; and
- 12) we conducted two decomposition studies.

In this final report, as mentioned previously we have used the above information in a series of analyses that we have included in two manuscripts. Since this project consisted of three separate contracts at the initiation of the study, namely, Florida Atlantic University (FAU), University of Wisconsin-Madison (UW) and University of Minnesota (UM), please note that only the manuscript from FAU is included in this final report. The second manuscript is included in the UW final

report and a third manuscript is in preparation and will be presented in the final report for UM. Other results and discussions that have not yet been put into manuscript format follow.

Decomposition

We conducted two decomposition studies. The final collection for the second decomposition study will occur on March 29 and 30, 2006. Following we report on the first decomposition study.

The goal of the decomposition study was to determine whether there is a difference in decomposition rates in different Everglades marsh communities (slough vs ridge communities) and in different regions resulting from current and past differences in water management.

Decomposition was estimated by deploying litter bags in four different community types in the four management regions: central and southern Water Conservation Area 3A, 3B and northeast Shark River Slough (NE SRS). After completing the vegetation analysis on 51 transects within the four regions, encompassing the pattern of slough/ridge/tree island, the average normalized composition was determined for several community types. From the analysis, it was decided to estimate decomposition rates on two slough communities: submerged marsh and emergent marsh; and on two ridge communities: short sawgrass and tall sawgrass.

The litter bags were made using nylon covered fiberglass screening with uniform weave and approximately 1 x 1.5 mm holes. The inside dimensions of all the bags measured 20 x 20 cm. The bags for the sample and control study were deployed side by side after filling them with five marbles, to keep them below the water surface, and 10 g of dried vegetation according to the composition described below. On each of the three permanent transects per region, a total of 216 litter bags were deployed containing 10 g of the decomposition mix characteristic of each community, 48 to 60 bags for each of the communities (n= 3 for each region / community type combination, with the exception of submerged marsh in SRS, where n = 2.) In addition, 216 bags were filled with 10 g of *Chrysobalanus icaco* (cocoplum) leaves and deployed at the same locations. Cocoplum was used in the first decomposition study as a control species to allow removal of variability among community samples due to the difference in species composition in different communities. In the submerged marsh the bags contained *Nymphaea* spp. (39.4%), *Periphyton* spp. (30.8%) and *Utricularia* spp. (29.8%) in the proportion characteristic of the submerged marsh community, as found in the vegetation transect study we conducted. In the emergent marsh the bags contained *Periphyton* spp. (55.4%), *Eleocharis* spp. (31.3%), and *Utricularia* spp. (13.3%). In the short sawgrass community they contained *Cladium jamaicense* (81.8%), *Periphyton* spp. (11.4%) and *Eleocharis* spp. (6.8%), while in the tall sawgrass community they contained *Cladium jamaicense* (88.5%),

Periphyton spp. (5.2%), *Crinum americanum* (2.1%), *Eleocharis* spp. (2.1%) and *Utricularia* spp. (2.1%). The bags were collected at different intervals after deployment. Litter bags in the marsh, where litter was expected to break down faster, were collected at 12, 20, 30, 60 and 90 days. In the ridge communities they were collected at 30, 60, 90 and 180 days. The same experimental design was replicated in the control study using cocoplum litter. Finally, retrieved decomposition bags were dried at 70 °C and dried mass is currently being analyzed for nutrient content. Abiotic data, such as water temperature, were collected at the same locations as the decomposition samples, and further analyses is being conducted on these environmental factors.

Two-way analysis of variance was used to test for differences in decomposition loss within each community type, within each management region, and for the interaction between communities and regions.

A significant difference ($P=0.002$) in mass loss appeared at the first collection date, 10 days after deployment, between the two marsh communities: submerged and emergent marsh, where the loss was 4.6 g (46%) and 2.2 g (22%), respectively, of the initial 10 g (Figure 2). No significant differences were detected at this first collection date among regions. Differences among communities remained significant after allowing for effects of differences in regions over all the following collection dates (P always <0.001), with the exclusion of the last collection date of 180 days, when only the ridge communities were sampled (Figure 2).

The first date at which significant differences among regions were detected was 30 days from deployment ($P=0.012$), when decomposition in 3A (both central and southern) was faster than in SRS (Figure 2). At 60 days from deployment mass losses were still significantly different among both communities and regions. Mass loss in communities varied from a high of 69% in submerged marshes to a low of 17% in tall sawgrass ridges. However, the significant regional difference ($P=0.028$) was detected solely between southern 3A and 3B (39% and 34%, respectively).

At 90 days, the difference between mass loss in marshes and ridges became more evident: 76% in submerged marsh compared to 19% in tall sawgrass. The only significant difference among regions ($P=0.005$) was between southern 3A (44%) and SRS (38%). Finally, at 180 days there were no significant differences between ridge communities among regions, where the average percent loss was 27% and 22% in short and tall sawgrass, respectively.

In the control study, significant differences among community types were detected starting from day 30, when mass loss in short sawgrass communities (25%) was significantly different ($P=0.015$) from tall sawgrass communities (19%). At day 60, the only significant difference in mass loss was detected between emergent marsh and tall sawgrass ($P=0.017$). Finally, at 180 short

(28%) and tall (25%) sawgrass were significantly different from each other again ($P=0.024$). In the control study, no significant differences were detected among regions.

A three-way ANOVA for the day 90 experiment on regions, communities and the comparison between sample and control resulted in significant differences in all three factors, with the controls always having significantly lower decomposition rates (Figure 3).

Decomposition Summary

The decomposition rate was significantly different among communities starting from day 10 and throughout the duration of the study. To test if such differences were due to the different species composition used in different communities, we deployed decomposition bags containing the same control species in all four communities. These bags yielded a decomposition rate which was significantly different in some community types at some dates, but our results did not prove a substantial and convincing difference in cocoplum decomposition rates in the four communities. Therefore, the detected difference among communities is not solely the result of species composition in these communities but other factors differing among communities contribute to the different decomposition rate.

After completing the first decomposition study during the wet season and analyzing its results, it became evident that a second study that lasted through both a wet and a dry season and that captured more of the early vegetation loss within the first few days of the study would substantially add to our understanding of the decomposition within these four common community types. Therefore, a year-round study was initiated in February 2005 with a similar experimental design. The last decomposition bags will be collected at the end of March 2006. The second decomposition study differs from the first study not only in that it lasted a full year, therefore covering both a wet and a dry season. It was also started earlier in the marsh communities, where biomass was found to begin breaking down immediately after deployment. Therefore, a first collection was done only 2 days after deploying the bags in the water. In addition, the control study was modified to include not only cocoplum leaves but also *Salix caroliniana*. Cocoplum, with its low specific leaf area, has thick leaves which are characterized by a slow decomposition rate. *Salix caroliniana* has high specific leaf area, its thin leaves are more likely to have a higher decomposition rate. By using this combination of species in our control samples, we expect to detect responses to the effect of environmental factors on decomposition which may be otherwise confounded by the different species composition used in different communities.

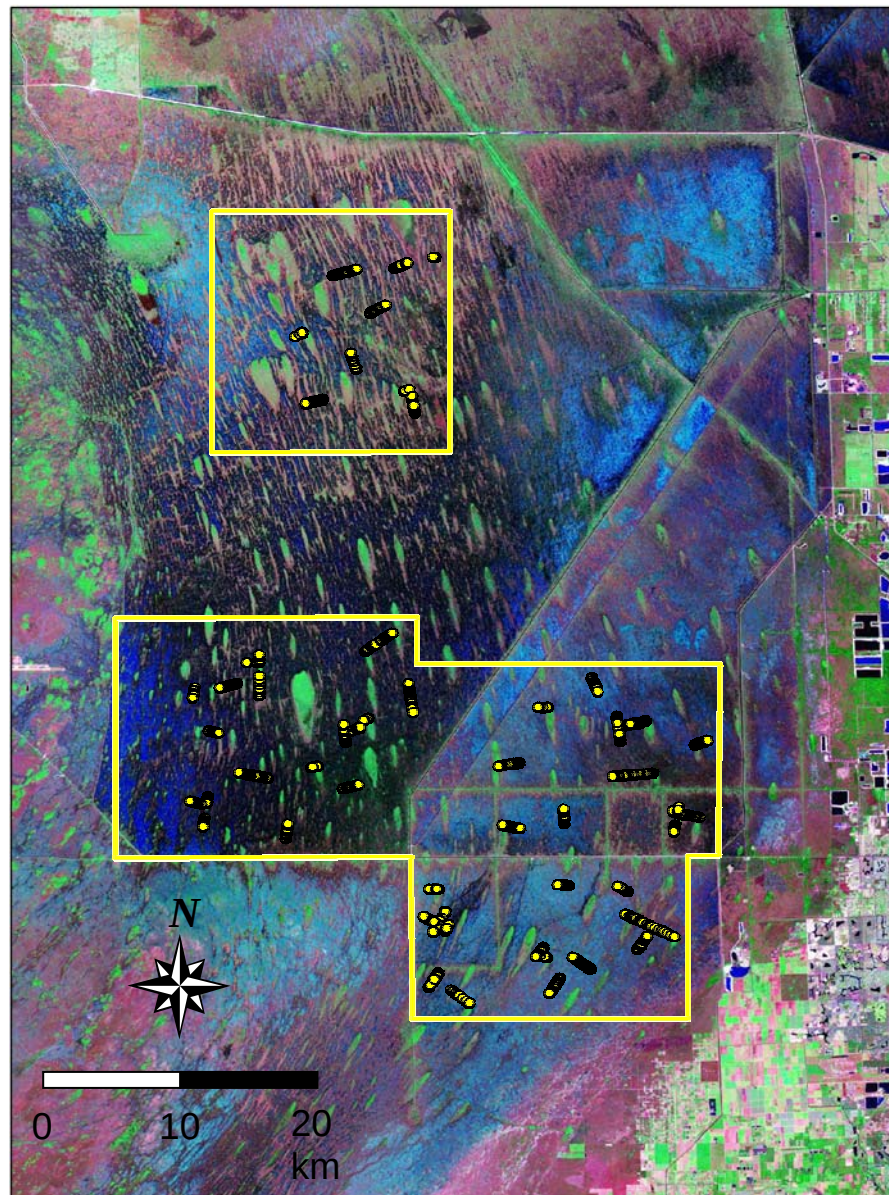


Figure 1. Project Study Area

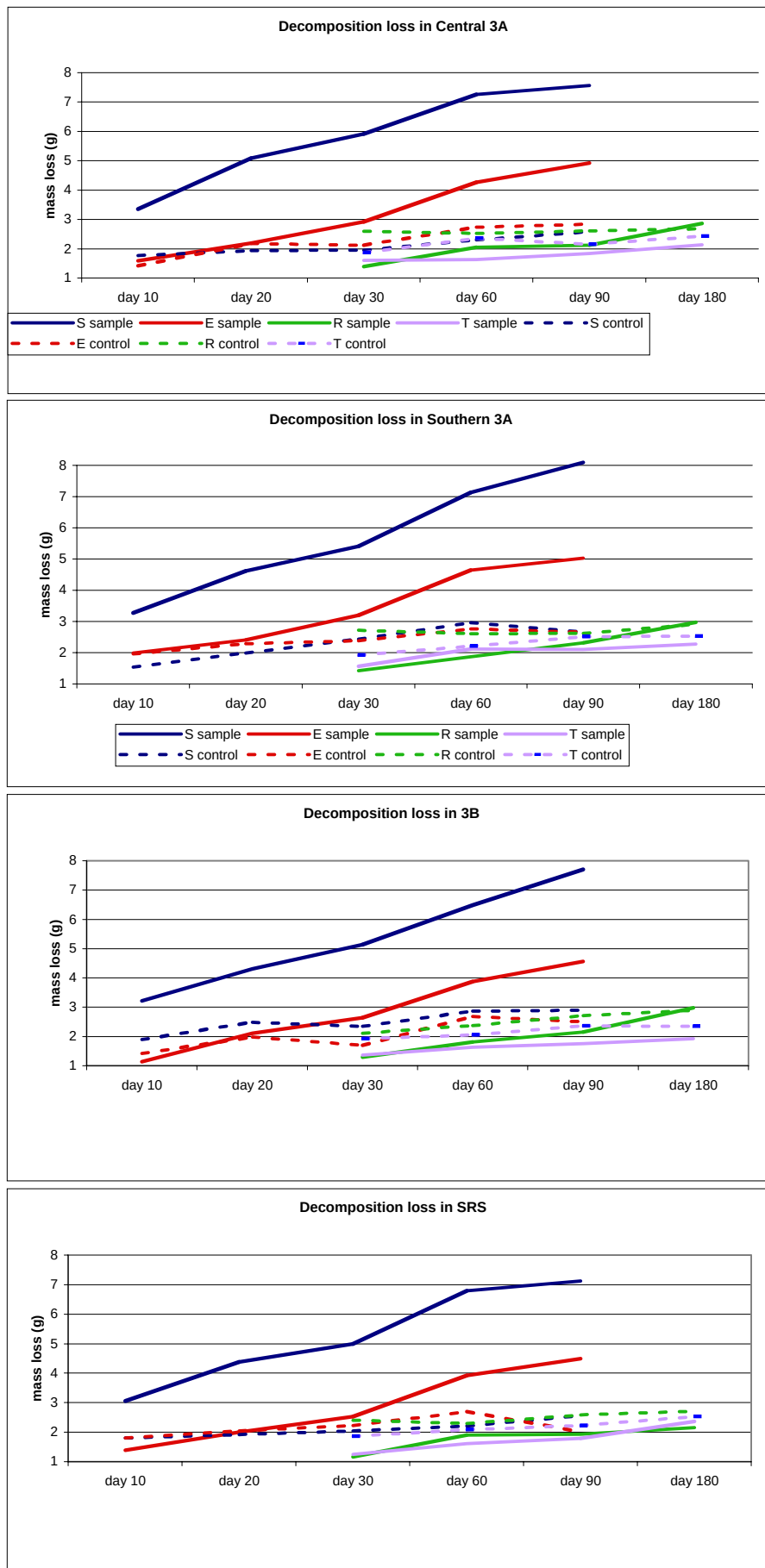


Figure 2. Decomposition Loss

Decomposition loss by community and region at 90 days

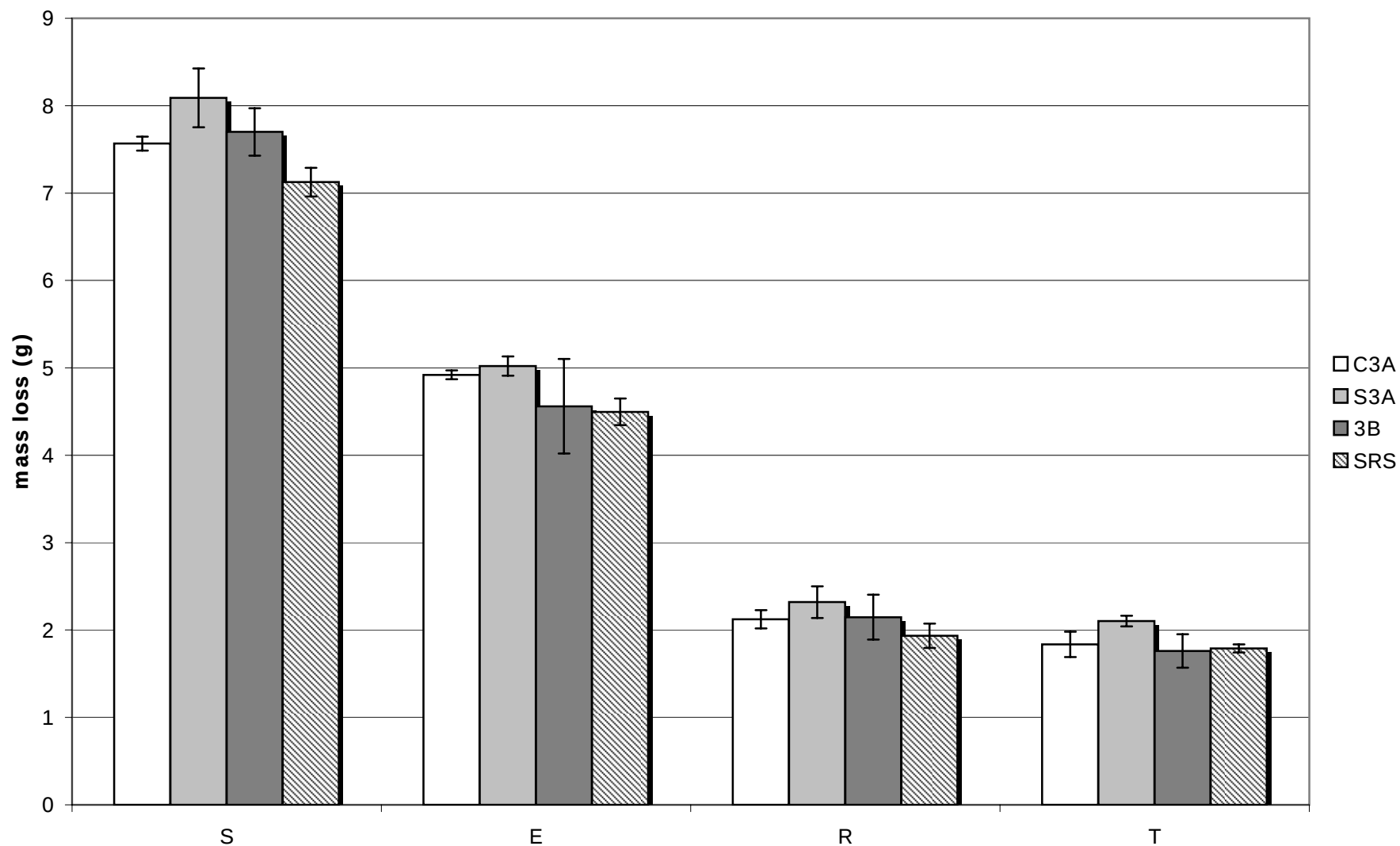


Figure 3. Comparisons of Decomposition Losses

Soil Project Summary

During the past year we have tried to solve the last remaining problems that have delayed the completion of our Everglades soils project. Our original plan to analyze soil cores from study areas in WCA-3A, WCA-3B, and Northeast Shark River Slough was based on the premise that these soils were composed of peat, which typically has an organic matter content that exceeds 80% of the dry mass. The sediments in our 4 study areas, however, differ from those of boreal peat deposits in several critical aspects. First, the upper part of the sediment profile consists of very soft flocculent sediment that is impossible to core and section with standard peat corers. Second, the sediment profiles are usually less than 1.5 m deep raising potential problems related to bioturbation, mechanical mixing of sediments, and contamination of radiocarbon samples by rootlets. Third, the sediments contain a significant fraction of carbonate minerals indicating that bulk samples for radiocarbon dating may be contaminated by the "reservoir effect" in which aquatic macrophytes and algae assimilate bicarbonate dissolved from calcite. Fourth, the large fraction of carbonate in these sediments requires a revision of our original modeling design for linking vegetation patterning to differential rates of organic sediment accumulation.

In order to complete this project we first designed, built, and successfully tested a new sampling device for coring and sectioning the very soft sediments located just below the sediment/water interface in the Everglades. We were usually able to collect a single core that spanned the entire sedimentary profile from the upper water/sediment interface to the basal contact with limestone bedrock. The soft near-surface sediments were then sectioned in 1 cm intervals with our new extruder device and stored in separate sample containers, whereas the firmer sediment below was then extruded and stored in longitudinally split sections of PVC pipe.

We were very concerned that the primary stratigraphy in these cores would be compromised by either mechanical mixing produced by extreme weather events (e.g. hurricanes) or bioturbation resulting from animals (including human activities). However, the detailed core analyses showed that the primary stratigraphy remained intact and that whatever mixing occurred was restricted to the very uppermost centimeters of the sedimentary profile. Core 4-23-04-4, for example from the NE Shark River Slough showed a clear cultural horizon marked by the sharp rise of anthropogenic pollen markers, such as *Ambrosia*, *Myrica/Casurina*, and *Eugenia/Melaleuca* at a depth of 13 cm. The fact that this cultural horizon occurs within the softer sediments at the very top of the sedimentary profile indicates that mechanical mixing or bioturbation has minimal effect on disturbing the sediment stratigraphy. The detailed pollen diagram from this site has 4 distinct pollen zones marked by changes in both the regional and local pollen types. These major pollen zones correspond to the important lithologic units in this core rather than sorting by grain size, which would be the likely product of mechanical mixing.. It was therefore concluded that the cores

contained reliable indicators for paleoenvironmental change in the Everglades region.

The initial core descriptions were delayed while the Limnological Research Center Core Lab at the University of Minnesota purchased and installed a new Geotek multi-sensor core logger. This automated instrument has sensors that measure a) core diameter, b) P-wave velocity (porosity), and c) gamma ray attenuation (bulk density) on whole cores and point magnetic susceptibility (to detect subtle mineral and charcoal layers) on longitudinally split core sections. The split core sections were then imaged with a RGB line-scanner at 300 dpi to provide a visible record of the stratigraphy. These images were then printed on initial core description sheets along with the point magnetic susceptibility data to provide a guide for the initial core descriptions using both a petrographic and dissecting microscopes.

A major finding of these initial core descriptions was that the Everglades sediments contain a significant fraction of inorganic minerals particularly carbonates and quartz with minor fractions of clay. The most conspicuous evidence for the presence of minerals are distinct marl layers that have a carbonate content that often exceeds 75% of the sediment's dry mass. These marl layers varied in depth, thickness, and composition across both local and regional transects. However, carbonates were also usually present as a minor component in strata largely composed of organic matter. In addition the cores contained shells of gastropods and ostracods as well as biogenic silica in the form of diatom frustules and sponge spicules.

As a result of these findings we decided to change our original sampling plan for sediment analyses by focusing on elemental analyses (total carbon, total inorganic carbon, total organic carbon, total organic nitrogen), stable isotopes (^{13}C and ^{15}N), and mineralogy (semi-quantitative X-ray diffraction, SEM-EDS, and XRF). Because the cost of these analyses were not anticipated in our original budget we initially limited our efforts to a core that was best suited to elucidate the paleoenvironmental drivers for marl vs. organic matter accumulation in the Everglades. This core (4-23-04-4) is located in the NE Shark River Slough immediately south of the Tamiami Trail.

Most of the analyses on this core are now complete. There is a close correspondence between the major lithologic units in this core and the pollen stratigraphy indicating a linkage between regional climatic change, hydroperiod, and marl accumulation patterns. The one remaining problem involves obtaining reliable radiocarbon dates for the most significant changes in the core stratigraphy. We could have sent in bulk samples for radiocarbon dating with the hope that the "reservoir effect" has not changed in time. This method at best would provide dates with a consistent error for the reservoir effect and hopefully a linear age model. However, this method more commonly produces anomalous dates that do not fit a believable age model because of the error associated with

a variable reservoir effect and also from contamination from rootlets (since modern rootlets can penetrate deeply into the sediment profile both now and in the past).

We therefore tried to apply other methods that were developed for obtaining AMS-14C dates from lake sediments subject to the reservoir effect. Samples from the NE Shark River Slough core initially were sent to Dr. Bruce Finney's lab at the University of Alaska-Fairbanks to separate pine pollen for AMS dating. Dr. Finney's lab tried 2 methods for separating the pine pollen without success. One method involves chemical treatments followed by sieving with a range of mesh sizes to separate pine pollen in the 35-78 micron size fraction. The other method involves separating pine pollen using a heavy liquid floatation method. Both approaches were compromised by the uneven size fractions in the sediment samples from the Everglades that overlap with the size range of the conifer pollen.

The samples were returned to us and we then applied an alternative method, which uses a micropipette with a 100 micron internal diameter to hand pick pine pollen under a 40x dissecting scope. Approximately 10,000 pine grains are needed for a single AMS 14C date. We now have the method about 80% perfected but decided to try alternative approaches because of the urgency to complete the project and publish our findings. As a result we have been searching the coarse fraction (>125 microns) of the pollen preparations for macrofossils or charcoal fragments that are suitable for AMS dating. At present there seems to be sufficient charcoal particles from 2 layers at 70-71 cm and 92-93 cm for AMS dating. Collecting suitable material from the upper portion of the core still requires work since the total organic content is low. Since our cores contain very few macrofossils (e.g. seeds, fruits, inflorescences), we are also trying to identify the vegetative plant fragments in these cores by comparison with herbarium material in the hope of obtaining organic remains from plant that only fix atmospheric carbon dioxide. The final fallback option is to use relative pollen dating in which the major changes in the regional pollen zonation in the Everglades cores are matched to a radiocarbon dated profile from a nearby site that is not subject to the reservoir effect.

Once we have acceptable dates for this core we will prepare a publication for a major journal hopefully in the coming months. We are also in the process of revising a previously submitted paper to *Limnology and Oceanography Methods* at the invitation of the editors.

We anticipate the following deliverables at the end of this project: 1) a core log containing the location, sediment depth, and major characteristics of all the 50 cores collected as part of this study, 2) initial core description sheets for all these cores including RGB images, point magnetic susceptibility curves, and Troels-Smith sediment descriptions, 3) raw data for all the analyses done on these cores, 4) orthophoto maps showing the location of the cores and the distribution

of marl sediments within the study areas, 5) a manuscript (currently being revised for publication in *Limnology and Oceanography Methods* at the invitation of the editors) that describes our new corer and extruder for soft near-surface sediments, 6) a manuscript (to be submitted to a major journal) describing the paleoenvironmental drivers for marl (i.e. carbonate) and organic sediment accumulation in the Everglades. 7) a report on a new method developed for quantifying charcoal influx into the Everglades sediments. and 8) potentially other papers describing vegetational change and influx of aeolian inorganic sediments into the cores depending on available funds for dating.