10-21-2009

The Monitoring and Assessment Plan (MAP) Greater Everglades Wetlands Module- Landscape Pattern- Ridge, Slough, and Tree Island Mosaics: Year 1 Annual Report

James B. Heffernan
Southeast Environmental Research Center, Department of Biological Sciences, Florida International University

Michael S. Ross
Southeast Environmental Research Center, Department of Earth and Environment, Florida International University

Matthew J. Cohen
School of Forest Resources and Conservation, University of Florida

Todd Z. Osborne
Wetland Biogeochemistry Laboratory, Soil and Water Science Department, University of Florida

Jay P. Sah
Southeast Environmental Research Center, Florida International University

See next page for additional authors

Recommended Citation
Heffernan, James B.; Ross, Michael S.; Cohen, Matthew J.; Osborne, Todd Z.; Sah, Jay P.; Ruiz, Pablo L.; and Scinto, Leonard J., "The Monitoring and Assessment Plan (MAP) Greater Everglades Wetlands Module- Landscape Pattern- Ridge, Slough, and Tree Island Mosaics: Year 1 Annual Report" (2009). *SERC Research Reports.* Paper 89.
http://digitalcommons.fiu.edu/sercrp/89

Authors
James B. Heffernan, Michael S. Ross, Matthew J. Cohen, Todd Z. Osborne, Jay P. Sah, Pablo L. Ruiz, and Leonard J. Scinto

The Monitoring and Assessment Plan (MAP) Greater Everglades Wetlands Module- Landscape Pattern- Ridge, Slough, and Tree Island Mosaics

Contract 4600001726

Year 1 Annual Report

Delivered 10/21/09

James B. Heffernan[1,2], Michael S. Ross[1,3], Matthew J. Cohen[4], Todd Z. Osborne[5], Jay P. Sah[1], Pablo L. Ruiz[1], Leonard J. Scinto[1,3]

[1] Southeast Environmental Research Center, Florida International University, Miami, FL

[2] Department of Biological Sciences, Florida International University, Miami, FL

[3] Department of Earth and Environment, Florida International University, Miami, FL

[4] School of Forest Resources and Conservation, University of Florida, Gainesville, FL.

[5] Wetland Biogeochemistry Laboratory, Soil and Water Science Department, University of Florida, Gainesville, FL.

Introduction – Goals, scope, and approaches

In the current managed Everglades system, the pre-drainage, patterned mosaic of sawgrass ridges, sloughs and tree islands has been substantially altered or reduced largely as a result of human alterations to historic ecological and hydrological processes that sustained landscape patterns. The pre-compartmentalization ridge and slough landscape was a mosaic of sloughs, elongated sawgrass ridges (50-200m wide), and tree islands. The ridges and sloughs and tree islands were elongated in the direction of the water flow, with roughly equal area of ridge and slough. Over the past decades, the ridge-slough topographic relief and spatial patterning have degraded in many areas of the Everglades. Nutrient enriched areas have become dominated by *Typha* with little topographic relief; areas of reduced flow have lost the elongated ridge-slough topography; and ponded areas with excessively long hydroperiods have experienced a decline in ridge prevalence and shape, and in the number of tree islands (Sklar et al. 2004, Ogden 2005).

Decoupling of soil elevations from underlying bedrock topography in areas of relatively conserved landscape pattern suggests that historic microtopography and landscape structure were self-organized by feedbacks between vegetation, hydrology, and soil elevations. Potential mechanisms for such positive feedbacks include differential peat production, sediment entrainment and deposition, transpiration-driven nutrient concentration (particularly in tree islands), and hydrologic competence (Larsen et al. 2007, Givnish et al. 2007, Ross et al. 2006, Watts et al *in review*). While the relative importance of and interactions between these mechanisms remains an active area of research, observations of pattern loss in response to hydrologic management, nutrient enrichment, and other disturbances points to the disruption of those feedbacks as a primary cause of landscape degradation (Sklar et al. 2004).

This monitoring project seeks to provide information necessary for the evaluation of efficacy of the Comprehensive Everglades Restoration Program (CERP), as delineated in the Water Resources Development Act (WRDA) of 2000. The work described provides indices of system-wide applicability of performance measures related to the response of the ridge-slough mosaic, tree islands, and other landscape features of the central Everglades to the restoration of historic hydrologic conditions, with the goal of informing the adaptive management of Everglades restoration as outlined in the CERP Monitoring and Assessment Plan (RECOVER 2004).

The general goals of restoration are to stem, and possibly reverse, degradation of the ridge-slough-tree island landscape by redirecting flows now released unused to coastal waters across the surface of this landscape (USACE and SFWMD 1999). The CERP MAP, Parts 1 and 2, presented the overarching monitoring framework for guiding restoration efforts throughout the entire process (RECOVER 2004, 2006). This requires not only a comprehensive assessment of the current state of the ecosystem and assessment of restoration endpoints (targets), but also ongoing monitoring and evaluation throughout the process that will aid the implementing agencies in optimizing operational procedures and project designs. The work described below is the first step toward full implementation of the system wide landscape monitoring design that was developed with RECOVER MAP funds and provides for a multi-year monitoring program for the Greater Everglades Wetlands ecosystem. This monitoring efforts supports the Greater Everglades Wetlands module of the MAP and is directly linked to the monitoring or research component identified in that module as number 3.1.3.6.

The primary objective of this monitoring project is to begin systematic implementation of a landscape sampling design across the Greater Everglades Wetlands ecosystem. This effort will establish the current condition of the ridge and slough ecosystem and will allow scientists to detect changes/trends in the patterns and vegetation communities of these systems as a result of water management operations, restoration initiatives and episodic events such as droughts, fire and hurricanes. Our secondary objective of this project is to work with other RECOVER researchers to integrate knowledge regarding landscape patterning, soil dynamics and community structure and composition with hydrologic data provided by Everglades Depth Estimation Network (EDEN) and other sources. We will pay particular attention to how these dynamics might: 1) be affected by restoration and 2) relate to CERP hypotheses from the MAP. The resulting data will be utilized to validate existing models and establish or revise restoration targets.

The specific objectives of this work are:

1) To determine extant reference conditions for each of the performance measures described below (including variability of those measures in time and space).

2) To establish present status of landscape performance measures throughout the central Everglades, particularly in areas of historic ridge-slough landscape patterning, identify spatial and temporal trends of those performance measures, and quantify their relationships to the present hydrologic regime.

3) To detect unanticipated changes in ecosystem structure and processes that result from hydrologic management or manipulation, CERP restoration activities, or climatic variation

4) To provide data in support of scientific studies of inter-relationships among vegetation, microtopography, and hydrologic regime that may provide insight into the causes of unanticipated ecosystem responses.

Overview of approaches

Monitoring efforts consist of three core components: (1) mapping vegetation features from aerial photographs, (2) aerial surveys for classification of tree island type, and (3) ground surveys of water depth and plant community structure (both tree island and marsh), which are used to quantify aspects of the hydrologic regime, determine relationships between vegetation structure and water depth, quantify the distribution and spatial structure of peat elevations, and ground-truth broader-scale maps based on remote sensing and aerial surveys. These activities are linked both logistically and analytically (Figure 1). For example, vegetation mapping from photographs is bolstered by aerial marsh reconnaissance that is itself folded into tree island characterization activities. Mapping accuracy can be determined from vegetation observations made during surface pattern sampling. Perhaps most importantly, analysis of pattern based on multiple variables (vegetation and soil micro-topography) at multiple scales (aerial photos, helicopter reconnaissance, ground surveys) will maximize the likelihood of change detection, allow inference about interrelationships among stressors and response variables, and present an integrated picture of the pre-restoration structure of the Greater Everglades Wetland Ecosystem.

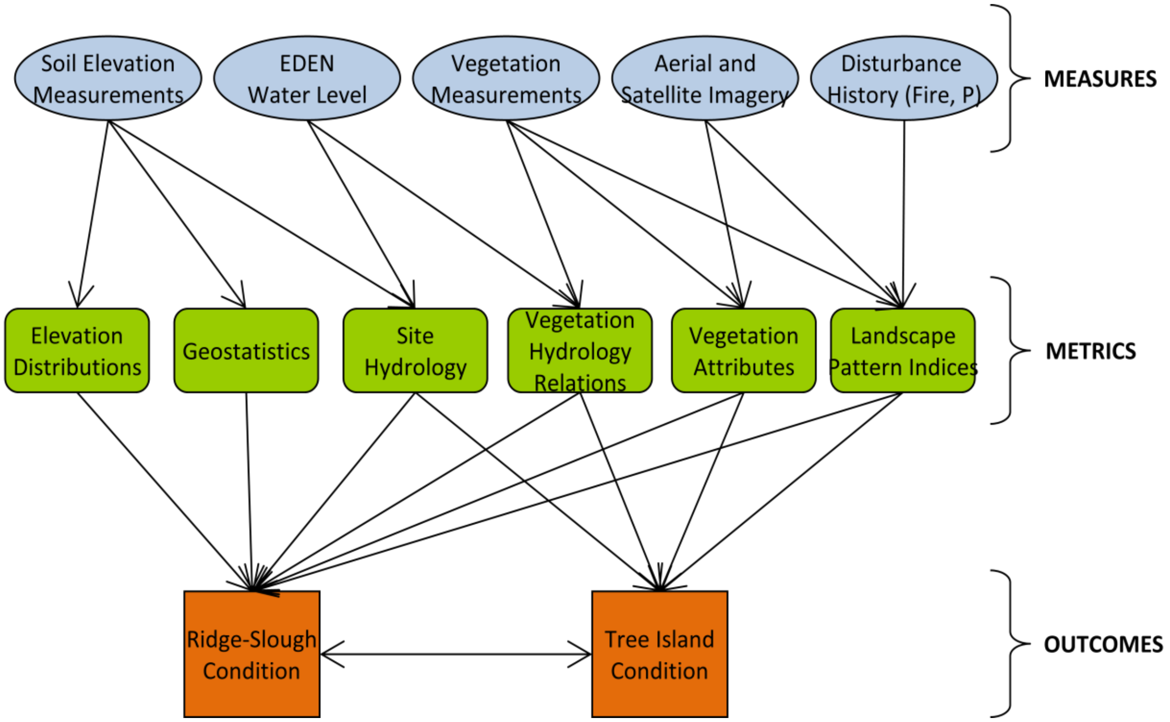


Fig. 1 Relationships among direct measurements to be collected, metrics derived from those measurements, and assessment outcomes.

Sampling Design

Site Selection and Schedule

The landscape monitoring design utilizes a Generalized Random-Tesselation Stratified approach (GRTS) of Stevens and Olsen (2003) and produces a spatially-balanced probability-design drawn from a tiling of the ridge and slough and sawgrass prairie areas into 2km * 4km cells oriented along the directions of ridges (Figure 2). The GRTS approach provides spatial balance for inferences about gradients of change, and for model-based inferences (spatial interpolation) of regional means. Further, it supports differing spatial and temporal intensity of measurement for different attributes while maintaining co-location for inferences about causal pathways. Thus, it maximizes the flexibility of subsequent analyses of the resultant monitoring data (Philippi 2007).

The landscape design allows for some flexibility in implementation to account for variable budget constraints. This design also provides flexibility for choosing the specific attributes of the ridge and slough that will be monitored over the long term. The long-term attributes to be monitored will be determined based on the results from the initial field work and from cost-benefit analyses. Full implementation of this monitoring design will not only enable a holistic assessment of the current ecosystem but will provide the data needed for adaptive management and evaluation model validation. As most landscape-level change is expected to occur slowly enough that sites need not be revisited every year, the plan is based on a revolving sampling design, with the sites being revisited on a recurring interval that will be determined based on the results from this monitoring effort. Where appropriate, analysis will incorporate monitoring data from within and outside the RECOVER MAP funding stream, including ridge and slough monitoring within Everglades National Park (National Park Service) previously funded through the Critical Ecosystems Studies Initiative in addition to new sampling locations located within the Water Conservation Areas (WCAs).

Initial formulation of the sampling plan envisioned sampling of 16 sites in each year of the project, with year 1 providing an opportunity to evaluate and refine monitoring protocols. The foreshortened first year of the project (ends 9/31/09) necessitates a revision of those goals. Previous sampling of the marsh ridge and slough using similar protocols (Watts et al *in review*) has included 8 landscape blocks located in the central and southern marsh (WCA3A, WCA3B, and ENP). Year 1 sampling applied these protocols in the northern marsh (WCA1, WCA2) where they have yet to be applied, and included sampling of marsh vegetation and microtopography . In year 1 we sampled 4 PSUs (1, 3, 4, 9), two of which are among those designated for the more intensive sampling regime.

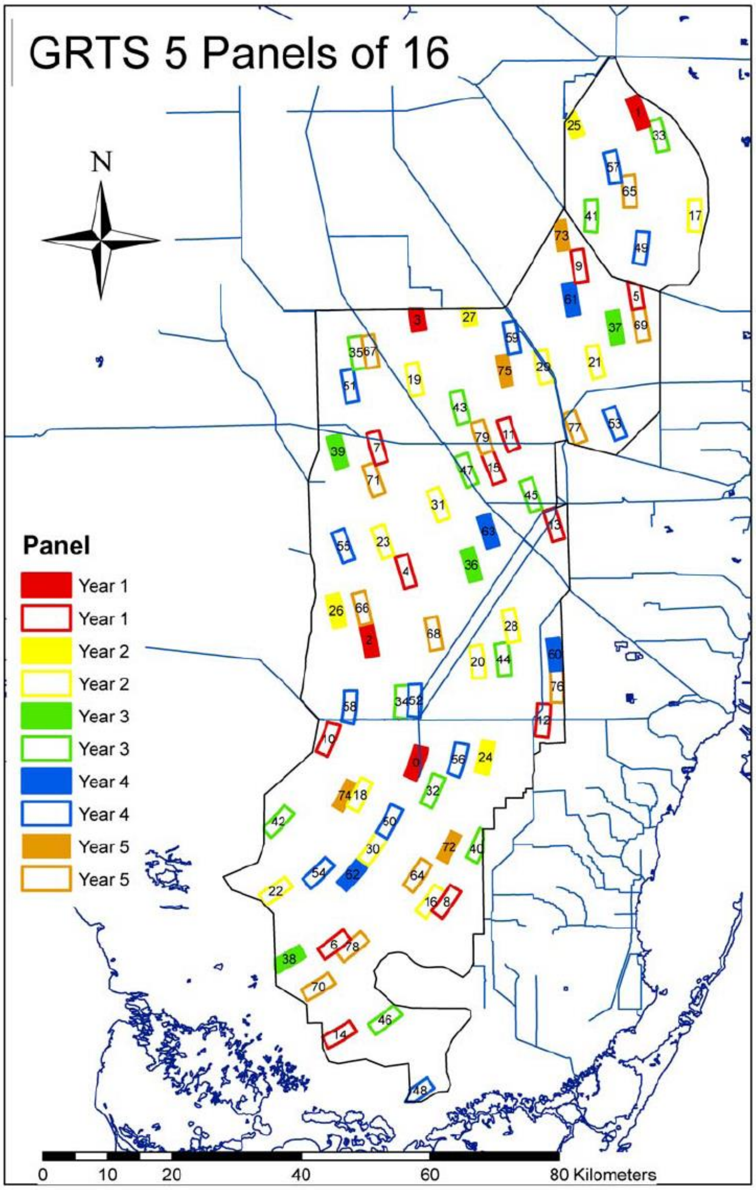


Fig. 2. Map of PSUs for landscape sampling (from Phillipi 2007). Colors indicate years for sampling of individual PSUs. Solid landscape blocks have been selected for intensive sampling. Sampling in FY09 included marsh vegetation and topography sampling in PSUs 1,3,4,and 9, mapping of marsh and tree island vegetation in PSUs 4 and 5, and ground sapling of tree island gradients in 0 and 2)

Data Collection and Analyses

Marsh vegetation and tree island mapping
Materials and Methods:

Imagery

The primary imagery used in this project consisted of a set of 2003 3-band color infrared (NIR,R, G) aerial photos flown as part of the Monitoring and Assessment (MAP) program within the broader RECOVER program. These aerial photos were flown at an attitude of about 3,657 meters (12,000 ft) and have a scale of 1:24,000. Each image covered an area of approximately 30.6 km^2 with an average overlap of 60% between adjacent images. The raw images provided by RECOVER were georeferenced and orthorectified using ERDAS Images 9.3. The images were projected to NAD83 UTM Zone 17N (units = meters) and had a spatial resolution of 0.3048 meters. On average, the planimetric accuracy (positional accuracy) of each of the newly created orthophotos is approximately 1.3 meters. As a result, overlapping pixels from adjacent images tended not to be coincident. However, this error fell within acceptable tolerances.

A secondary set of 2004 1-meter resolution multispectral imagery, 4-band (Red, Green, Blue, NIR), were also used in this project. This image data set, correspond to the regularly flown, about once every 5-years, National Aerial Photography Program (NAPP) digital ortho quarter quadrangles (DOQQs). These images, which were flown at 6,096 meters (20,000 feet), had a scale of 1:40,000 and covered an area approximately 64.8 km^2. These images had the same projection as outlined above for the 2003 RECOVER imagery. The native format for this image catalogue was GeoTIFF, however, these images were only available as JPEG 2000 compressed images and, as such, were prone to ringing and blocking artifacts, which tended to blur the image. As a result, their overall utility and usefulness were limited.

Mapping

Vegetation communities inside a perimeter denoted by a 250 m buffer around PSU 4, located in central Water Conservation Area 3B, and PSU 5, located in northern Water Conservation Area 2, were screen-digitized using the 2003 RECOVER imagery. Community boundaries were digitized at an average screen scale of 1:1000 using ESRI® ArcMap™ 9.3 and stored in a Personal Geodatabase. The minimum mapping unit (mmu) was set to 400 m^2, but notable objects smaller than 400 m^2 were mapped based on the photo-interpreter's discretion. This was particularly true for woody patches classified as tree islands. Digitized polygons were classified to the highest feasible level of resolution within the six-tiered hierarchical vegetation classification system developed by Rutchey et al. (2009) v6.15.09. Level 3 of the hierarchy was the minimum resolution set for this project. However, some polygons (communities) were identified beyond the Level 3 resolution; in some cases Level 6 was reached. The map projection was set to NAD83, UTM Zone 17N (units = meters).

To facilitate the identification and mapping of community types within each PSU, the Normalized Difference Vegetation Index (NDVI) was calculated for each image data set (RECOVER & NAPP) as a 1-band 32-bit floating point raster in ERDAS Imagine 9.3. NDVI is calculated by subtracting the Red spectral band from the NIR spectral band and then dividing this difference by the sum of the NIR and Red spectral bands (Equation 1).

Equation 1: $\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$

A second index, the Photosynthetic Vigor Ratio (PVR) was similarly calculated but only on the 2004 NAPP image data set. The PVR index is the quotient of the Green and Red spectral bands (Equation 2).

Equation 2: $\text{PVR} = \text{Green} / \text{Red}$

Technically, NDVI & PVR should be calculated on the corrected radiant flux of each pixel within an image so that comparisons within and across images are meaningful. For space-borne platforms (e.g. Landsat, SPOT, ASTER) this process is well documented. However, for small footprint scanned suborbital photography, like the 2003 RECOVER imagery, the calibration process is much more complicated because of the inherent variability in contrast within and among images resulting from multiple flight paths & flight dates, time of day (sun angle), changing cloud cover or haze, which create ground shadows and scatter light, and from subtle differences in the sensitivity associated with multiple rolls of CIR film. When the study area is small or when distances between study regions are not great, a color balanced mosaic of the imagery usually suffices as a means of correcting for the spectral differences between and across images. To that end, a color balanced mosaic consisting of the 2004 NAPP imagery, which have a larger image footprint than the 2003 RECOVER imagery, was created and resampled using a moving window, 5 x 5, statistical filter in ERDAS Imagine 9.3. This filter mitigated the blurring effects caused by the ringing and blocking artifacts inherent in JPG2000 compressed imagery. NDVI and PVR were then calculated using the resampled 2004 NAPP imagery. Using the newly resampled imagery, a 6-band stack image was created using the four spectral bands (R,G,B,NIR) and the two vegetation indexes (NDVI & PVI) calculated. For the 2003 RECOVER imagery this methodology was deemed inappropriate. However, NDVI was still calculated using the original (raw) pixel brightness values. As a result, trends in NDVI, within the RECOVER image data set, were only interpreted for the image or scene being analyzed and not uniformly across all the RECOVER images used to map PSU 4 & 5.

Unsupervised Classification

When thematic maps are a key component of long term monitoring projects, it is important for the mapping methodologies to be standardized and applicable to all regions being monitored. One of the most effective ways of accomplishing this is by applying computer aided classification algorithms. In general, these methodologies work by reorganizing the spectral information contained within aerial or satellite imagery into spectrally similar pixel clusters that are then grouped into meaningful thematic classes. For this project, a two step computer aided unsupervised mapping classification was evaluated for PSU 4 using Principal Component Analysis (PCA) and an ISODATA (Self-Organizing Data Analysis Technique) clustering algorithm. PCA is a statistical technique used to reduce the dimensionality of multidimensional data into fewer and easier to interpret uncorrelated variables or principal components (PC). The resulting PC can then be analyzed using any one of several clustering algorithms, in this case, ISODATA clustering—an iterative process that groups spectrally similar pixels into clusters that are then classified *a posteriori* into meaningful thematic classes. The number of clusters used in the ISODATA clustering algorithm is determined empirically and is, generally, a function of landscape complexity. The more complex the landscape, the greater the number of clusters needed. In this case, the reduced spectral information obtained in the PCA was grouped using ISODATA clustering into 32 distinct spectral clusters. These clusters were then categorized into discrete thematic classes to produce an unsupervised thematic raster map of PSU 4. The resulting map was then evaluated against the screen-digitized thematic vector map of PSU 4 created using the 2003 RECOVER imagery.

Results:

Vegetation maps

The vector (screen digitized) thematic maps for PSU 4 and 5 are shown in Figures 3 & 4, respectively. In total, nine days were used to make these two maps. PSU 4 because of its larger size, ~ 1370 ha, took about 5 days to create, one more day than PSU 5. On average, 275 ha were mapped within each PSU per day.

The marsh in and around PSU 4 is a typical "ridge and slough" landscape dominated by water lily sloughs and sawgrass ridges interspersed with woody patches (Table 1, Figure 3). Most of the woody patches in PSU 4 are transitional scrub communities (Bayhead Swamp Scrub), which lack forest structure (Table 1, Figure 3). Tree Islands in the form of Bayheads and willow heads are present within this PSU but are a minor component of the landscape and account for no more than 0.1% of the total area mapped. No Hardwood Hammocks were identified within the extent of this PSU.

Table 1: Summary statistics for all units mapped in PSU 4 & 5

Community Type	**PSU 4**		**PSU 5**	
	Total Area (ha)	**Percentage of Area**	**Total Area (ha)**	**Percentage of Area**
Bayhead Forest	< 0.1	< 0.1%		
Willow Forest	1.0	0.1%		
Bayhead Shrubland	5.2	0.4%		
Willow Shrubland	1.5	0.1%	83.3	7.5%
Bayhead Swamp Scrub	82.4	6.0%		
Willow Scrub	< 0.1	< 0.1%		
Cattail-Willow Shrubland			790.6	70.7
Cattails			149.5	13.4%
Sawgrass	590.1	43.1%		
Mixed Freshwater Marsh	9.6	0.7%		
Water lily	679.7	49.6%		
Common Reed			15.9	1.4%
Wild Taro			3.5	0.3%
Water	< 0.1	< 0.1%	71.4	6.4%
Levee			3.7	0.3%

In contrast, PSU 5 is dominated by a mixed matrix of cattails and willow patches interspersed with irregular shaped monotypic stands of 2-5 meter tall willows (*Salix caroliniana* Michx.) (Table 1, Figure 4). Tree islands within this PSU are exclusively willow heads (Figure 4) with no signs of relic Hammock or Bayhead forest types. Sawgrass ridges and spikerush/water lily sloughs are also absent from this landscape (Figure 4). However, the elongated shape of several willow head islands (Figure 4) suggest that, historically, ridges and sloughs might have occurred within this landscape.

Unsupervised classification

The PCA analysis transformed the spectral information contained in the NAPP imagery into 6 principal components (Table 2). The first three principal components explained nearly 98% of the total variation observed within the NAPP imagery (Table 2). PC 1 accounted for most of the variation observed and was heavily weighted towards the three visible spectral bands and the NIR band (Table 3). PC 2, which explained 15% of the total variation in the imagery (Table 2), had a high loading in the computed NDVI index (Table 3) and likely represents contrasting differences in leaf area between community types. PC 3, however, was negatively correlated to the green spectral band, where chlorophyll has the highest reflectance, and the two vegetation indexes calculated, NDVI & PVR. This suggests that PC 3 is keying in on a non-vegetative signal, possibly the background water signature that permeates throughout the imagery. PC’s 4-6 account for no more than 2% of the total variation observed in the imagery and were excluded from the ISODATA clustering algorithm. The results of the ISODATA clustering algorithm were categorized *a posteriori* into 3 thematic classes: ridge, slough, and woody (Figure 5). This entire analytical process took about one day to complete.

Table 2: Computed Eigenvalues and total variance explained by each Principal Component derived from the 6-band stack NAPP imagery.

PC	**Eigenvalue**	**Variance Explained**	**Cumulative**
1	5425.094	0.781	0.781
2	1037.166	0.149	0.930
3	339.024	0.049	0.979
4	145.125	0.021	1.000
5	1.333	< 0.01	1.000
6	0.027	< 0.01	1.000

Table 3: Degree of correlation between each spectral band and the six Principal Components derived from the 6-band stack NAPP imagery.

Spectral Band	**Principal Component**					
	1	**2**	**3**	**4**	**5**	**6**
Red	0.899	-0.365	0.197	0.133	0.001	0.000
Green	0.907	-0.186	-0.374	0.002	0.000	0.000
Blue	0.896	-0.206	0.166	-0.347	0.000	0.000
NIR	0.846	0.528	0.043	0.023	0.000	0.000
NDVI	0.069	0.805	-0.124	-0.062	0.070	-0.571
PVR	-0.152	0.153	-0.357	-0.075	0.929	0.002

At a visual scale of 1:25,000, the unsupervised thematic raster map of PSU 4 (Figure 6) appears to have successfully captured the overall physiographic nature of this PSU. At this broad scale, the similarities between the two mapping methodologies used to map PSU 4 are striking (Figure 7), particularly with respect to the delineation of ridge and slough (Figure 8). However, close inspection of the unsupervised thematic raster map, at an increased scale: e.g. 1:5,000 vs 1:25,000, reveals a significant breakdown in the unsupervised classification (Figure 9). At this higher resolution, 1:5000, we find many inconsistencies with the unsupervised thematic raster map, which led to a significant number of omission and commission errors (Figure 9). Compared to the screen digitized map, the unsupervised ISODATA clustering algorithm overestimated the ridge thematic class by nearly 30% (Table 4). This increase was at the cost of slough and woody thematic classes, which decreased by 23 and 4 percent, respectively (Table 4).

Table 4: Comparison of total area mapped (%) within PSU 4 as a function of mapping methodology.

Community Type	**Screen Digitized Thematic Map (%)**	**Unsupervised Classification Thematic Map (%)**	**Difference**
Ridge	43.1	70.7	27.6
Slough	49.6	26.3	-23.3
Woody	6.6	3	-3.6
Other	0.7	0	

Discussion:

In the short term, i.e., 1-3 years, Everglades vegetation pattern appears stable and resistant to structural and/or composition changes. However, at intermediate temporal scale, 3-15 years, plant communities can change significantly in response to landscape level physical and chemical processes, perturbations, both natural and anthropogenic, and/or management practices. As a result, remote sensing projects within the Florida Everglades should rely, as much as possible, on the most recent acquired imagery. However, because of budget constraints and the logistics associated with image acquisition, it is not uncommon for large scale monitoring and remote sensing projects, like this one to utilize imagery several years old, acquired for a separate project with a slightly different scale of interest.

As noted in the methods section, the imagery being used on this project dates back to 2003 and 2004. As such, the imagery, which is currently about 6 years old, is at the cusp of its usefulness since the communities depicted on the imagery may no longer reflect those currently observed and sampled in the field. Aerial surveys and field sampling conducted this year indicate that temporal changes not reflected in the available imagery have taken place. Most of these changes are associated with minor shifts in community boundaries. However, some community level shifts have also been noted. Inasmuch as hydrologic changes associated with restoration are likely to quicken the pace of vegetation change, such discrepancies between dated image and current condition are likely to become more problematic in the future. If the primary goal of our mapping effort is to document fine-scale changes in vegetation in sentinel sites (PSU's), then more timely imagery is needed.

Unquestionably, the acquisition of up-to-date digital imagery would improve the planimetric and thematic accuracy of the remote sensing products produced through this project. Furthermore, a new set of high quality digital images will improve and build upon the results already obtained, albeit limited, through the unsupervised ISODATA mapping classification. However, there is no certainty that a finer scale thematic classification that includes communities beyond the three broad thematic classes—ridge, slough, and woody, currently discernable—would be attainable. In general, the success of an unsupervised mapping classification in classifying features within an image depends on 1) the spatial resolution of the imagery, which determines the size of the smallest object that can be detected, 2) the radiometric resolution of the sensor, which determines the number of discriminable signal levels available to detect subtle differences in the spectral signature of the objects being measured, and, most importantly 3) the spectral signature of the objects themselves, which determine how well objects can be separated from each other and classified into discrete thematic classes (e.g. sawgrass vs water lily or willow head vs. bayhead vs. hardwood hammock, in this case).

The inability to distinguish fine scale community types is not just limited to the unsupervised mapping classification. The ocular identification of community types is also limited by these three factors outlined above. Yet, an experienced analyst, who understands the physiography of the landscape, can usually overcome these limitations and increase the level of detail attainable, but at a cost.

For an average PSU, an unsupervised thematic raster map can be produced in a day or so. In contrast, a screen digitized 1:1000 scale thematic vector map of the same PSU can take four to five days to produce. While the latter is likely to contain more detail then the former, the amount of extra effort needed overextends the resources allocated to this task. As a consequence, if the total number of PSUs currently being mapped in this project remains constant (16 per year) then the scale and thematic detail of each PSU would have to be reduced accordingly. These lower resolution screen digitized thematic maps may be comparable to a thematic raster map created by an unsupervised classification algorithm. Given the time needed to produce both types of maps, a map created through an unsupervised classification may be the better choice, particularly with a current set of digital images. Alternatively, a reduced number (4-6 PSUs per contract year) of fine scale thematic maps, meeting the same standards as those created for this project, could be screen digitized without overextending the resources allocated to this task. Another possibility would be to map all PSUs at a scale of 1:7500 and then map a horizontal strip, 2.0 km by 1.5 km, centered on each PSU at a scale of 1:1000 (see Figure 10). It is believed, that each PSU could be mapped within two days using this two scale approach—one day to create the 1000 ha map at 1:7500 and a second day to map the 300 ha strip at 1:1000—with minimal loss of information at the whole PSU scale (Table 5). This two-scale mapping effort allows for each PSU, including tree islands, to be mapped without limiting the ability to calculate the proposed fine scale landscape metrics for each PSU.

Lastly, the thematic classification used in this project is esoteric and requires an *a priori* determination of vegetation structure, particularly height. As a result, if a stereoscope is not available to properly determine the height of the vegetation, it becomes very difficult to properly assign a structural class to the community being classified. Consequently, omission and commission errors are likely to occur. An alternative is to use the vegetation classification recently developed by Sah et al. (2009). This is a field-data based classification, and has been developed using a hierarchical cluster analysis of data from 3515 herbaceous sites. Vegetation data were obtained from a broad group of plant scientists working in South Florida. The classification differs from that of Rutchey et al. (2009) at Level 3, in that ecological criteria are used to classify both freshwater and salt marsh vegetation. In compliance with a gradient of increasingly hydric condition, freshwater marsh is classified into three groups: seasonally flooded wet prairie, seasonally flooded marsh, and semi-permanently flooded marsh. Likewise, the classification of salt marsh into three groups: oligohaline, mesohaline and hypersaline marsh, is based on a gradient of increasing salinity. These ecological groupings, particularly for freshwater marsh, are in concurrence with the criteria used in the Terrestrial Ecological Classification for Tropical Florida (NatureServe 2006), and also have important management implications.

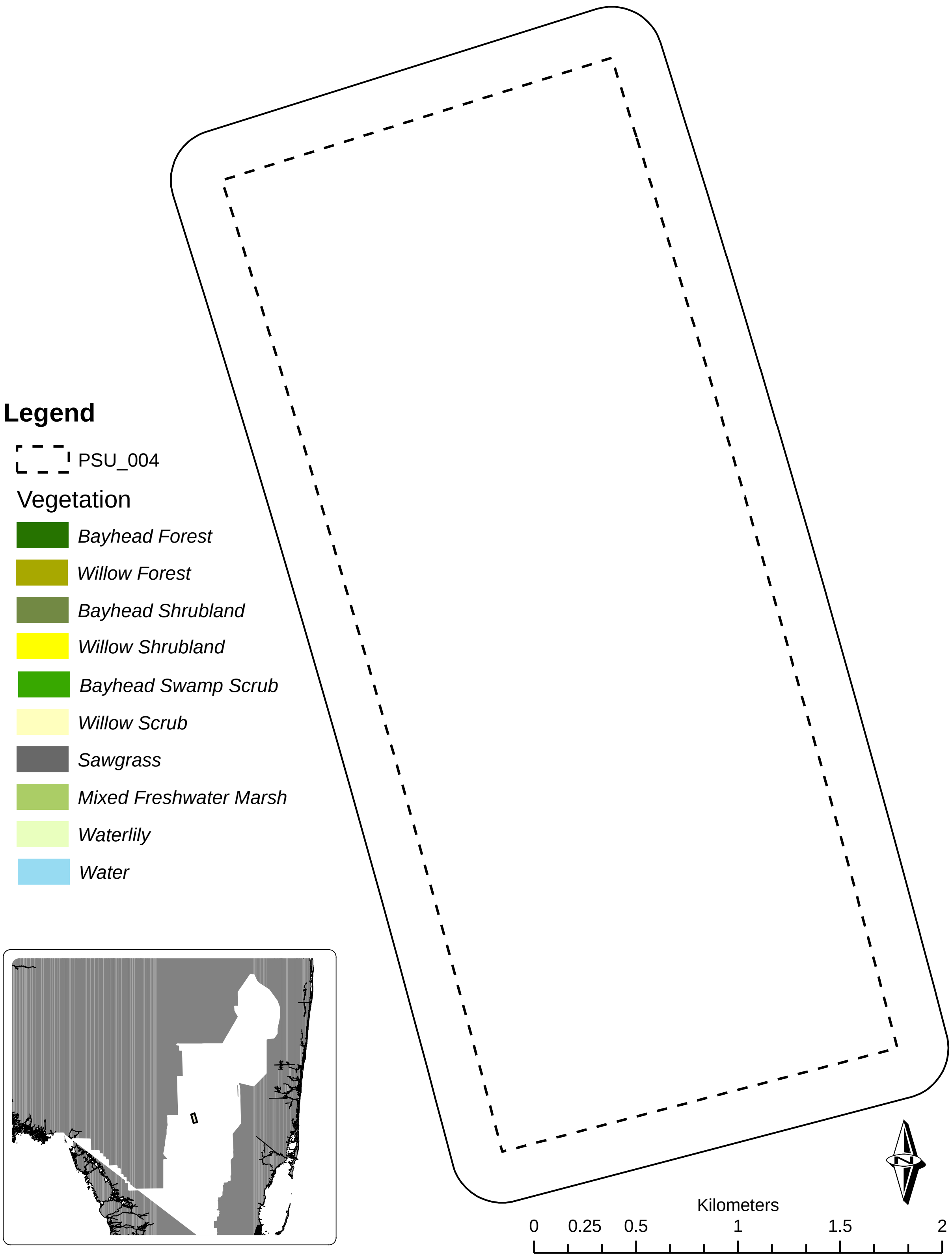


Figure 3 Thematic map of PSU 4 located in WCA 3A.

Figure 4 Thematic map of PSU 5 located in WCA 2.

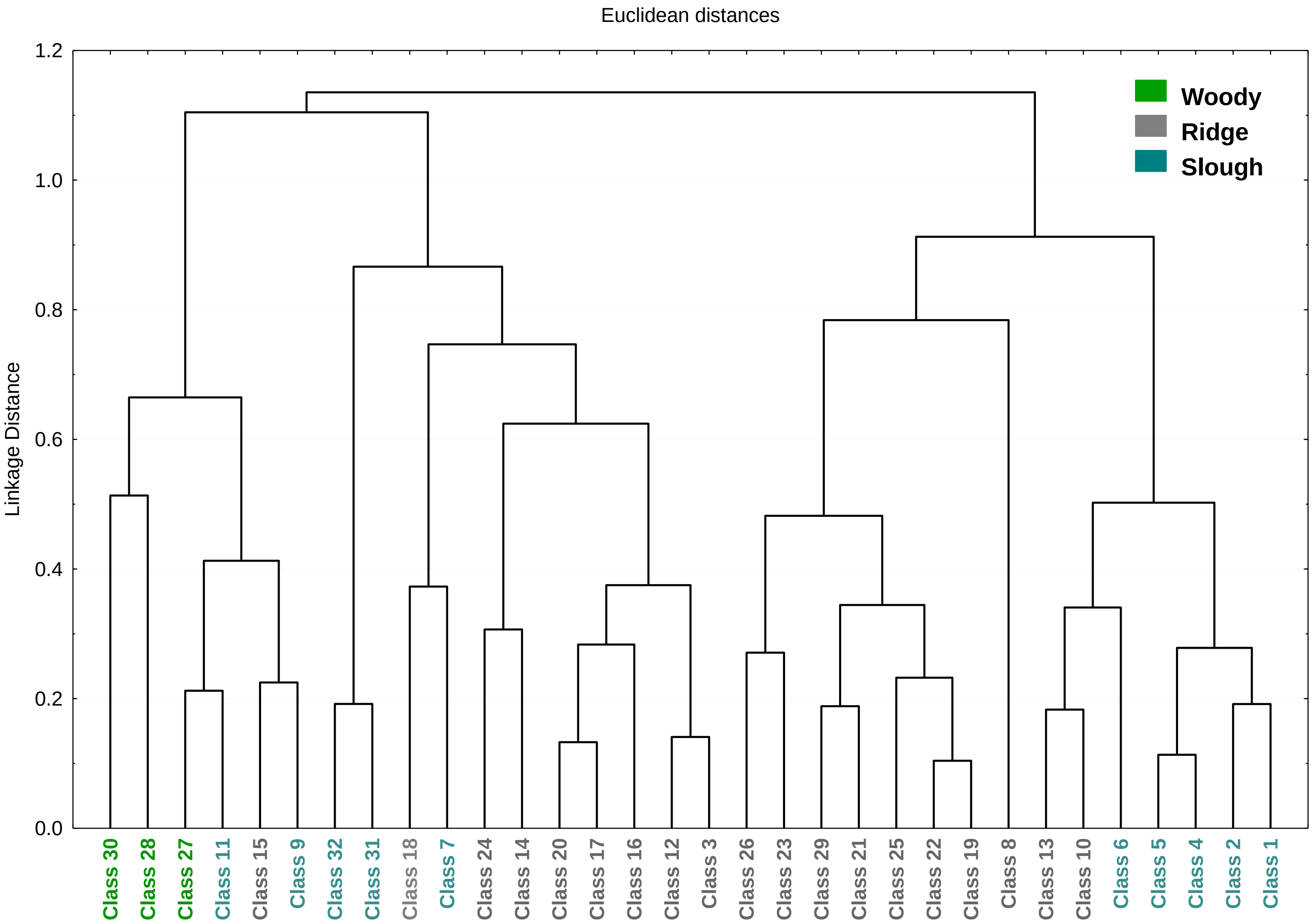


Figure 5: Dendogram of ISODATA clustering algrorith for PSU 4 with *a posteriori* classification.

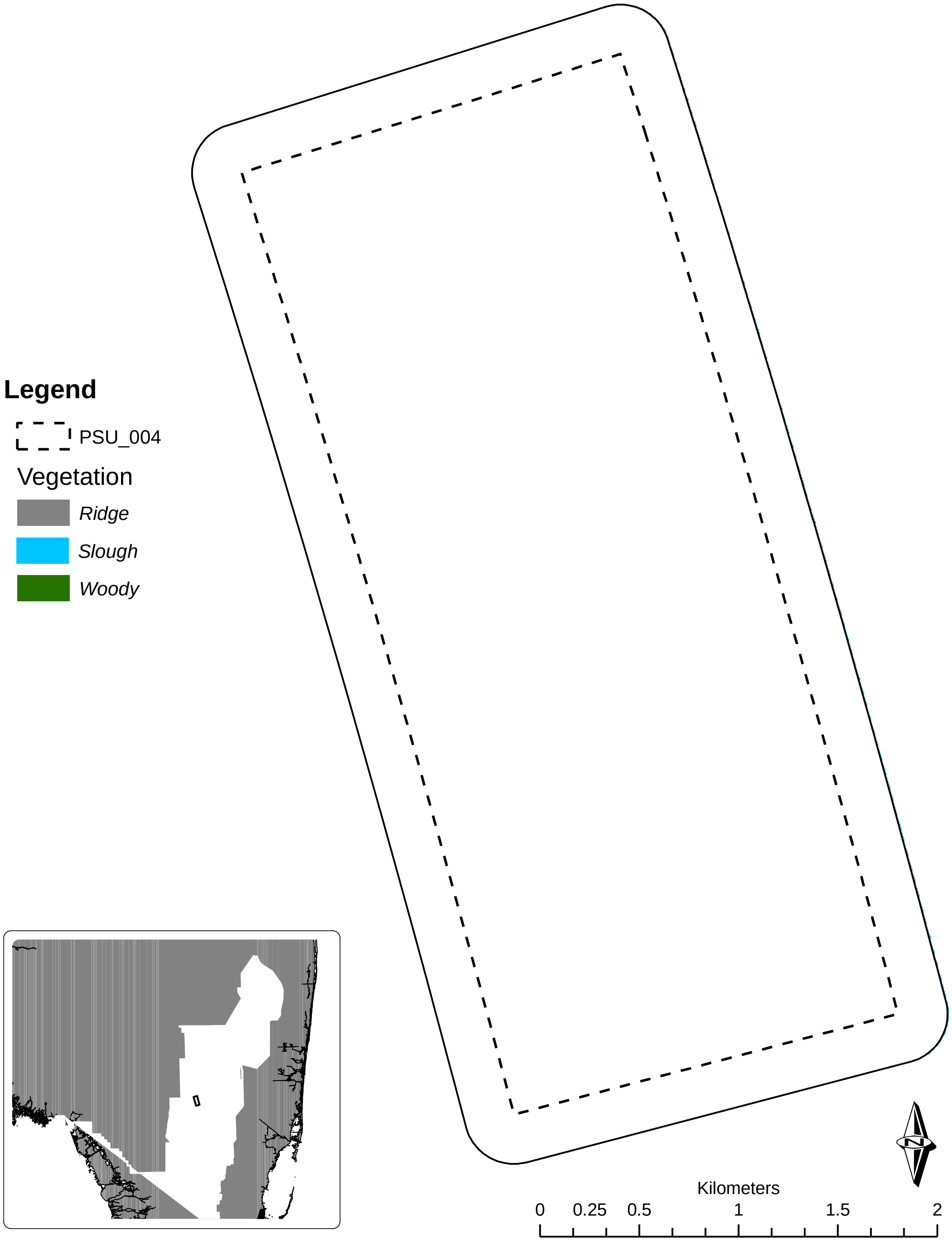


Figure 6 Unsupervised ISODATA thematic raster map of PSU 4 located in WCA3A.

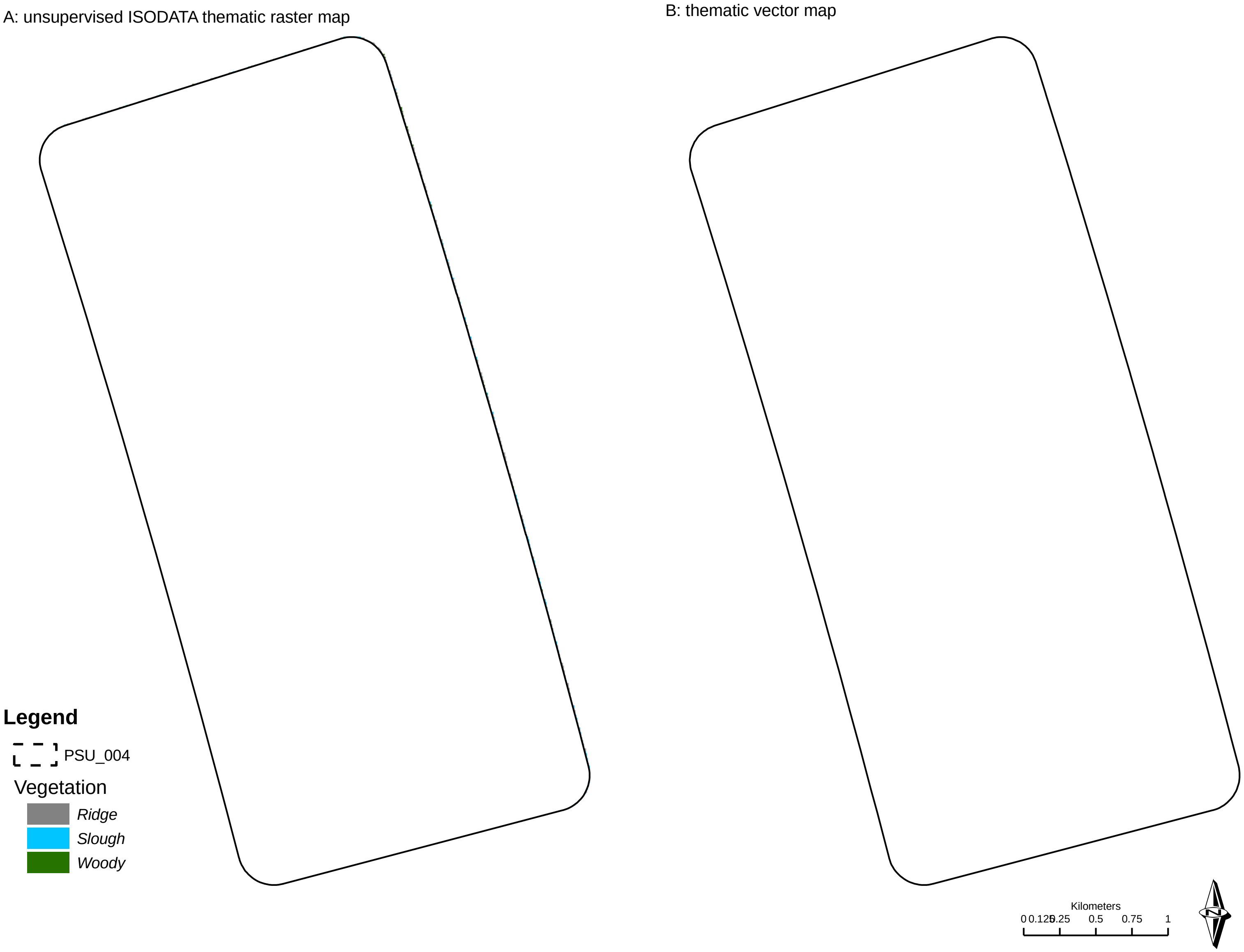


Figure 7 Side by side comparasion of A) unsupervised ISODATA thematic raster map & B) thematic vector map of PSU 4.

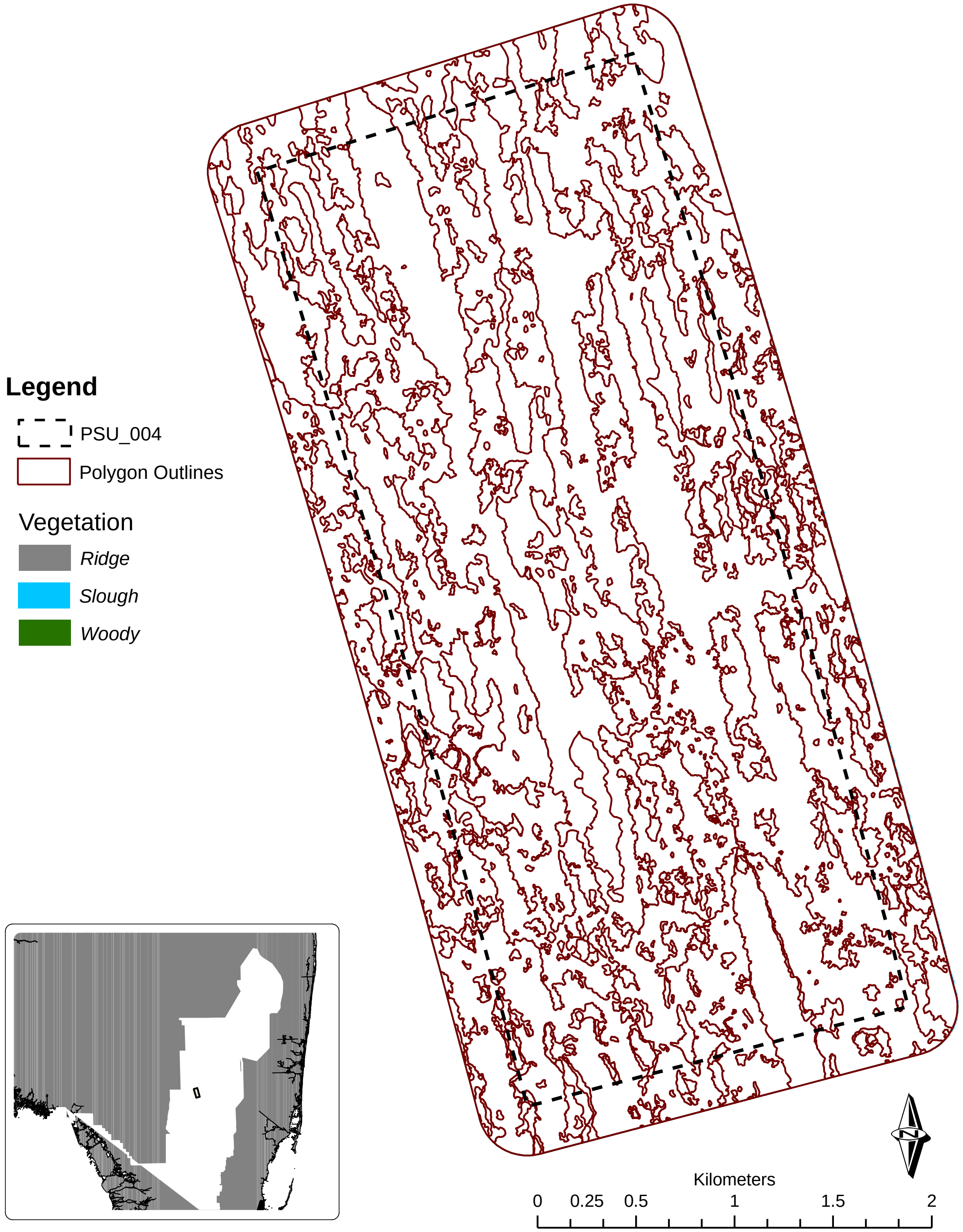
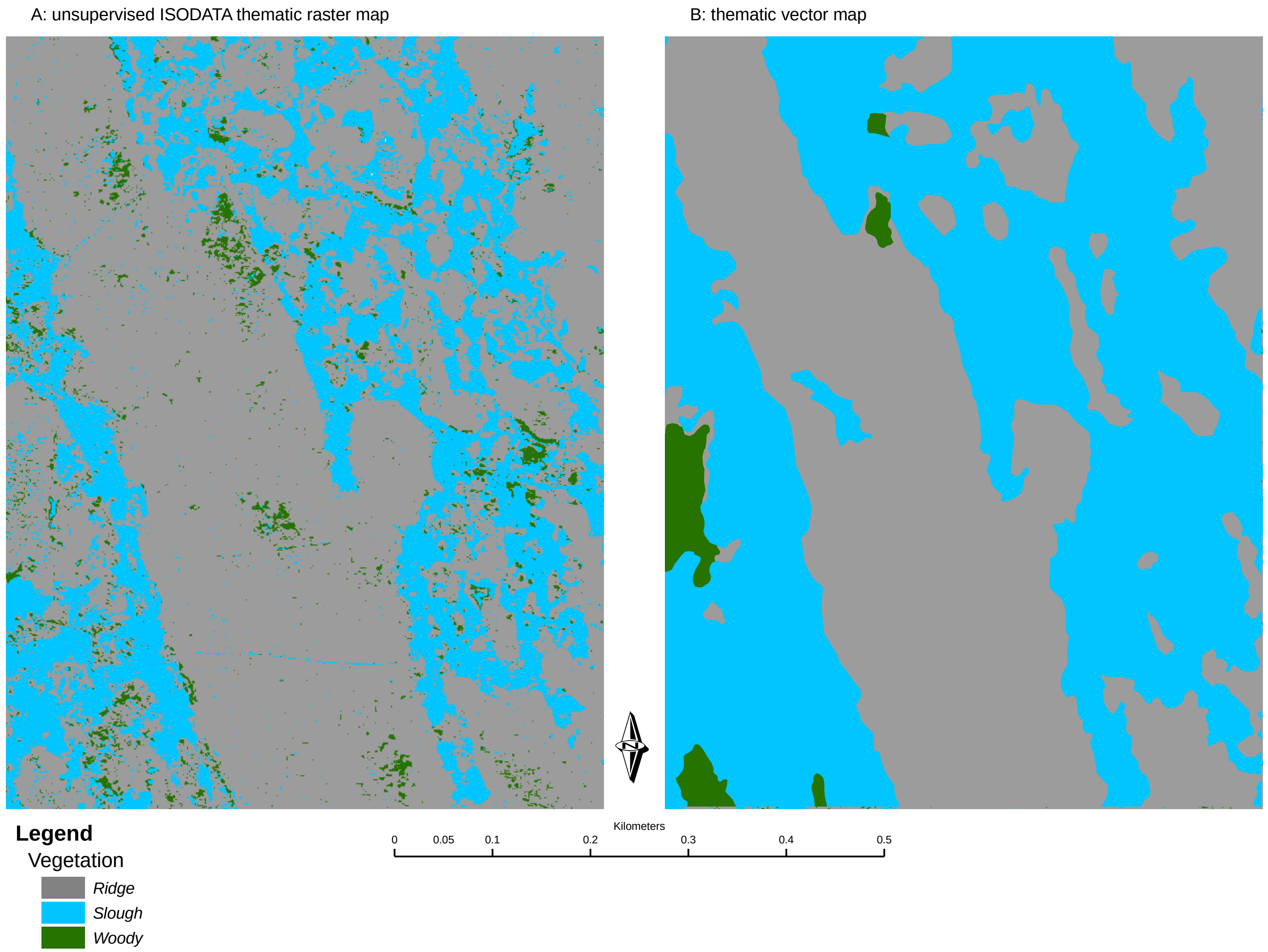


Figure 8   Unsupervised ISODATA thematic raster map of PSU 4 overtoped by the vector outlines from the thematic map in Figure A.


A: unsupervised ISODATA thematic raster map

B: thematic vector map

Figure 9 Side by side close-up comparasion of A) unsupervised ISODATA thematic raster map & B) thematic vector map of PSU 4.

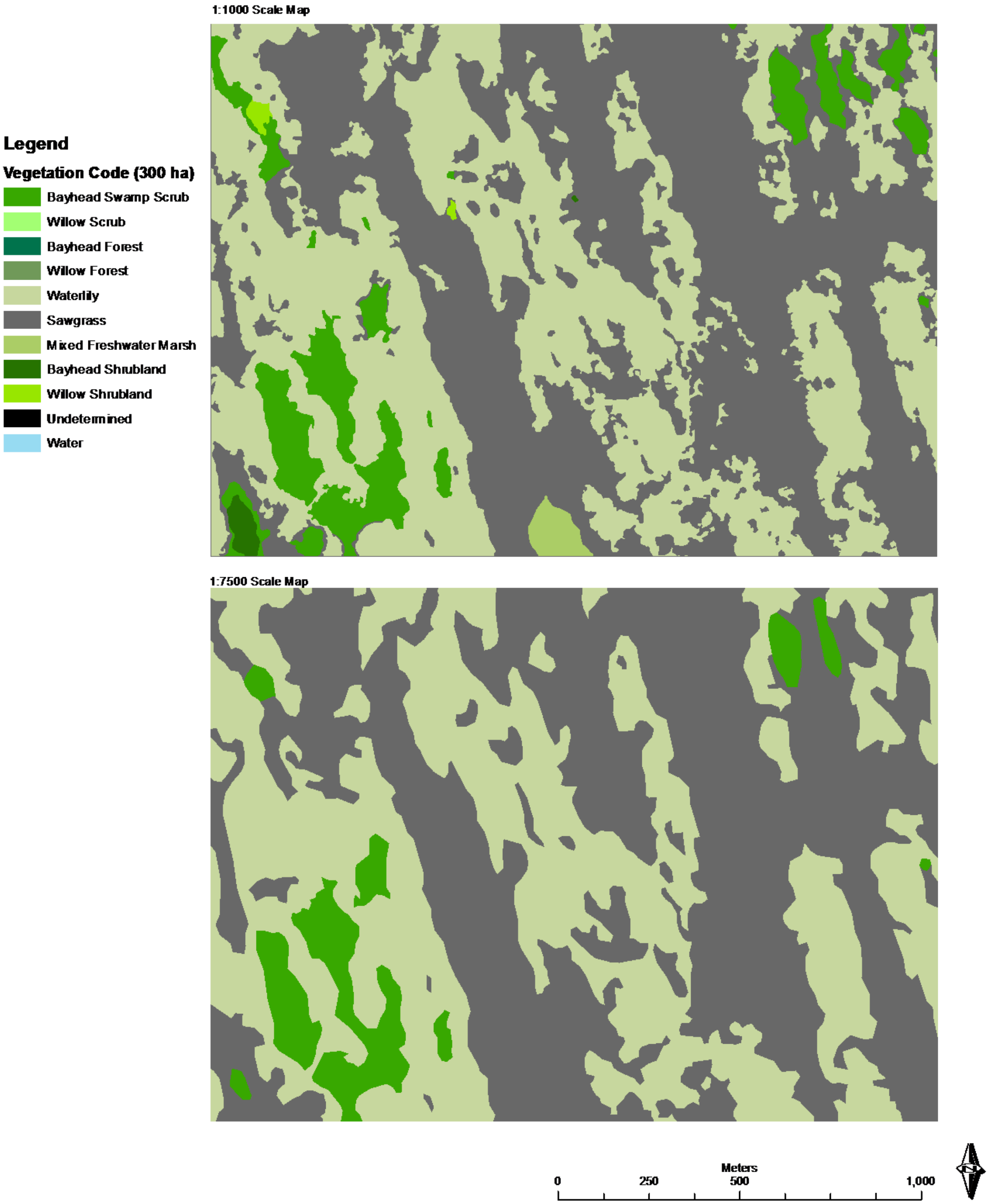


Figure 10. Maps of central PSU 4 created at 1:1000 and 1:7500 scale aerial photographs. Future mapping efforts will be conducted at the 1:7500 scale for the entirety of PSUs and at a 1:1000 scale for a 200-300 ha subsection of each PSU.

	Area (ha)		
Map Scale	Ridge	Slough	Woody
1:7500	156.12	127.32	16.56
1:1000	150.46	126.65	22.89
Δ%	3.6%	0.5%	-38.2%

	Average Polygon Size (ha)		
Map Scale	Ridge	Slough	Woody
1:7500	8.22	6.70	1.84
1:1000	1.79	3.84	0.92
Δ%	78.2%	42.7%	50.2%

Table 5. Differences in landscape abundance and average patch size of ridge, slough, and woody vegetation at 1:7500 and 1:1000 scales.

Peat surface and fine-scale vegetation mapping

Field Sampling Design and Modifications

The sampling design is focused first on obtaining a random sample of peat elevations and vegetation class, composition, and cover data across a primary sampling unit, and second on ensuring an even distribution of sample spacing for geostatistical analyses. To accommodate both objectives, we modified the sampling design slightly from the scope of work.

Each PSU is subdivided into 4 rows (each 1.25 km tall) and 4 columns (each 500 m wide). Within each of the resulting 16 sampling blocks (1 for each row-column pair), a 200 x 200 m frame is placed at a random location, and within each frame, 3 clusters are placed randomly. This results in a total of 48 clusters per PSU. Each cluster consists of 5 sampling locations: a center point and a sampling location to the north, south, east and west; offsets to accommodate historical flow directions were included, so, for example, the "north" sample was located using a constant azimuth for each PSU. The north and south distances are complimentary, with a total distance of 36 m; that is, the north distance from the center point was a random number between 3 and 36 m, and the south distance was the 36 m minus that distance. A similar arrangement was developed for the east-west distances. This particular sampling regime effectively populates the data set for getostatistical analysis. Specifically, each 30-m lag spacing in directions parallel and orthogonal to flow contain 30 or more pairs, allowing comparatively robust estimation of semi-variance and autocorrelation.

Sampling in PSU001 (in WCA1) required a modification of this design to accommodate the low-cohesion sediments in that region that made long distance walking impossible. For that system, the sampling was done using the airboat and short distances (<10 m). To ensure the same distribution of observations for geostatistical analysis, the clusters were modified to consist of 1 center point and 1 point a random distance and direction from that point. In that case, 90 sample clusters were sampled for a total of 180 water depth observations.

At each point, we measured water depth using a meter stick attached to a 10 cm plastic foot to ensure repeatable contact with the peat surface. We assigned each point to a vegetation class based on the presence of sawgrass (ridge), dominance by floating leaved and submerged species (slough), emergent species other than sawgrass (wet prairie), and presence of woody species (tree island). We also recorded each species present within a 1 m radius of the depth measurement, and assigned each species a cover class of 1 (0-5%), 2 (5-25%), 3 (25-50%), 4 (50-75%), 5 (75-95%) and 6 (95-100%) based on visual estimates of canopy cover.

Peat Elevation Distributions

We used water depth measurements and vegetation class at all points within a PSU to describe microtopo-graphic patterns in each PSU and their relation to vegetation.

We obtained historic water level estimates at each point spanning 2000-present from the Everglades Depth Estimation Network. We used EDEN water elevation data from the date of sampling to convert each water depth measurement to an estimate of soil elevation.

We used this elevation to calculate the mean and standard deviation of water depth at each site, and to calculate the average hydroperiod (# days where water elevation exceeds peat surface elevation per year) over the period of record.

For each PSU, we calculated the mean, standard deviation, skewness, and kurtosis of peat elevations for all points within the PSU. Kurtosis, the fourth moment of a distribution, measures the density of observations in the shoulders of a distribution vis a vis the peak and tails, and as such provides a reliable metric of bimodality. We calculated the median water depth for the whole PSU as the difference between the median soil elevation (in space) and the median water level (over time). For each vegetation class within each PSU, we also calculated mean, standard deviation and skewness of the distribution of peat elevations, mean water depth, and the mean and standard deviation of hydroperiod. These data thus describe the variability in soil elevations and hydrologic conditions in space within each PSU and within vegetation classes within each PSU.

Spatial Structure

The geostatistical analysis of the elevation data consisted of 6 analytical elements:

1. Semi-variance parameters (sill, nugget)
2. Semi-variogram range (in meters)
3. Spatial structure ((sill-nugget)/sill)
4. Semi-variogram model fit (as measured using r^2)
5. Anistropy factor (computed based on the estimated range parallel vs. orthogonal to the historical flow direction)
6. Autocorrelations (for 30-m lags both parallel and orthogonal to flow).

These variables collectively permit the testing of three primary questions. First, is there evidence of local positive feedbacks? This can be explored using the spatial structure, the short-lag spacing autocorrelation, the goodness-of-fit for the fitted semi-variogram, and the magnitude of the nugget variance. Second, is there evidence of distal negative feedbacks? The principal indicator is the presence of significant negative autocorrelation at some lag separation distance. Third, what is the apparent geometry of the distal negative feedback? Inference of this is based on the range, the measure of anisotropy, and the distance at which any significant negative autocorrelation is observed.

Pattern Metrics

Vegetation maps can be used to compute spatial pattern attributes of the landscape. Previously, Wu et al. (2006) proposed several metrics for the inference of landscape health. These are:

- *Lacunarity* – this metric measures the extent of clumping within patches. High values indicate areas where the variance within a moving window (2 x 2 pixels) is high. They showed that the best conserved ridge-slough landscapes occur at intermediate values of lacunarity.
- *Straight flow* – one of the hallmark features of the ridge-slough is the linearity of the patches. The mean length of straight lines parallel and orthogonal to flow was used to measure the average length of straight flow (ALS) and average length of gaps (AWS), both in m. Wu et al. (2006) indicate that healthy ridge slough landscapes have intermediate values of both indices.
- *Fraction Ridge* – the proportional contribution of ridges within the sample area was judged to be a valuable indicator, though they lump ridges and tree islands together.
- *Length to width ratio* – this measures the linearity of the landscape by relating the length (parallel to flow) to the width (orthogonal to flow) of the ridge (and tree island) patches.

We have not yet completed the implementation of pattern metrics proposed by Wu et al. (2006), but have begun development of two new metrics that we believe will provide useful complementarity to those metrics (Fig. 11). They are:

- *Cross sectional area* – the Everglades is a flowing water wetland, and as such is intrinsically constrained by the requirement of water routing. We have argued previously (Cohen et al. in review) that the demand creates the necessary anistropic feedbacks to create the flow-oriented pattern. This metric, which quantifies the cross-sectional area along 20 transects (Fig. 11) orthogonal to the historical flow direction, allows us to test the hypothesis that the cross-sectional area is longitudinally constant where the ridge slough landscape is conserved. The mean water depths for each community type (ridge, slough, tree island) will eventually be used for this effort. The prediction that the cross-section will remain constant follows from our contention that, where the landscape is conserved, the main driver of patch expansion is the need to route water. As such, where tree islands are important parts of the cross-section, reduced ridge area is required to maintain the same discharge capacity.
- *Londitudinal fractional area* – much like the Wu et al. (2006) fraction ridge metric, this considers the relative abundance of each patch type on transects orthogonal to historical

flow. We predicted that slough area would be relatively constant, and that the area of tree islands and ridges (both of which inhibit discharge by being shallower) would trade-off. Moreover, the fractional contribution of sloughs should be a function of PSU-scale hydrologic conditions (mean water depth, water depth variance), as observed in Watts et al. (in review).

- *Minimum cost flows* – one of the features of the best conserved landscape is the continuity of sloughs along a particular flow path. That is, water can reside principally in sloughs during passage from north to south. This can be measured by estimating the lowest cost pathway from north to south along the historical flow line; the compute flow costs, we assign a value of 1 to sloughs (low cost), a value of 5 to ridges (since they have a specific discharge competence of roughly 20% of sloughs – Harvey et al. 2009), and a value of 45 to tree islands, indicating the high cost of water flow when a tree island presents an impediment. Two attributes can be extracted for each PSU. The first the ratio of flow costs vs. the minimum possible flow costs (i.e., where flow occurs entirely in sloughs). The relative costs should be low in conserved areas, and increasingly high with hydrologic drying or stabilization. The condition in impounded areas should be uniformly low travel cost. A second measure is the degree of lateral variability in travel costs. Our conceptual model of ridge-slough formation suggests that the patches of ridges and tree islands self-organize into elongated shapes because of the negative feedbacks that ensue due to impounding effects when ridges expand laterally. As such, we hypothesize that any given flow path from north to south should have approximately equal cost to avert flow short-circuiting (i.e., uniform flow).

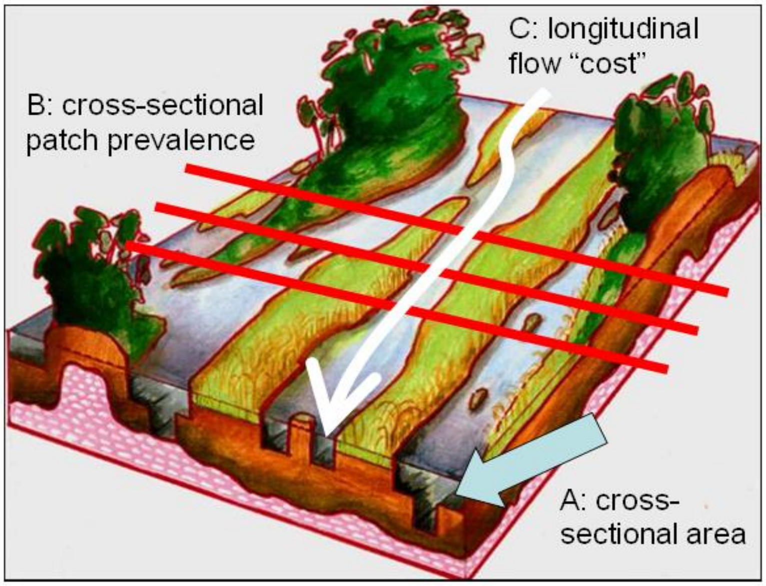


Fig. 11 – Summary of new proposed hydrologic-process metrics to be computed from landscape vegetation maps.

<u>Results</u>

Consistent with previous findings (and with the mapping from aerial photography; Figure 3, Table 5), we observed nearly even abundance of ridge and slough in PSU 4 in central WCA 3A

(Table 6). Peat elevations in this landscape block were also distinctly bi-modal (Fig.12), indicating that positive feedbacks between vegetation, peat accretion, and local hydrology continue to maintain distinct ridge and slough attractors. Mean differences in elevation between

	PSU 1 (WCA1)	PSU 3 (WCA 3A-N)	PSU 4 (WCA 3A-S)	PSU 9 (WCA 2A)
Whole Landscape (# obs.)	164	80	215	200
†Mean Soil Elevation (cm)	439.8	283.7	220.0	331.5
Standard Deviation	6.4	4.0	12.8	4.3
Soil Elevation Skewness	-0.59	-0.68	0.16	0.36
Soil Elevation Kurtosis	1.48	0.57	-1.01	0.94
†Mean Water Depth (*SD*; cm)	16.6	12.9	37.9	21.5
Standard Deviation	6.4	3.4	12.1	4.0
*Water Level Variance (cm)	14.6	27.5	24.5	27.5
‡Hydroperiod (days yr-1)	310.1	260.3	339.8	301.0
Standard Deviation	32.3	22.9	29.1	19.8
Ridge (% of landscape)	***48.2%***	***100.0%***	***44.2%***	***92.0%***
†Mean Soil Elevation (*SD*; cm)	441.9	283.7	228.8	331.7
Standard Deviation	4.2	4.0	7.6	4.2
Soil Elevation Skewness	0.17	-0.68	0.55	0.46
†Mean Water Depth (*SD*; cm)	**<u>14.3</u>**	12.9	29.4	21.2
Standard Deviation	4.4	3.4	7.2	4.1
‡Hydroperiod (days yr-1)	303.0	260.3	322.1	299.6
Standard Deviation	20.6	22.9	27.3	19.2
Tree Islands (%)	***11.0%***	***0.0%***	***0.9%***	***0.0%***
†Mean Soil Elevation (*SD*; cm)	449.2	N/A	240.1	N/A
Standard Deviation	6.4	N/A	11.2	N/A
Soil Elevation Skewness	-1.3	N/A	.	N/A
†Mean Water Depth (*SD*; cm)	7.5	N/A	17.0	N/A
Standard Deviation	6.6	N/A	8.1	N/A
‡Hydroperiod (days yr-1)	261.0	N/A	257.5	N/A
Standard Deviation	54.0	N/A	47.8	N/A
Slough (%)	***40.2%***	***0.0%***	***47.4%***	***8.0%***
†Mean Soil Elevation (*SD*; cm)	434.9	N/A	210.6	329.2
Standard Deviation	3.7	N/A	10.5	4.1
Soil Elevation Skewness	0.3	N/A	-0.7	-0.5
†Mean Water Depth (*SD*; cm)	21.7	N/A	47.0	24.2
Standard Deviation	3.5	N/A	9.5	2.6
‡Hydroperiod (days yr-1)	331.8	N/A	358.4	318.0
Standard Deviation	11.3	N/A	15.3	19.0
Wet Prairie (%)	***0.6%***	***0.0%***	***7.4%***	***0.0%***
†Mean Soil Elevation (*SD*; cm)	429.0	N/A	225.5	N/A
Standard Deviation	N/A	N/A	7.3	N/A
Soil Elevation Skewness	N/A	N/A	0.5	N/A
†Mean Water Depth (*SD*; cm)	23.8	N/A	33.2	N/A
Standard Deviation	N/A	N/A	6.7	N/A
‡Hydroperiod (days yr-1)	324.9	N/A	336.9	N/A
Standard Deviation	N/A	N/A	21.5	N/A

Table 6. Statistical features of peat elevation (reported as measured water depths) in 4 PSUs sampled summer 2009. Patch type abundances are based on field designations. [†]Standard deviations in soil elevation and water depth refer variability among points in space. [*]Standard deviation of water level in each PSU describes the magnitude of hydrologic variability over time. [‡]Hydroperiod is the mean frequency of inundation over the period of record (2000-2009); standard deviation of hydroperiod refers to spatial variation in the mean POR hydroperiod.

ridges and sloughs were 18 cm, somewhat less than in our previous study (Watts et al *in review*); we estimated the mean ridge and slough hydroperiods as 322 and 358 days, respectively.

Also consistent with previous findings, we observed moderate to severe loss of sloughs and increasing abundance of ridges in the dryer PSUs (1,3,9), which also exhibited unimodal peat elevations (Figure 12). Elevation differences between ridge and slough vegetation classes were much lower, hydroperiods more similar, than was observed in PSU 4. Tree islands were sampled infrequently in all PSUs except PSU 1 in WCA 1, where we estimated that tree islands occupy ca. 11% of the landscape. Similarly, wet prairie assemblages were rare in all PSUs except PSU 4. In the PSUs where these patch types were of sufficient abundance, we estimated their hydroperiods as 261 and 334 days.

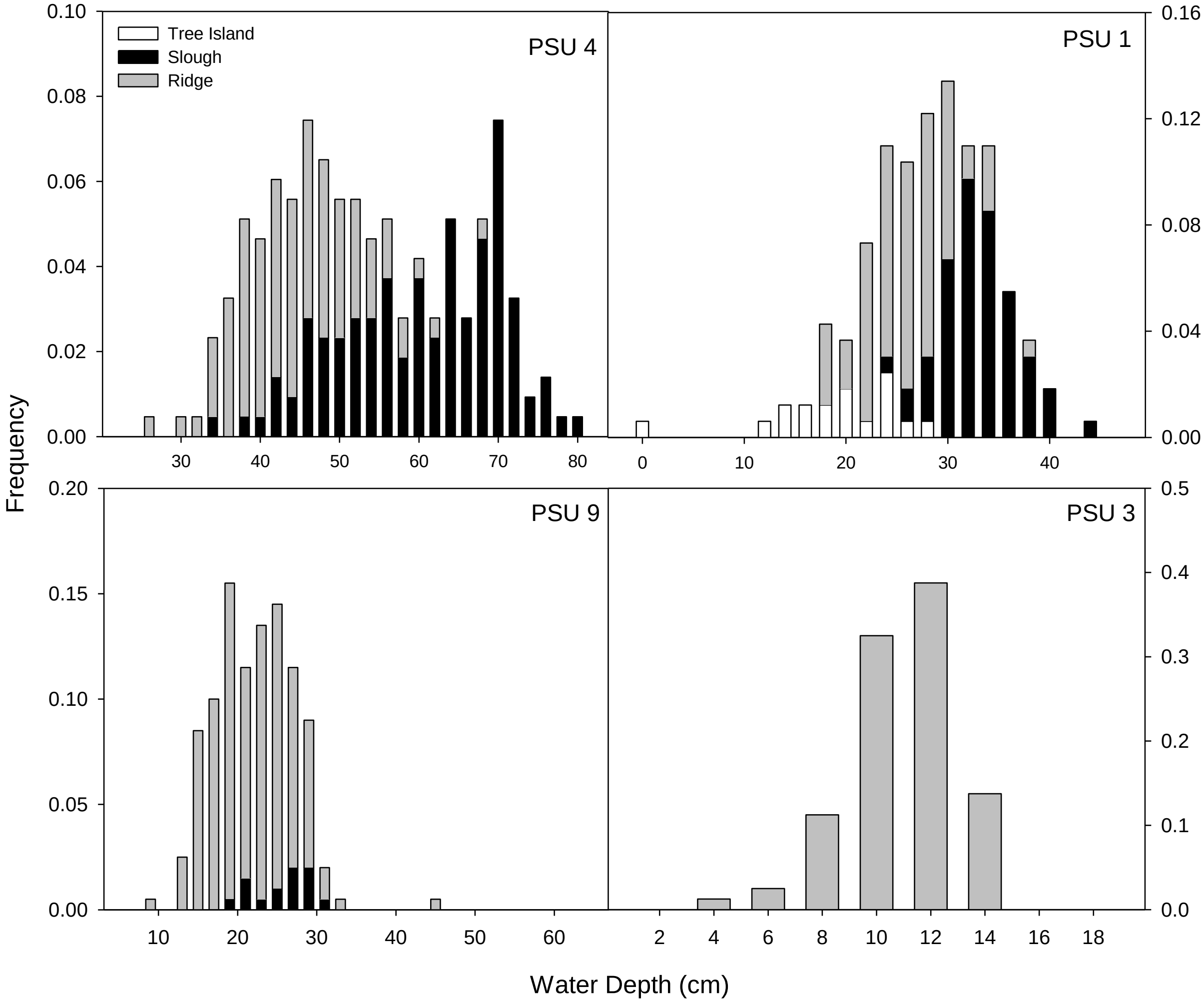


Figure 12. Distribution of peat elevations by patch type within 4 PSUs. Bars are stacked so that frequency at each water depth is the sum of observations within each patch type.

Pattern Metrics

The Wu et al. (2006) metrics of landscape condition have yet to quantified, though the techniques for their implementation in Idrisi (Clark Labs) have been explored. We have, instead focused on implementation of new pattern metrics that focus more on the underlying hydrologic mechanisms of formation. These are summarized in Figures 13 (cross-sectional area), 14 (cross-sectional patch prevalence), and 15 (minimum flow cost). Data have been analyzed for only 1 PSU to date (PSU004, a generally well conserved area in central WCA3AS). As shown, the cross sectional area of the water flow is very close to a constant despite a comparatively complex patch geometry and clear latitudinal gradients in ridge area and tree island area (the former low in the south, the latter more abundant in the south). Areas where there are lower cross sectional areas could, in principle, be areas for which vegetation change is ongoing, though the small variance between transects suggests that this effect may be very subtle.

The cross-sectional patch prevalence (Fig. 13) enumerates the observation that ridges and tree islands appear to be complements on the landscape, with strong negative association between them, and comparatively constant proportion of sloughs (around 50% of the landscape). Note that the ridge proportion metric proposed by Wu et al. (2006) can be inferred from this figure; ridges (which for that metric includes tree islands) occupy roughly 50% of the area for the entire PSU. Future work exploring these values for other PSUs will help determine the relative importance of the different metrics for early detection of landscape pattern loss.

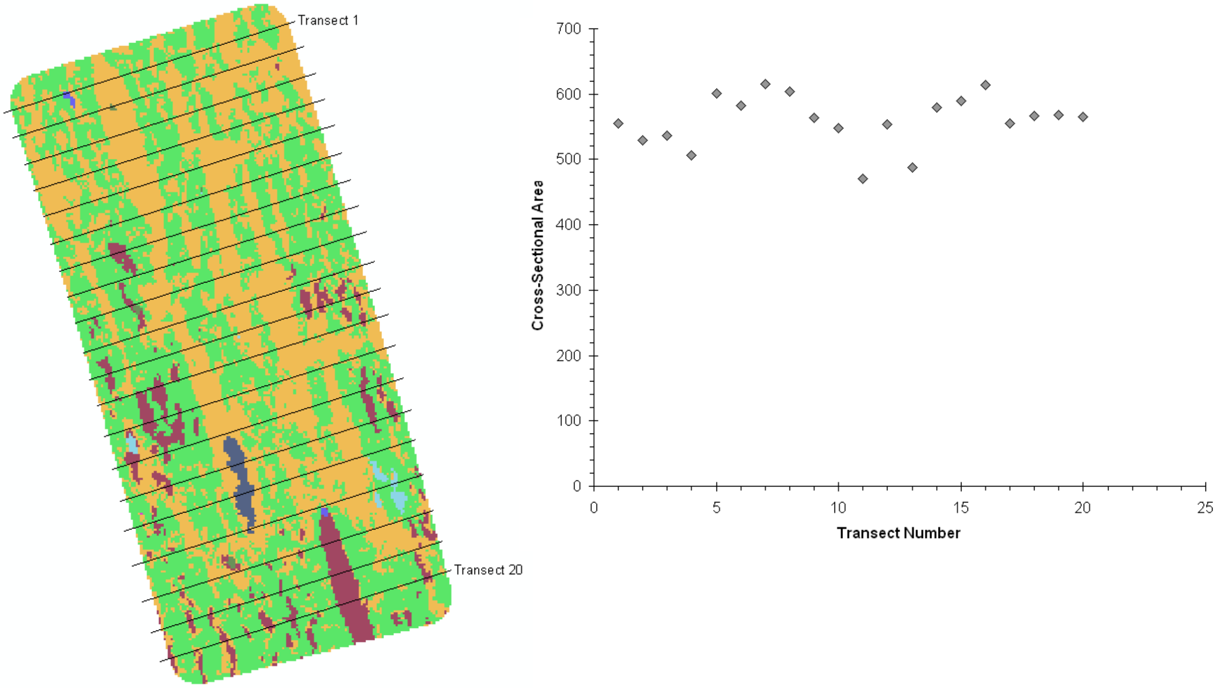


Fig. 13 – Cross-sections and area estimates for PSU-004 (conserved region). Transects are shown overlying a rasterized vegetation map (at left; green indicates slough, blue indicates wet prairies, gold indicates ridge, and maroon indicates tree islands of various types). The resulting longitudinal distribution of cross-sectional areas is shown at right (units of m^2).

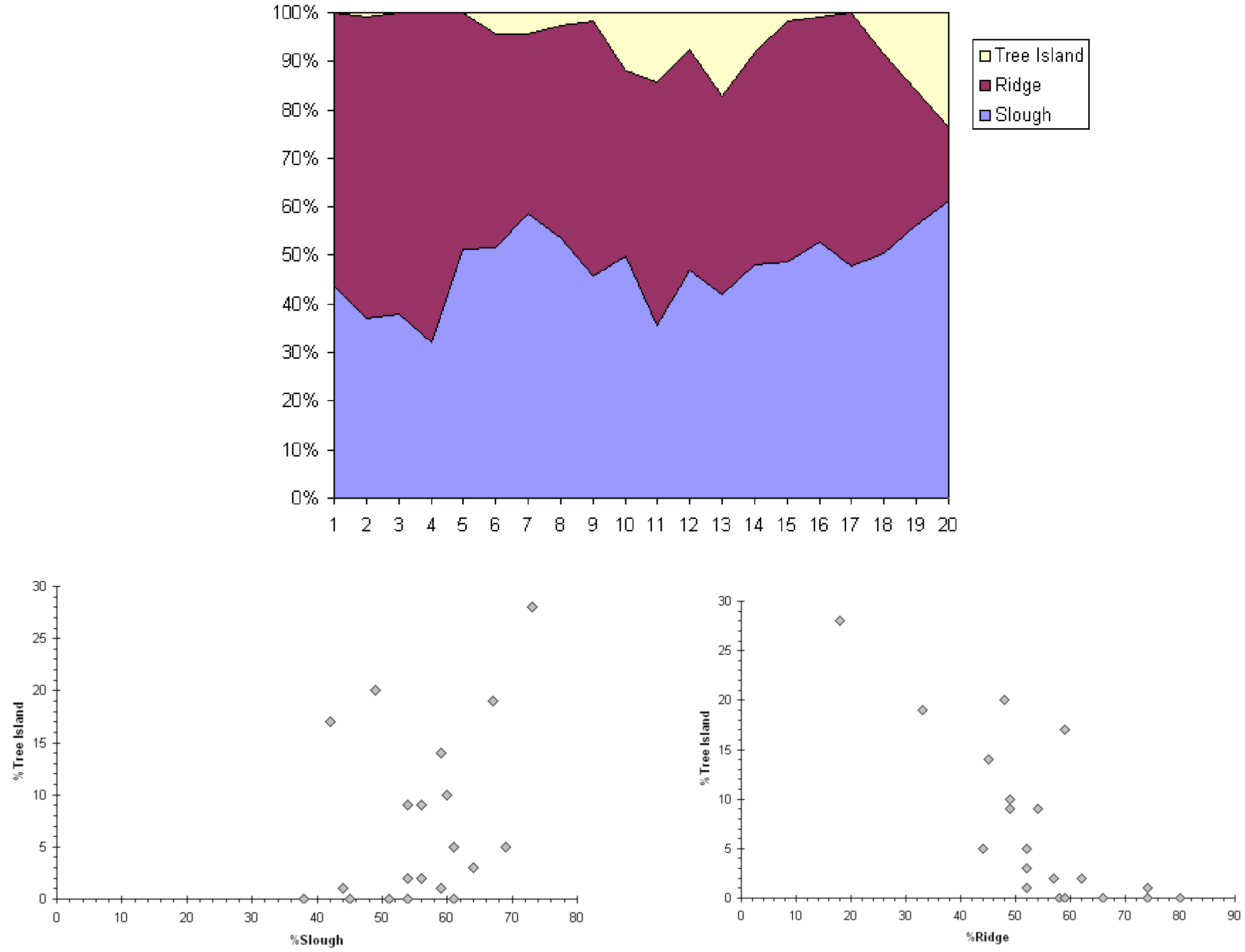
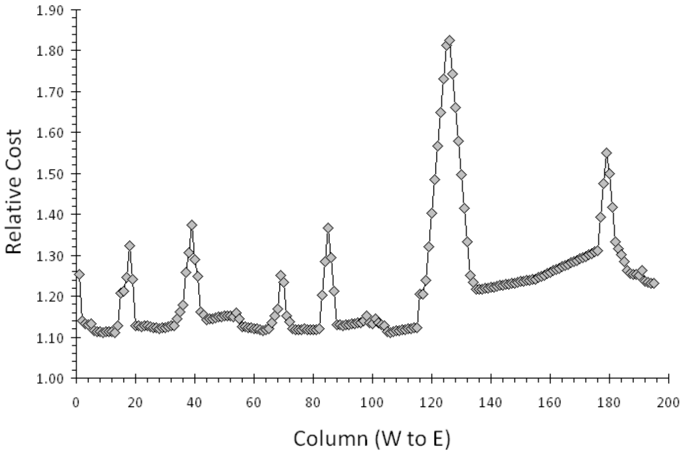


Fig. 14 – Cross-sectional patch distributions for PSU-004 (conserved region). Transects are shown overlying a rasterized vegetation map in Fig. 2. The patch prevalence (above) and the correlation of patch prevalence between sloughs, ridges and tree-islands (below) both indicate a marked trade-off in prevalence between ridges and tree islands.

The final patch geometry figure describes the travel cost from the upper-most row in the rasterized vegetation map to the lower-most row. As discussed, different patch types have different frictions. This metric essentially computes the connectivity of the landscape as determined by the relative cost vis-à-vis passage from north to south in a straight line in sloughs only. As shown, the landscape flow costs are generally quite low (with the exception of the locations where tree-islands are present at the lowest row). They also appear to increase from left to right, consistent with the qualitative observation from the vegetation map that the ridges on east side of the PSU create isolated sloughs and inhibit connectivity. There are a number of flow velocity predictions that follow from these lateral differences; specifically that flow velocities should be higher where connectivity is improved. We presume this because it is reasonable to presume that water will follow the lowest friction path through the marsh. However, the magnitude of the flow inhibition effect is unknown, and therefore the ability to detect those flow variations is also unknown.

- Assigned friction
  - Slough – 1
  - Ridge – 5
  - TI – 25
- Values along bottom row are longitudinal flow costs
  - Relative to 305 rows (so value of 1 is passage in only sloughs)



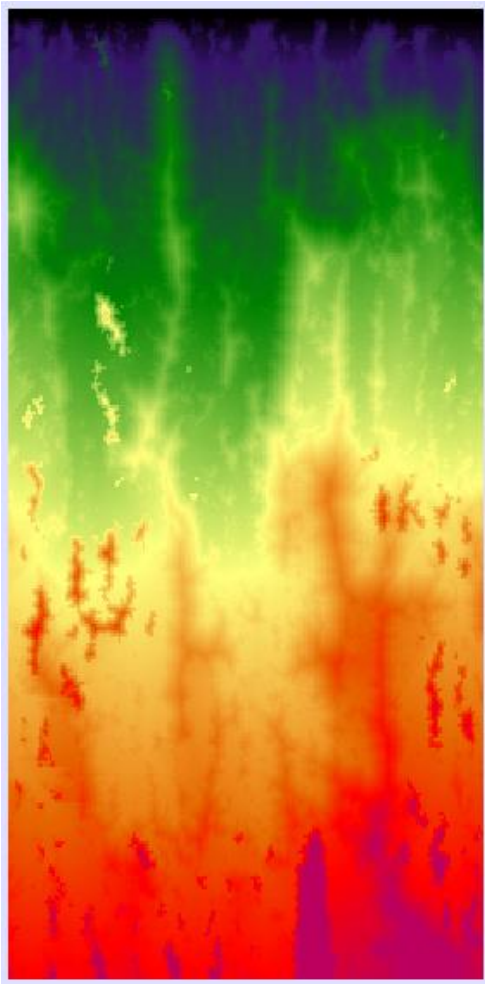


Fig. 15 – Longitudinal travel cost figure for PSU-004, and lateral variance in travel costs in the lowest row. Note that the vegetation map was rotated so that the original flow direction (NNE) was due North. The assigned flow frictions are shown. Note that the lateral costs (plot in lower left) are scaled to the minimum flow value (305 rows). Values are higher in the vicinity of tree islands, and towards the right side of the sampling unit where ridges in the northeastern quadrant confine continuous flow. Overall, the values are comparatively low (relative costs between 1.10 and 1.30, excluding the friction effects of tree islands.

Geostatistical Metrics

The geostatistical properties of the peat surface have been proposed as disgnostic measures or landform change. We present 4 primary metrics here (1 – goodness of fit statistics that give a sense of the strength of spatial structuring, 2 – measure of anisotropy in the semi-variogram, 3 – the relativized nugget variance, which indicates the magnitude of short range variability). We plot these with the kurtosis values for the entire distribution, negative values of which indicate biomodality. Notably, the only PSU that was bi-modal (PSU004) also had the highest goodness of fit, was the only site that exhibited evidence of spatial anisotropy, and exhibited low relative nugget variance.

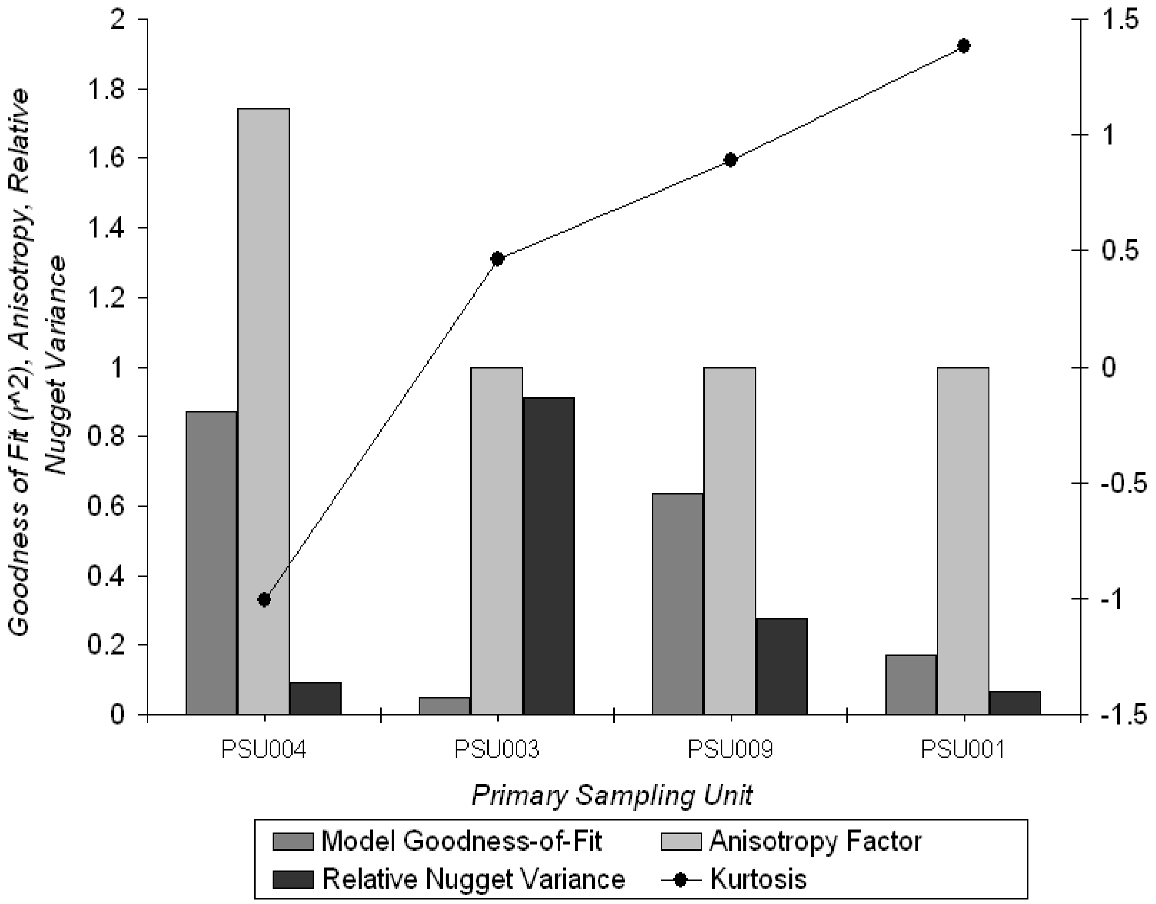


Fig. 16 – Summary of geostatistical properties of peat elevation for the 4 primary sampling units sampled during year 1. Kurtosis (a measure of bi-modality) indicates that only PSU004 (in central WCA3AS) was bi-modal. PSU003 is in the dessicated areas of WCA3AN, PSU009 is in the P enriched areas of WCA2A, and PSU001 is in northern WCA1.

In addition to the geostatistical metrics, we evaluated evidence for scale dependent feedbacks (local positive, distal negative) based on patterns of spatial autocorrelation. As shown (Fig. 17), the presence of strong short-range positive autocorrelation was observed in PSU004 (WCA3AS) and PSU009 (WCA2A), while short range autocorrelation was absent in the other two PSUs. Moreover, only PSU004, which is the site we assert to be the best conserved, exhibits a negative autocorrelation at distance (indeed two: at 90 m and 170 m), and only in the direction orthogonal to flow. In short, it appears that the patterns of autocorrelation are particularly illustrative of the presence and absence of the self-organizing feedbacks, and these are consistent with measures of kurtosis as well.

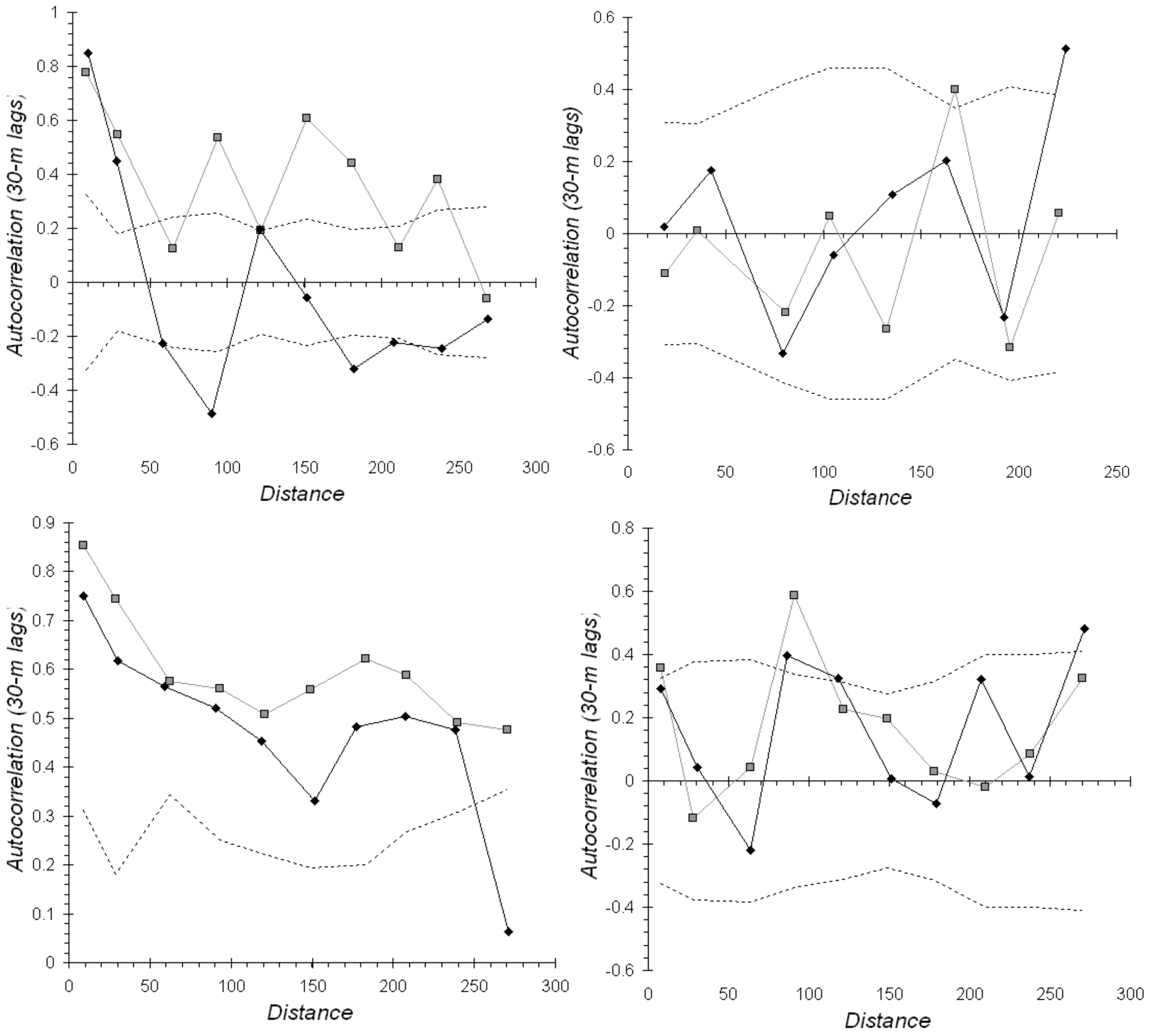


Fig. 17 – Summary of autocorrelation for each PSU (PSU004 – upper left; PSU003 – upper right; PSU009 – lower left; PSU001 – lower right). Shown are autocorrelations orthogonal (black diamonds) and parallel (grey squares) to flow. Dashed lines indicate autocorrelation levels that are significantly greater (or less) than 0 at 95% confidence.

Tree island ground sampling

C. Tree island gradients

i) Sampling sites

Tree islands are of different types, such as hardwood hammock, bayhead, bayhead swamp, willow head, cypress dome, and exotics-dominated island. The islands (>25 m^2) within the PSUs examined in 2009 (PSU-00 and PSU-02) were first digitized and classified using aerial photos, and the classification was then verified in the field by inspecting them from the helicopter. The number of tree islands belonging to different types varied among PSUs, and not all PSUs, studied this year had all types of islands. With an objective of studying vegetation along environmental gradients within tree islands, extending into the adjacent marsh, our intent was to randomly select one island (>400 m^2) in each of the three most common island types in each intensive PSU. However, due to the time constraints in FY 2009, we sampled only three tree islands, two in PSU-00 and one in PSU-02 (Figure 18). The two islands surveyed in PSU-00 were Hardwood Hammock and Bayhead, and the island in PSU-02 was a Willowhead. In PSU-00, we were not able to sample an island of a third category present in the area, Willowhead, primarily because the target island was accessible only by helicopter, and we were constrained by time in obtaining the necessary permits. In contrast, in PSU-02, we did not find islands other than Willowheads that reached the minimize size criteria (>400 m^2) for studying vegetation gradient.

ii) Field Sampling

Vegetation sampling

Once the islands were selected for sampling, the azimuth of the longest axis and the orientation of transect to be laid in the field were determined from the aerial photos. In the field, tree island vegetation was sampled within nested belt-transects that were established perpendicular to island's longest axis and from the apparent highest point to approximately 8-10 m beyond the edge of the visible forest-marsh interface. In the three islands studied this year, transect length ranged from 20 to 108 meters. The hardwood hammock in PSU-00 had the longest transect, while transects were 20 m and 45 m in Bayhead (PSU-00) and Willowhead (PSU-02), respectively. In those islands, the method used to sample trees (>= 5 cm dbh) was consistent, whereas the saplings (dbh >1 and <5 cm)) were sampled differently. Trees of 5-10 cm dbh class were sampled within 1 m of the line, trees of 10-25 cm dbh within 2 m of the line, and trees >25 cm dbh within 5 of the line. For each tree, we recorded species, position to the nearest 0.1 meter along the transect line, and its diameter in 5-cm dbh classes. On the hardwood hammock transect, all saplings within 1 meter of the transect line were sampled, while on other two tree islands saplings were sampled within 1-m radius plots, as described below.

Understory vegetation was sampled in a series of 1-m radius circular plots along the belt transect. However, depending on the length of transect, the number of plots and distance between adjacent plots varied among islands. The plots were arrayed at 2 m, 3 m and 6 m intervals for transects <=30 m, 30 to 60 m, and >60, respectively. In each plot, we estimated cover class of each species of ground layer vegetation (non-woody vascular plants and woody individuals of <= 1 m height), and recorded the number of stems of each species in the shrub layer (>1 m height and < 1 cm diameter). In two of the three islands, we also recorded the number of saplings in understory vegetation plots. In addition, we recorded density of seedlings (<=1 m tall) of each tree species in 3 height categories: <30 cm, 30-60 cm, and 60-100 cm, in 0.57 m radius plot centered on the midpoint of the understory vegetation plots.

Canopy openness was measured using densiometer readings (Englund et al. 2000) in understory vegetation plots. In each plot, two measurements, one each in two cardinal directions, north and south, were taken. Hemispherical photo were not taken on these islands.

Soil depth, ground elevation and hydrology

In each understory vegetation plot, we measured soil depths at 1-3 random locations, and recorded relative ground elevation in relation to existing water table. In plots where water level was above the ground surface, we measured water depths at three random points. In plots where water table was at or below the ground level, relative elevations were surveyed using an auto level, from the most interior plot (the first plot on the transect) to the first plot with standing water. We then calculated the ground elevation of each plot based on the relative elevation and the water surface elevation. Since nearest stage recorder was located at >1 mile distance from the tree islands, we used the EDEN (Everglades Depth Estimation Network) estimate of stage elevation as a measure of water surface elevation at the marsh point, i.e. at the end of the belt transect, for the date of sampling. For an island in the PSU-002, however, EDEN data were not yet available for the date of sampling (09/03/2009), and we substituted the EDEN estimate of stage elevation for 09/02/09, one day prior to sampling.

Combining the elevation of ground vegetation plots and the EDEN daily estimates of stage elevation for the respective locations, we calculated hydroperiod, annual mean water depth, and mean 30-day maximum water depth for each water year (May 1 to April 30), and the frequency and mean duration of flooding and dry downs over 9 years between Jan 1, 2000 and April 30, 2009.

Soil & plant tissue nutrients

A soil core of known dimensions (usually 2.35 cm inside diameter) is collected from 3 locations to a 10 cm depth at the center of each vegetation-habitat zones. The three cores are composited to result in 1 sample 0-10 cm surface soil from each zone present. Zones are tree island heads (H), bayheads (B), or marsh (M). Cores are transported on ice to the Soil/Sediment Biogeochemistry Laboratory (SBL) at FIU. Soils are analyzed for total fresh weight, bulk density (BD), pH, EC, total C, N, P, and organic C by standard methods. Newly matured leaves from co-dominant species in each island are also be collected, and analyzed for total C, N, and P.

Soil samples will be weighted for total wet and dry weights (after drying at 80º C until constant weight as a modification of the 105° C mineral soil methods of Topp and Ferre, 2002) to determine bulk density and percent moisture. Subsamples are combusted in a muffle furnace at 550º C for 3 h to obtain ash content and organic matter by loss on ignition (LOI; Nelson and Sommers, 1996). A known mass of fresh soil (field condition) is mixed with distilled, deionized water in a 1:1 sediment to solution ratio (w/w), allowed to stand for 10 minutes and then measured for pH (Thomas, 1996) after which they are capped shaken for 1 h and measured for

EC with standard electrodes (Rhoades 1996). The dried subsample is then analyzed for TP, TC, and TN. A portion of the ashed material will be analyzed for TC yielding Total inorganic C (TC - TIC = TOC by difference). Leaf tissues will undergo similar analysis for TP, TC, and TN.

Colorimetric analysis is conducted on a Technicon Autoanalyzer II System (Pulse Instruments Ltd.). Total phosphorus in sediments will be determined using the ashing/acid hydrolysis method of Solorzano and Sharp (1980) with the resulting soluble reactive phosphorus (SRP) being colorimetrically determined on the Technicon (USEPA-365.1). Sediment and leaf tissue Total C and N are analyzed using a Perkin Elmer Series II 2400 CHNS/O Analyzer (Nelson and Sommers, 1996).

To date, eight soil samples have been submitted from three tree islands (some tree islands do not contain all zones). Samples were collected in late August and early September 2009 and are undergoing processing and analysis but data is not ready for presentation at this time.

iii) Vegetation analysis

Species abundance data gathered on transects in each tree island were summarized separately for ground vegetation and tree layers. For ground vegetation, species abundance was the percent cover in each plot, and for the tree layer, it was the importance value (IV) of each species, calculated as: (relative density + relative basal area)/2. Since trees were sampled within the belt transect, the species abundance of trees were summarized for 2, 3, 6-m segments of the belt, depending on the length of transects and the interval between understory vegetation plots.

We used a split moving-window (SMW) boundary analysis (Ludwig and Cornelius 1987; Cornelius and Reynolds 1991) to describe variation in vegetation composition and to identify boundary or discontinuities between vegetation units along the gradient present in the tree islands and from the tree island to the adjacent marsh. The method, first developed to detect spatial variability in soil characteristics (Webster 1978), has been widely used to delineate boundaries and describe community composition along environmental gradients (Cornelius et al. 1991; Hennenberg et al. 2005; Munoz-Reinoso and Garcıa Novo 2005; Munoz-Reinoso 2009). The method is useful in achieving our monitoring objectives, which were (1) to delineate discrete vegetation units arranged along gradients outward from the center of the tree island, and (2) to identify the underlying environmental drivers that determine the vegetation pattern at the landscape level. In the SMW method, the position of boundaries, defined as the location of maximum variance in species-abundance based dissimilarities between adjacent groups of sampling plots, was identified through the following steps: i) A window of even-numbered size (the number of plots) was introduced at the beginning of the transect, (ii) The window was then divided into two half-windows, iii) Species abundance-based Bray-Curtis dissimilarity was calculated between two half-windows, iv) The window was then moved by one plot, repeating steps 2 and 3 until the end of the transect was reached, and v) finally, dissimilarity profile diagrams were created by plotting dissimilarity against location of the window mid-point along the transect. In the dissimilarity profile diagram, the sharp peaks in dissimilarity were identified as boundaries between adjacent communities. Results of SMW analysis are scale dependent, and are affected by the choice of window size. Use of a small window size often creates noise, resulting in many peaks, while a wide window may result in fewer peaks, overshadowing the fine scale variation. First we explored the pattern using windows of different sizes (2, 4, 6 and 8), and then selected a window of appropriate size that resulted in boundaries which appeared to be ecologically meaningful.

The delineation of the boundary between vegetation units along gradients was based primarily on ground vegetation rather than tree composition. Due to the paucity of individuals in the tree layer on two of the three islands, use of the split moving-window approach on the tree layer data was not feasible there. However, the method was tested on tree data gathered on one island in PSU-00. In the tree layer, variation in species abundance along the environmental gradient was analyzed by simply plotting the abundance of species groups. Tree species present on the islands were grouped into three categories (flood intolerant, intermediate tolerant and flood tolerant), depending on their hydrologic optima and tolerance to flooding identified by researchers (Sah 2004; Jones et al. 2006; Stoffella et al.-unpublished).

Once the different vegetation units were identified via the SMW technique, the relationships among hydrologic regimes, soil characteristics and vegetation communities across the islands were examined at the landscape level, using vegetation units as discrete entities. To explore the relationship between vegetation units and measured environmental variables, we standardized cover data to the species maxima, and used non-metric multidimensional scaling (NMDS) ordination and vector-fitting procedure, as incorporated in the computer program DECODA (Kantvilas and Minchin 1989). Vector fitting is a form of multiple linear regression that finds the direction along which sample coordinates have maximum correlation with the fitted variable within the ordination space. The significance of the vectors was assessed using a Monte-Carlo procedure with 10,000 random permutations of the species data.

3. Results

C. Tree island gradient sampling

Detection of vegetation boundaries

Vegetation composition in both tree and understory layers varied along the transect, and hence along environmental gradient(s), in all three islands. The dissimilarity profiles from SMW boundary analysis from a small window size of 2 plots were noisy, whereas the dissimilarity profiles for window size 4 (or higher) were less noisy, and revealed peaks that represented vegetation boundaries. Island size, which determined the range of hydrologic gradient on the islands studied, also influenced both the tree layer and understory vegetation. Tree layer vegetation was very sparse in two of three islands, and was represented by only 1-3 species. In the large hardwood hammock island in PSU-00, tree species were clearly arranged along a gradient defined primarily by hydrologic condition. SMW analysis of tree (>5 cm dbh) and saplings (1-5 cm dbh) data from this island revealed the presence of two boundaries, separating three vegetation units that differed substantially from each other in vegetation composition, and measured in environmental characteristics, including ground elevation, mean annual water depth, and soil depth. Along the gradient from interior towards island-marsh interface, species were arranged according to their tolerance to water depth (Figure 19). At the highest ground, where the mean annual water table ranged between 66 and 79 cm below the surface, the tree layer vegetation was dominated by gumbo limbo (*Bursera simaruba*), white stopper (*Eugenia axillaris*) and jamaican nettletree (*Trema micrantha*). At middle elevation, coco plum

(*Chrysobalanus icaco*) and red bay (*Persea borbonia*) were dominant. Water tolerant species, such as pond apple (*Annona glabra*), wax myrtle (*Morella cerifera*), willow (*Salix caroliniana*), and Dahoon holly (*Ilex cassine*) were dominant in the peripheral region of tree island where the ground remained flooded for the majority (7 to 9 months) of the year.

The dissimilarity profile of the large island based on understory vegetation also suggested high variability in species composition along the gradient. Particularly in the hammock portion of the island, understory vegetation was very patchy and species turnover in this section of the transect was very high, as evidenced by the presence of high B-C dissimilarity (> 0.8) between each subsequent pair of half windows (Figure 20). Within the hammock, understory vegetation was composed of tree seedlings (*Eugine axillaris, Trema micrantha*), grasses (*Dicanthelium commutatum*), semi-woody forbs (*Verbesina virginica*), ferns (*Blechnum serrulatum)* and non-native species (*Lantana camara*, *Schinus terebinthifolius*). In the bayhead portion of the tree island, species composition was more uniform, primarily dominated by the ferns *Acrosticum danaefolium*, *Blechnum serrulatum*, and *Thelypteris interrupta*. However, the presence of a prominent peak at about 70 m from the interior suggests a change in environmental drivers that affect understory vegetation. Towards exterior portion of the island, where the canopy was relatively open, ferns became mixed with sawgrass (*Cladium jamaincense*), which was dominant in the adjacent marsh.

In very small islands such as the PSU-00 Bayhead, where the range of hydrologic conditions was narrowest, understory vegetation was uniform, and a well-defined vegetation boundary was found mainly between woody shrubland present at the higher ground and herbaceous marsh vegetation. With the transect extending only for 20 m, the dissimilarity profile showed the presence of such a forest-marsh boundary only at a window size of 2, (Figure 21). Understory vegetation within the island was dominated by tree seedlings (*Chrysobalanus icaco*, *Morella cerifera*, *Persea borbonia*) and fern (*Blechnum serrulatum*). In the Willowhead, where estimates of understory vegetation abundance included the cover of non-woody species, shrubs and saplings, the vegetation composition was much more heterogeneous. SMW analysis revealed the presence of three boundaries separating four communities (Figure 22). The highest dissimilarity at meter 4.5 and 40.5 suggested that half-window (2 plots) at both the ends of the transect were very different from neighboring half-window in species composition. In the interior part of island, where the ground was relatively high, the vegetation was dominated by coco plum (*Chrysobalanus icaco*) and the middle portion was dominated by willow (*Salix caroliniana*) and ferns (esp. *Thelypteris interrpta*). The exterior part of the island was dominated by cattail (*Typha domingensis*), buttonbush (*Cephalanthus occidentalis*) and sawgrass (*Cladium jamaicense*). In the outermost two plots, where the standing water was the deepest, the vegetation was dominated by *Nymphaea odorata* and *Utricularia* sp.

Vegetation: environment relationships

Understory vegetation units identified on the three islands showed some degree of clustering in ordination space, and were more or less arranged along hydrologic gradient (Figure 23). Vector fitting of environmental variables in the ordination space showed that hydroperiod, mean annual water depth, and canopy cover were significantly correlated with the sample scores, whereas soil depth was not significant (Table 7).

Table 7: Mean (± SD) of environmental variables used for vector fitting in the non-metric multidimensional scaling (NMDS) ordination. R_{max} is the maximum correlation between fitted vector and sample coordinates in the ordination space.

Environmental variables	**Mean (± SD)**	**R_{max}**	**p-value**
Canopy cover (%)	58.8 ± 39.1	0.8759	0.0027
Soil depth (cm)	124.5 ± 53.2	0.2532	0.7892
Hydroperiod (days)	230 ± 105	0.7916	0.0321
Mean annual water depth (cm)	7.6 ± 29.6	0.7727	0.0397

On the high ground of the hardwood hammock and bayhead portions of the large island and Willowhead where water table remains below or very close to the ground level during most of the year, understory vegetation was dominated by tree seedlings growing under dense canopy. At the other extreme, the marsh vegetation present adjacent to Bayhead and Willowhead islands were dominated by *Eleocharis cellulosa, Nymphaea odorata, Panicum hemitomon,* and *Utricularia* sp. These species are characteristics of slough vegetation in the Everglades. Under intermediate hydrologic conditions, species assemblages were represented by water-tolerant tree seedlings and ferns in the understory of the Bayhead Island., and tree seedlings, ferns and sawgrass in the bayhead swamp of the Hardwood Hammock Island. In the Willowhead, however swagrass and cattail were dominant. On the three islands, understory/herb layer vegetation composition present along the hydrologic gradient was also strongly influenced by canopy openness, as was evidenced by the highly significant (p-value <0.01) canopy cover vector in the ordination space.

4. Discussion and Conclusions

b. Tree island vegetation

Sampling along transects extending from the interior of a tree island through surrounding marsh allowed us to study pattern in plant communities along environmental (hydrologic, edaphic) gradients. However, the sampling methods proposed in the work plan were modified slightly when put in practice. While the number of understory plots and distance between them were retained, i.e., plots distributed at 2, 3 and 6 m intervals for transects of <30, 30-60 and >60 m length, shrubs and tree seedlings were sampled in each understory plot instead of every 6 m. Though this modification increased the sampling effort for small islands (<60 m transect), it was deemed essential to improve the quality of the data, as it enabled a continuous analysis of variation in various life forms along the environmental gradients. Other changes in sampling protocol involved estimation of shrub and tree sapling abundance. In particular, we substituted cover estimates for density counts for shrubs, in which clonal growth made identification of individuals difficult. While we did not alter our planned sampling protocol for trees, they also tend to be stunted and multi-stemmed in bayhead swamps and willowheads. In this type of forest, a line intercept method that is based on cover estimates may be more effective than a census of individual trees in expressing the vegetation gradient.

Historically, Everglades tree islands evolved in relation to climate driven shifts in hydrologic regime. However, noticeable changes in tree island morphology during the last few decades appear to be primarily in response to management-induced hydrologic changes, which are expected to continue (in different and hopefully more beneficial form) when CERP is fully implemented. A methodology to identify the boundaries between vegetation units, and periodically monitor any shift in their positions is considered essential. Split moving window (SMW) analysis is a powerful tool for characterizing patterns of variation and detection of discontinuities, both abrupt and gradual, in species composition along known environmental gradients. In the study of tree island – marsh gradients, a transition from woody vegetation to herbaceous marsh communities was prominent at the small window size, even when a small dataset (number of plots along the transect) were used (eg. the Bayhead Island in PSU-00). Nevertheless, the results of SMW analysis are scale dependent, and the window size affects the outcome. The discontinuity detected at small scale may no longer be present at the large scale. This is a problem for transects where a 'blind zone', i.e., a small number of plots equal to a half-window size that differs markedly in vegetation composition from the neighboring half-window, exists at the end of a transect (Int Panis and Verheyen 1995). In our transects, blind zones occurred most often at the downslope (marsh) end of the transect. The use of window size >2 would have masked this important discontinuity between woody island and herbaceous marsh vegetation. A similar problem could be present in the tree islands where hardwood hammock or bayhead forest extends over only small area at the interior end of the transect. To address the scale (window size) issue, some authors (Cornelius and Reynolds 1991; Boughton et al. 2006) use a dissimilarity profile consisting of pooled standardized dissimilarities from different window sizes. However, this method requires a large number of data points arrayed along long transects, which are not possible in application to some of the small tree islands.

Transition between two vegetation units can be abrupt, signifying high rate of relative change, or gradual. In the Willowhead, the presence of a gentle slope between 20.5 m and 28.5 m, with gradually decreasing but still high dissimilarity, probably reflects a wide transition zone between two communities, *Salix* Shrubland and *Typha-Cladium* mixed marsh vegetation. The vegetation composition within this ecotonal zone was much more heterogeneous (*Salix-Typha-Cladium* mixed marsh) than the vegetation on either side, and could represent a community in transition from marsh to tree island, or *vice versa*. The use of SMW method in the present study is exploratory. A robust analysis, similar to the ones used by Walker et al. (2003) and Hennenberg et al. (2005) to quantify the width of the ecotones and relate them to underlying causal mechanisms may be possible as data from repeated censuses becomes available in coming years.

Despite local scale variation in environmental conditions, a broad scale pattern in vegetation composition in relation to hydrology was evidenced from vegetation environment analysis using vector fitting in ordination space. Hydrology, together with fire and nutrient availability, is considered a primary determinant of vegetation pattern throughout the Everglades. In the vegetation work completed this year, variation in composition within tree islands, along the island-marsh gradient, and among sampling sites in areas managed differently, especially in terms of water management, strongly correlated with the hydrologic conditions prevailing at the sites. For instance, understory vegetation present in the bayhead swamp i.e. the exterior portion of the Hardwood hammock island was similar to the vegetation present in the small Bayhead Island, and marsh vegetation near both the Bayhead and Willowhead islands were similar (Figure 23). In contrast, islands similar to the Hardwood Hammock and Bayhead sites sampled in PSU-00 were not found in PSU-02, as these two PSUs, located in ENP and WCA-3A, respectively, differed remarkably in their hydrology. Differences in hydrologic regimes across the Everglades landscape are due primarily to different water management practices. In a heavily impacted region such as WCA-3A, a shift in vegetation composition has already occurred, and current vegetation is more or less in harmony with hydrology prevailed in last few years (Zweig and Kitchen 2008). A well understood pattern of community transition along known gradients will allow managers to adjust water management operations to achieve desired vegetation pattern throughout the landscape, including tree islands and surrounding marshes. Likewise, other scale dependent ecological processes, including soil-water interactions, nutrient dynamics, and biological processes are also important in determining tree island vegetation pattern (Ross and Jones 2004; Wetzel et al. 2005, 2008; Ross et al. 2006; Givnish et al. 2006). While the present study of three islands in FY 2009 has established a methodological framework, and we will continue in studying tree islands and surrounding marsh over the landscape, only a comprehensive synthesis of results after multiple years of sampling, including the ongoing monitoring work and related works done by several other researchers, would help to explain the detail of community pattern and process in the Ridge, Slough and Tree islands of the Everglades.

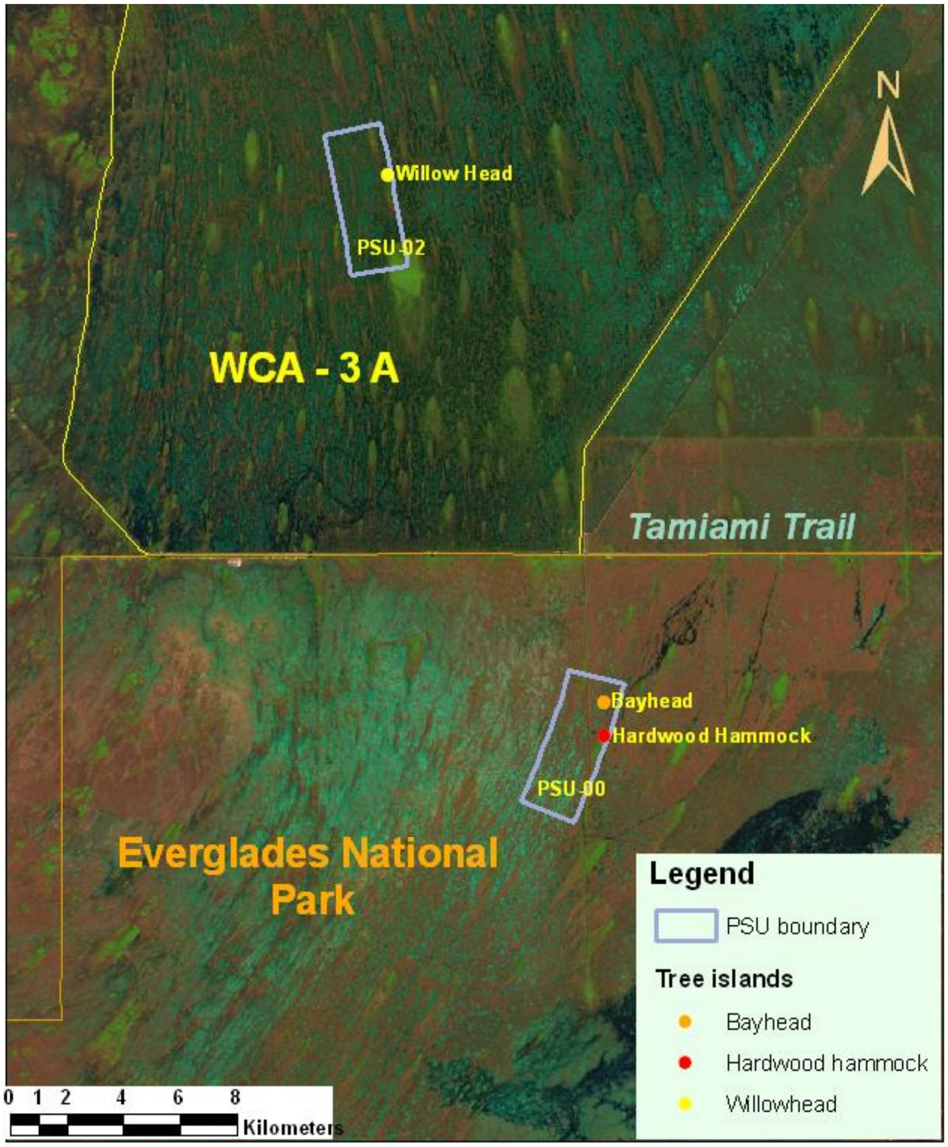


Figure 18: Location map of tree islands sampled in FY 2009.

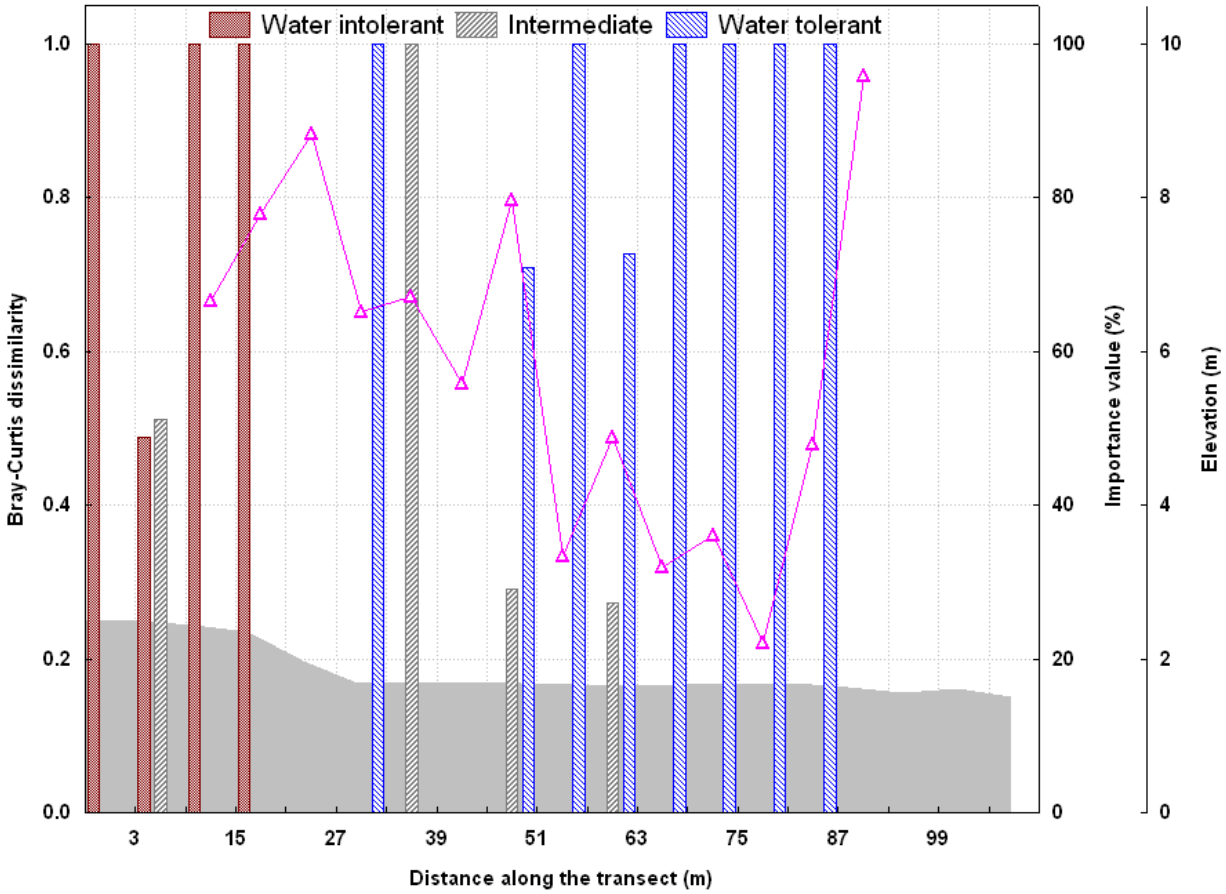


Figure 19: Tree and sapling data based dissimilarity profile derived from split moving window (SMW) method (window size 4 plots), and trees' relative abundance (Importance value) summarized by 6 m sections of the belt transect overlaid on ground elevation.

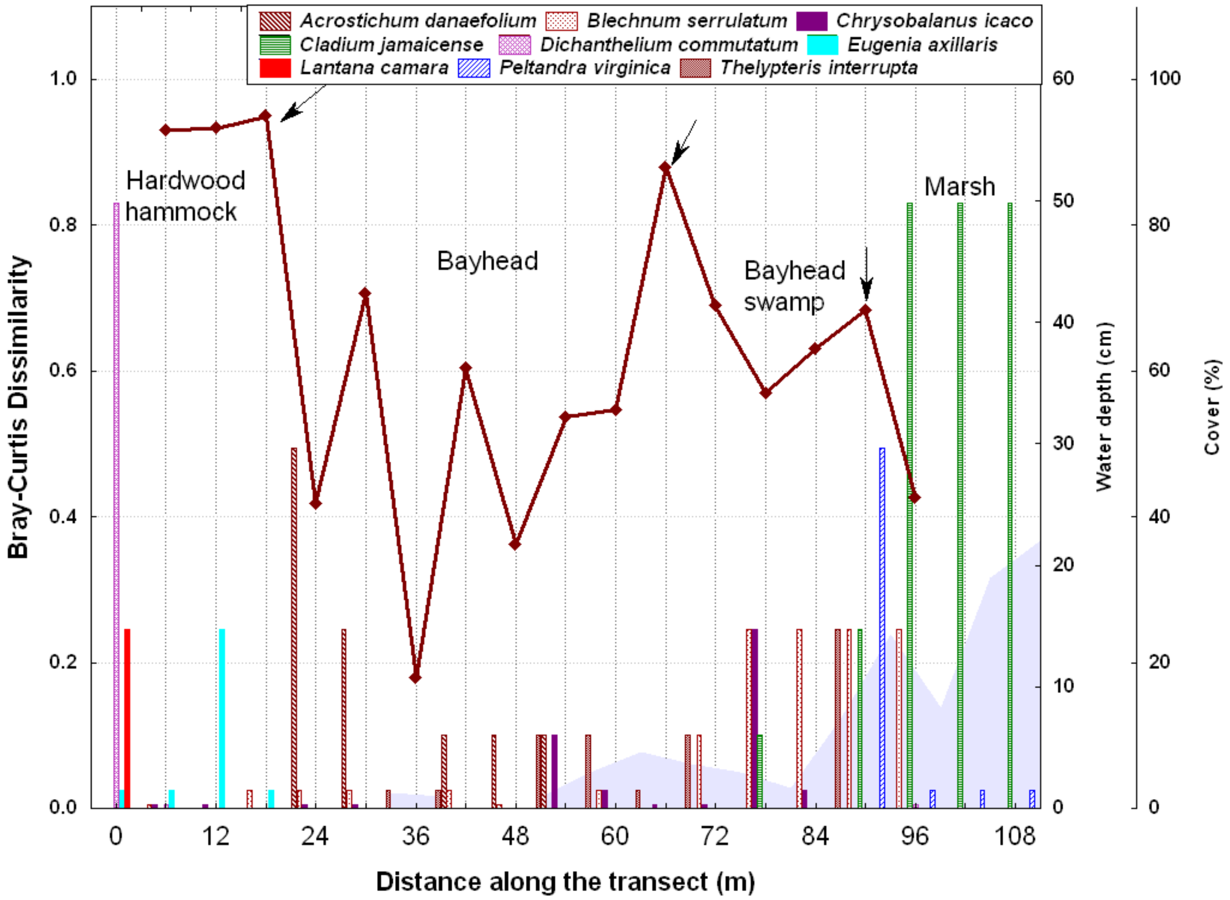


Figure 20: Vegetation units identified using split moving window (SMW) boundary analysis (window size 4 plots) of understory vegetation in the Hardwood Hammock Island in PSU-00

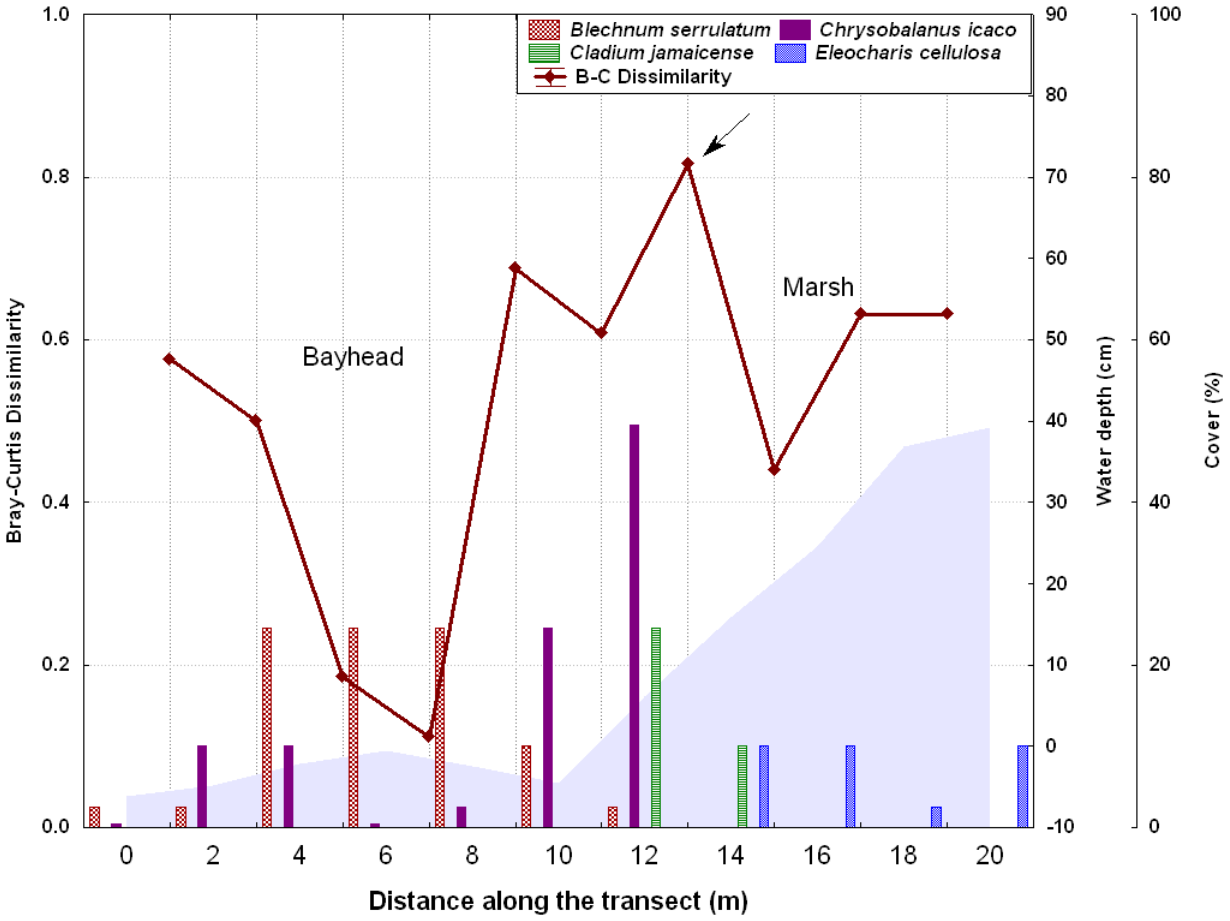


Figure 21: Vegetation units identified using split moving window (SMW) boundary analysis (window size 2 plots) of understory vegetation in the Bayhead Island in PSU-00

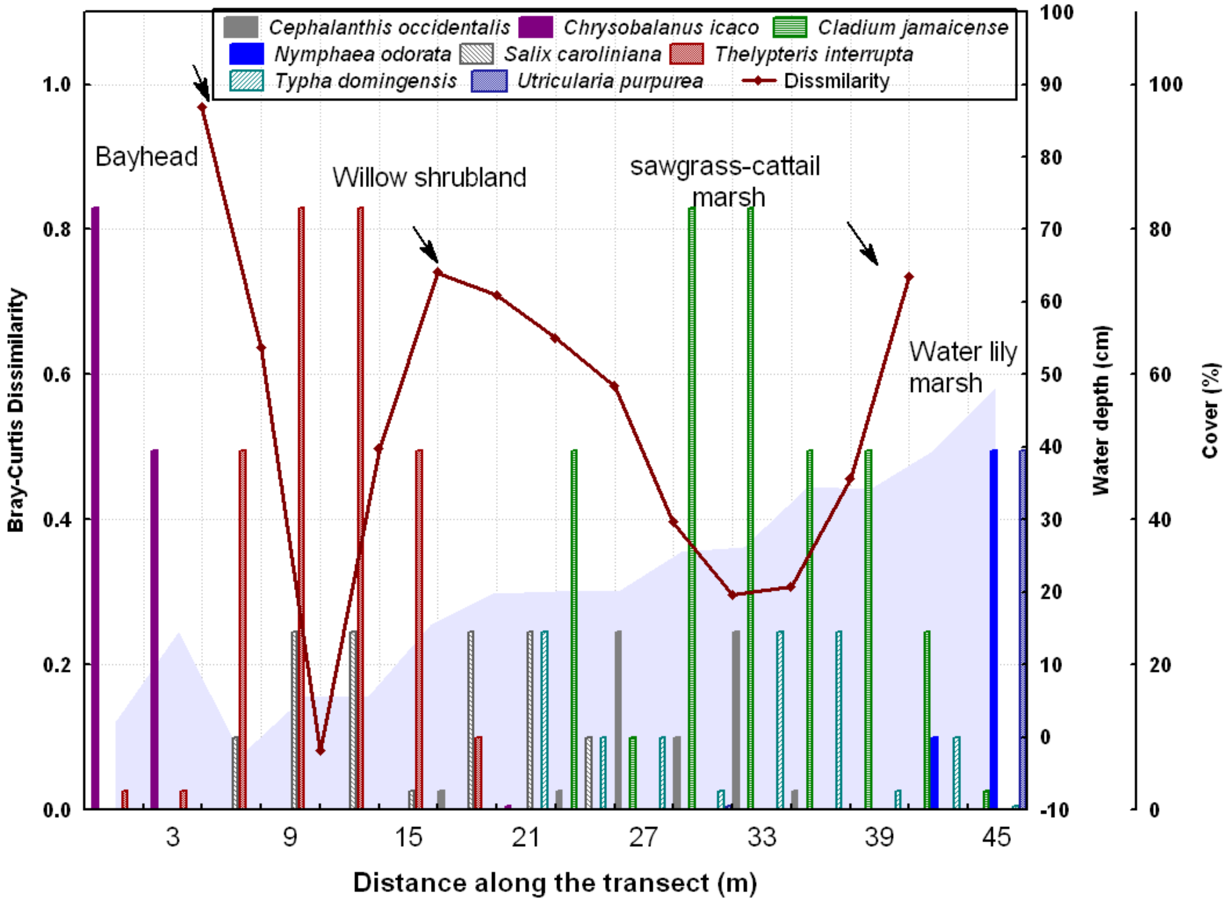


Figure 22: Vegetation units identified using split moving window (SMW) boundary analysis (window size 4 plots) of understory vegetation in the Willowhead in PSU-02

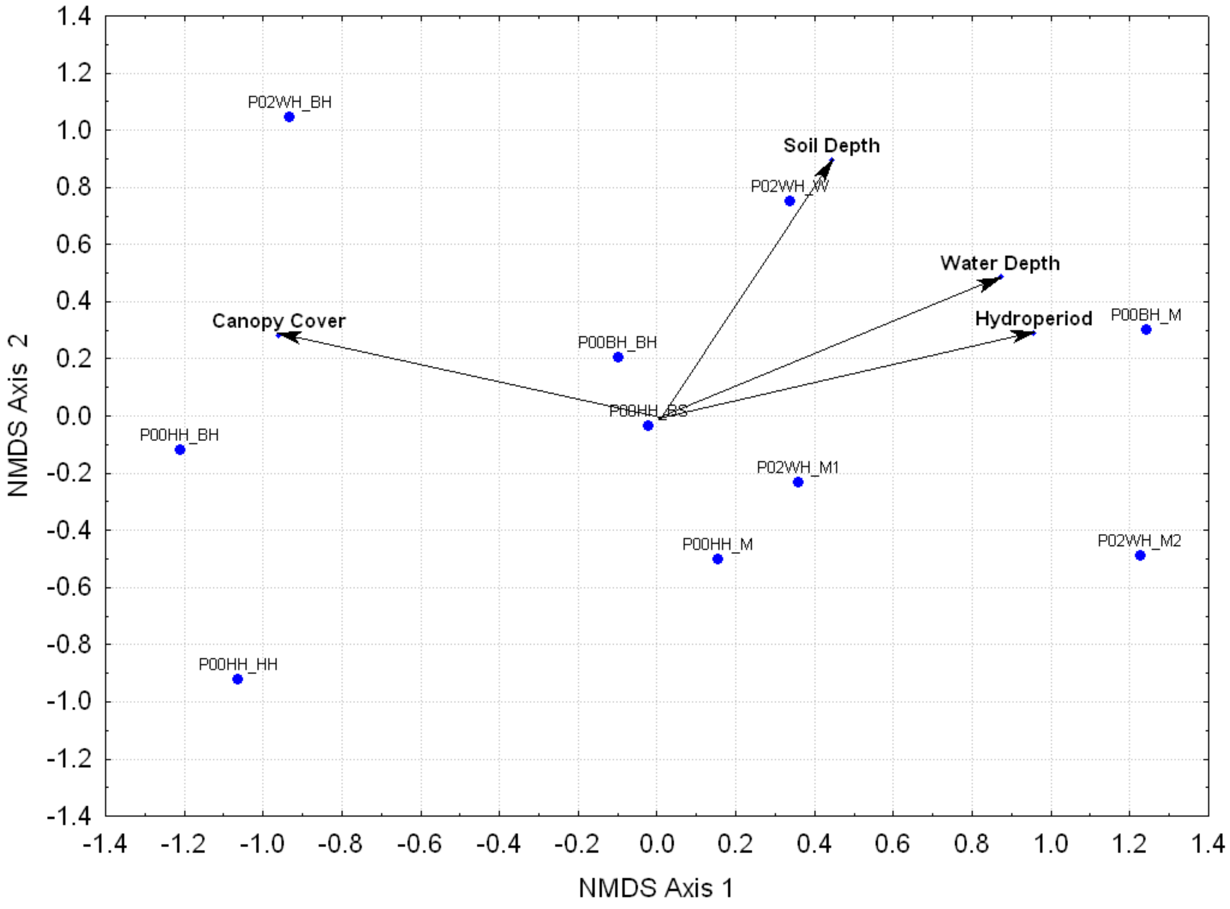


Figure 23: Vectors fitted on the NMDS ordination of 10 understory (herb-layer) vegetation units identified on three islands using split moving-window (SMW) boundary analysis

Summary and synthesis

Summary and synthesis

The primary goal of year 1 efforts was to determine the feasibility of the proposed workplan. Our experience to date suggests that for the most part, our proposed sampling schema are feasible, and provide data sufficient for the proposed analyses. One exception is that mapping of PSU vegetation from aerial photographs at the proposed resolution seems to be intractable given available resources. Because of the value of having landscape-level metrics of marsh and tree island vegetation that is comparable across all sites and for comparison to ground sampling data, we intend to reduce the resolution of mapping in order to cover all PSUs, rather than reduce the number of PSUs to be sampled. Our present planned approach for years 2-4 of this project are to map the entirety of each PSU with aerial photographs viewed at 1:7500 scale. This level of resolution allows description of more subtle features of landscape patch geometry than is presently available from more extensive mapping efforts, but is tractable given available resources. However, we continue to believe that the maps produced at 1:1000 scale provide additional information about fine-scale patch structure. As such, we intend to map a 1 or 1.5 km wide east-west transect across each PSU to characterize a representative subsection of each PSU in this more information-rich manner. In addition, we will continue to map patches of woody vegetation throughout each PSU at the 1:1000 scale to better characterize the distribution, abundance, and characteristics of tree islands.

Our ground sampling efforts in the marsh and along tree island gradients proved generally tractable at the scale and intensity envisioned, and both sampling designs proved flexible enough to accommodate complicating field conditions (e.g. non-wadeable peat in WCA1, short gradients from small tree islands). We anticipate that further expansion of our efforts to other sections of the GEW may require additional, slight modifications, but our experience to date suggests that our sampling and analytical designs can accommodate such modifications with little impact on results and conclusions. We do not anticipate any major changes to our tree island sampling regime, with the possible exception of our soil sampling effort. Because of limited budgeting for soil sampling, our goal is to maximize the value added by our efforts to other existing soil data sets. In particular, our view is that expenditure of greater effort to characterize patterns of tree island soil with depth will maximize this contribution.

Largely for logistical reasons, the overlap between PSUs used for mapping, marsh sampling, and tree island gradient sampling was minimal. As such, meaningful integration of these disparate results is not possible for the most part at this time, particularly in light of the low statistical power. We are aware of the need for an integrated perspective on the dynamics of tree island and marsh components of the landscape, and look forward to the opportunity to provide such a perspective given sufficient data. However, the results of these individual efforts are, to date, largely consistent with our previous findings and those of other researchers. For example, resampling of PSU 4 this past year yielded results extremely similar to those reported by Watts et al (in review), suggesting that the sampling and analysis design used in the marsh produces fairly repeatable results. We also note that the supervised PSU 4 map yields estimates of ridge and slough abundance that is extremely similar to those estimated from ground sampling. Moreover, SMW boundary analysis portrays the ecotonal characteristics between vegetation types within tree islands and at island-marsh interface. Finally, we emphasize that the new landscape metrics (cross-sectional area, etc.) presented here provide important information about the integrated effects of marsh and tree island topography on hydrologic processes (and vice versa). We anticipate further development of such integrated approaches over the remaining duration of this project.

References

Boughton, E. A, Quintana-Ascencio, P. F. Menges, E. S. and Boughton, R. K. 2006. Association of ecotones with relative elevation and fire in an upland Florida landscape. *Journal of Vegetation Science* 17: 361-368.

Cohen, M.J., D.L. Watts, J.B. Heffernan, and T. Osborne. *In review.* Reciprocal biotic control of hydrology, nutrient gradients and landform in the Greater Everglades. *Critical Reviews in Environmental Science and Technology.*

Cornelius, J. M. and Reynolds, J. F. 1991. On determining the statistical significance of discontinuities within ordered ecological data. *Ecology* 72: 2057-2070.

Cornelius, J. M., Kemp, P. R., Ludwig, J. A. and Cunningham, G. L.1991. The distribution of vascular plant species and guilds in space and time along a desert gradient. *Journal of Vegetation Science* 2: 59-72.

Englund, S. R., O'Brien, J. J. and Clark, D. B. 2000. Evaluation of digital and film hemispherical photography and spherical densiometry for measuring forest light environments. *Canadian Journal of Forest Research* 30 (12):1999-2005.

Givnish, T. J., Volin, J. C., Owen, D., Volin, V. C., Muss, J. D. and Glaser., P. H. 2007. Vegetation differentiation in the patterned landscape of the central Everglades: importance of local and landscape drivers. *Global Ecology and Biogeography*:1-19.

Grossman, R.B., and T.G. Reinsch. 2002. The solid phase. p. 201-228. *In* J.H. Dane and G.C. Topp (eds.) Methods of soil analysis. Part 4. Physical methods. SSSA, Madison, WI, USA.

Harvey, J. W., Schaffranek, R. W., Noe, G. B., Larsen, L.G., Nowacki, D.J., and O'Connor, B. L. 2009. Hydroecological factors governing surface water flow on a low-gradient Floodplain. Water Resources Research 45: W03421. doi:10.1029/2008WR007129

Hennenberg, K. J., Goetze, D., Kouamè, L., Orthmann, B. and Porembski, S. 2005. Border and ecotone detection by vegetation composition along forest-savanna transects in Ivory Coast. *Journal of Vegetation Science* 16: 301-310.

Int Panis, L. and Verheyen, R. F. 1995. On the use of split moving window analysis for boundary detection in ordered data series from benthic communities. *Netherlands Journal of Aquatic Ecology* 29 (1): 49-53.

Jones, D. T., Sah, J. P., Ross, M. S., Oberbauer, S. F., Hwang, B. and Jayachandran, K. 2006. Growth and physiological responses of twelve tree species common in Everglades tree islands to simulated hydrologic regimes. *Wetlands* 26 (3): 830-844.

Kantvilas, G., and Minchin, P.R. 1989. An analysis of epiphytic lichen communities in Tasmanian cool temperate rainforest. *Vegetatio* 84: 99–112.

Larsen, L. G., Harvey, J. W., Crimaldi, J. P., 2007. A delicate balance: ecohydrological feedbacks governing landscape morphology in a lotic peatland. Ecological Monographs 77: 591-614.

Ludwig, J. A. and Cornelius, J. M. 1987. Locating discontinuities along ecological gradients. *Ecology* 68: 448-450.

Munoz-Reinoso, J. C. and Garcıa Novo, F. 2005. Multiscale control of vegetation patterns: the case of Donana (SW Spain). *Landscape Ecology* 20: 51–61

Munoz-Reinoso, J. C. 2009. Boundaries and scales in shrublands of the Donana Biological Reserve, southwest Spain. *Landscape Ecology* 24:509–518.

NatureServe. 2006. International Ecological Classification Standard: Terrestrial Ecological Classifications. NatureServe Central Databases. Arlington, VA. U.S.A. Data current as of 23 October 2006.

Nelson, D.W., and Sommers, L.E. 1996, Total carbon, organic carbon, and organic matter. P. 961-1010. In D.L. Sparks (ed.) Methods of Soil Analysis No.5 Part 3, Chemical Methods. Soil Science Society of America , Inc. Madison, WI. USA.

Ogden, J. C. 2005. Everglades ridge and slough conceptual ecological model. Wetlands **25**:810-820.

Philippi, T. 2007. Ridge and Slough Landscape Monitoring Design Final Report. Report to the South Florida Water Management District, West Palm Beach, FL.

RECOVER. 2004. CERP Monitoring and Assessment Plan: Part 1 Monitoring and Supporting Research. Restoration Coordination and Verification Program, c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida.

RECOVER. 2006. 2006 Assessment Strategy for the Monitoring and Assessment Plan. Final Draft. c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida.

Rhoades, J. D. 1996. Salinity: Electrical conductivity and total dissolved solids. p. 417-435. In

D.L. Sparks (ed.) Methods of Soil Analysis No.5 Part 3, Chemical Methods. Soil Science Society of America , Inc. Madison, WI. USA.

Ross, M. S. and Jones, D. T. 2004. Tree Islands in the Shark Slough Landscape: Interactions of Vegetation, Hydrology and Soils. A final report submitted to Everglades National Park, National Park Service, U.S. Department of the Interior, USA.

Ross, M. S., Mitchell-Bruker, S., Sah, J. P., Stothoff, S., Ruiz, P. L., Reed, D. L., Jayachandran, K. and Coultas, C. L. 2006. Interaction of hydrology and nutrient limitation in the Ridge and Slough landscape of the southern Everglades. *Hydrobiologia* 569:37-59.

Rutchey, K., T. Schall, B. Doren, A. Atkinson, M. S. Ross, D. T. Jones, M. Madden, L. Vilchek, K. Bradley, J Snyder, J. Burch, T. Pernas, B. Witcher, M. Pyne, R. White,T. J. Smith, J. Sadle, C. S. Smith, M. Patterson, and G. Gann. 2009. Vegetation Classification System for South Florida Natural Areas. Version 6.19.09.

Sah, J. P. 2004. Vegetation structure and composition in relation to the hydrological and soil environments in tree islands of Shark Slough. In: M. S. Ross and D. T. Jones (Eds.) Tree islands in the Shark Slough landscape: interactions of vegetation, hydrology and soils. A Final Report submitted to Everglades National Park, Homestead, FL.

Sah, J. P., Ross, M. S. and Stoffella, S. 2009. Developing a Data-driven Classification of South Florida Plant Communities. A Report submitted to National Park Service: South Florida Caribbean Network (NPS/SFCN), Miami, FL, USA

Sklar, F. H., C. A. Coronado-Molina, A. Gras, K. Rutchey, D. E. Gawlik, G. Crozier, L. Bauman, S. Hagerthy, R. Shuford, J. A. Leeds, Y. Wu, C. J. Madden, P. B. Garrett, M. Nungesser, M. Korvela, and C. McVoy. 2004. Ecological effects of hydrology. Pages 6-58 *in* Everglades Consolidated Report. South Florida Water Management District, West Palm Beach, FL.

Solorzano, L., and Sharp, J.H., 1980, Determination of total dissolved phosphorus and particulate phosphorus in natural waters: Limnol. Oceanogr., v. 25, p. 754-758.

Stevens, D.L., Jr., and A.R. Olsen 2003. Variance estimation for spatially balanced samples of environmental resources. Environmetrics 14:593-610.

Walker, S., Wilson, J. B., Steel, J. B., Rapson, G. L., Smith, B., King, W. M. and Cottam, Y. H. 2003. Properties of ecotones: evidence from five ecotones objectively determined from a coastal vegetation gradient. *Journal of Vegetation Science* 14: 579-590.

Watts, D.L., M.J. Cohen, J.B. Heffernan, T. Osborne, and M.W. Clark. *In review*. Hydrologic modification and the loss of self-organized patterning in the Everglades ridge-slough mosaic. *Ecosystems*.

Webster, R. 1978. Optimally partitioning soil transects. *Journal of Soil Science* 29: 388-402.

Wetzel, P. R., van der Valk, A. G., Newman, S., Gawlik, D. E., Troxler Gann, T. Coronado-Molina, C. A. Childers, D. L. and Sklar, F. H. 2005. Maintaining tree islands in the Florida Everglades: nutrient redistribution is the key. *Frontiers in Ecology and the Environment* 3:370–376.

Wetzel, P. R. Pinion, T., Towles, D. T., and Heisler, L. 2008. Landscape analysis of tree island head vegetation in Water Conservation Area 3, Florida Everglades. *Wetlands* 28 (2): 276–289.

Wu, Y., N. Wang, and K. Rutchey. 2006. An analysis of spatial complexity of ridge and slough patterns in the Everglades ecosystem. Ecological Complexity **3**:183-192

Zweig, C. L. and Kitchens, W. M. 2008. Effects of landscape gradients on wetland vegetation communities: information for large-scale restoration. *Wetlands* 28 (4):1086-1096.