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Foliar nutrient and water content in subtropical tree islands: A new chemohydrodynamic link between satellite vegetation indices and foliar δ^{15}N values

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ABSTRACT

We examined the relationships between two satellite-derived vegetation indices and foliar δ^{15}N values obtained from dominant canopy species in a set of tree islands located in the Everglades National Park in South Florida, USA. These tree islands constitute important nutrient hotspots in an otherwise P-limited wetland environment. Foliar δ^{15}N values obtained from a previous study of 17 tree islands in both slough (perennially wet) and prairie (seasonally wet) locations served as a proxy of P availability at the stand level. We utilized five cloud-free SPOT 4 multispectral images (20 m spatial resolution) from different times of the seasonal cycle to derive two atmospherically corrected vegetation indices: the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI), averaged for each tree island. NDWI, which incorporates a shortwave infrared (SWIR) band that provides information on leaf water content, showed consistently higher linear fits with island foliar δ^{15}N values than did NDVI. In addition, NDWI showed greater variation throughout the seasonal cycle than did NDVI, and was significantly correlated with average water stage, which suggests that the SWIR band captures important information on seasonally variable water status. Tree islands in slough locations showed higher NDWI than prairie islands during the dry season, which is consistent with higher levels of transpiration and nutrient harvesting and accumulation for perennially wet locations. Overall, the results suggest that water availability is closely related to P availability in subtropical tree islands, and that NDWI may provide a robust indicator of community-level water and nutrient status.

1. Introduction

Tree islands are unique and important features in many large wetland ecosystems. Tree islands are patches of woody vegetation within a freshwater wetland matrix dominated by non-woody species (Wetzel, 2002b). These habitats are developed after wetland formation as a result of landscape processes and feedback between hydrological and climatic factors (Foster et al., 1983; Glaser, 1987; Gumbricht et al., 2004; Wetzel, 2002b). As the only elevated woody habitats in a non-woody wetland matrix, tree islands can affect local hydrology and redistribution of materials and are often the focus of nutrient concentration and species richness in wetland ecosystems (Slack et al., 1980; Wetzel, 2002b).

In this study, we focused on tree islands of the South Florida Everglades. The Everglades ecosystem is the largest subtropical wetland ecosystem in the United States. Similar to most other large wetland ecosystems in the world, tree islands in the Everglades exist as upland plant communities scattered in a matrix of fresh water marshes that spread over the Everglades' vast slough and marl prairie landscape. Although they occupy only a small portion of the landscape, tree island habitats constitute biodiversity and nutrient hotspots in the Everglades ecosystem (Slack et al., 1980; Wetzel, 2002b). Everglades tree islands provide essential habitats for wildlife and plant species that do not tolerate flooding, and they have two-to-three times the species richness of surrounding marshes (Willard, 2003).

Tree islands are also the focus of nutrient accumulation in the otherwise oligotrophic Everglades ecosystem, with soil phosphorus (P) concentrations up to 100 times higher than in surrounding fresh water marshes (Wetzel et al., 2005). However, the P distribution is not homogenous among different tree islands (Shamblin et al., 2008). Tree islands have a wide range of nutrient sources such as precipitation, surface water surrounding the tree island, groundwater, plant litter and bird guano deposition, and bedrock mineralization by tree exudates (Wetzel et al., 2005). Givnish et al. (2008) suggest that bird guano deposition is the major P input for the tree islands. While others propose the chemohydrodynamic nutrient accumulation model, which suggests that transpiration drives nutrient accumulation through groundwater harvesting (Ross et al., 2006; Wetzel et al., 2005). This model hypothesizes that high transpiration rates of tree

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island hardwood hammock plant communities cause them to take up water and nutrients from the surrounding groundwater, especially during the dry season when rain water is limited. Nutrients accumulate through this process in the tree island soil as the heads of the tree islands are never flooded. This model has been supported by previous studies showing that tree island plants can switch their water source from rain water to marsh-associated groundwater during the dry season (Ross et al., 2006; Saha et al., 2009).

In a previous study, we compared the geographical patterns of community level P and water availability of different tree islands. The results supported the chemohydrodynamic nutrient accumulation model by showing that tree islands with higher dry season water deficits and water use efficiency accumulate less P than tree islands with plenty of water available during the dry season (Wang et al., 2010). In that study, we used foliar nitrogen stable isotope ratio (expressed as foliar δ^{15}N) as proxy for P availability, and showed that foliar δ^{15}N is a superior index for long-term, community level measurements of P availability than soil or foliar P concentrations that often show a larger variation with time and sampling locations (Wang et al., 2010).

Work by Saha et al. (2009) and Wang et al. (2010) established a link between water deficits and nutrient availability in tree island habitats. In order to extend these findings in both space and time, we examined satellite-derived vegetation indices over a three-year span to examine how photosynthetic activity and stomatal conductance relate to measurements of foliar δ^{15}N values. Among the many vegetation indices available, we selected the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI) for our analysis because they are well studied and have well-established links between plant physiological processes and states. At the canopy scale, NDVI provides an indirect measurement of absorbed photosynthetically active radiation and canopy stomatal conductance (Verma et al., 1993) and has been widely used in vegetation monitoring for plant canopy characteristics such as chlorophyll content and leaf area index (LAI)(Tucker, 1979). In the Florida Everglades, NDVI has been shown to be a good indicator of P availability in sawgrass and cattail-dominated freshwater marshes (Rivero et al., 2009). The NDWI, which incorporates a shortwave infrared (SWIR) band (Gao, 1996), provides an indirect measurement of canopy water content and has been used for drought monitoring (Chen et al., 2005; Gu et al., 2007; Jackson et al., 2004).

NDVI and NDWI show different responses with leaf water content, atmospheric effects and soil background reflectance. NDVI is most closely related to chlorophyll concentration and photosynthetic activity, which may relate to canopy water content (Tucker, 1980). However, Ceccato et al. (2001) noted that although it has been used to assess canopy water stress, NDVI has been found to be insensitive to leaf water content in some cases. Using laboratory measurements and model simulations the authors also showed that both the shortwave infrared (SWIR) and the near infrared (NIR) wavelength ranges provide direct information on the equivalent water thickness (EWT), which corresponds to a hypothetical thickness of a single layer of water averaged over the whole leaf area. Further, Gao (1996), who introduced the NDWI, showed that this index may be sensitive to soil background effects, that most soils possess negative NDWI values and that NDWI may be reduced by approximately 0.05 in a pixel with 50% canopy cover. He also demonstrated these effects do not differ greatly for wet and dry soils and it is possible to infer EWTs over areas with complete vegetation cover, such as the tree islands analyzed in our study. Gao (1996) also demonstrated that at large NDVI values (>0.63), this index typically saturates while NDWI values remain sensitive to liquid water in green vegetation. Finally, both indices may be sensitive to shadowing to some extent; however, several authors (Asner & Warner, 2003; Galvao et al., 2009) have shown that red reflectance (and hence NDVI) is weakly affected by shadow fraction. SWIR reflectance may also be affected by shadowing (Deering et al., 1999), although systematic evaluation of these effects on NDWI appears lacking.

According to the chemohydrodynamic nutrient accumulation model, water status and nutrient status are closely related to each other in tree island habitats (Ross et al., 2006; Saha et al., 2010; Wang et al., 2010; Wetzel et al., 2005). Therefore, we hypothesize that the two vegetation indices can be used as indicators of water deficits and P status, as it is reflected by foliar δ^{15}N values, in Everglades tree islands. However, given sources of variation in these vegetation indices described above, we expect that NDWI may provide a more robust index for our analysis of average foliar δ^{15}N values than NDVI.

2. Methods

2.1. Study site

The study was done in the Everglades National Park, which is part of the South Florida Everglades ecosystem (Fig. 1). The Everglades ecosystem has an annual rainfall averaging 1300 mm, approximately 70–90% of which falls during the wet season, from June to November (Renken et al., 2006). The region has a gentle elevation gradient of less than 4.5 cm per kilometer with a 48 km-wide sheet flow of surface water concentrated in the Shark River Slough (Fling et al., 2004). The Everglades is a complex wetland ecosystem composed of a variety of terrestrial and marine habitats, including upland pinelands and hammocks, freshwater marshes, tree islands, mangroves, and coral reefs (Lodge, 2004). The freshwater marsh habitat covers about 70% of

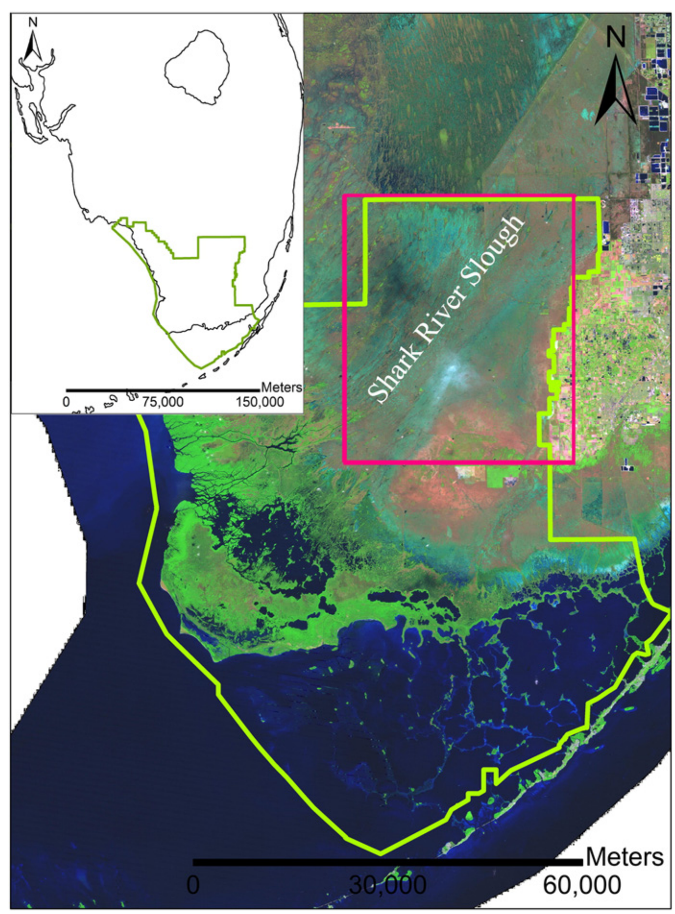

Fig. 1. Map of south Florida and false color Landsat-7 imagery of Everglades. Green lines mark the boundary of Everglades National Park. Pink quadrat marks the study area. Landsat image was taken on 4/18/2004 and bands shown are band 5, 4 and 3. Image obtained from Florida Coastal Everglades Long Term Ecological Research data network (FCE. LTER, http://fce.lternet.edu/data/GIS/).

the Everglades area, and consists of two distinct types of landscape: the mixed ridge–slough matrix (hereafter referred to as slough) and the marl prairies (hereafter referred to as prairie) (Bernhardt & Willard, 2009). The sloughs are flooded throughout the year, with maximum water depths of ~1 m; while the prairies are characterized by shallow water (<0.5 m) and short (<180 day) hydroperiods. The Shark River Slough is the largest slough in the Everglades National Park, with water flowing southwestwards into the Gulf of Mexico.

Tree islands are common features in both slough and prairie landscapes. The Everglades tree islands have a unique tear-dropped shape, which are composed of a never-flooded upland head dominated by subtropical hardwood hammock plant communities, and a lowland tail dominated by partially flood-tolerant swamp forest (Sklar & van der Valk, 2002; Wetzel, 2002a). In this study, we selected 17 tree islands from the Shark River Slough and its adjacent marl prairies in the Everglades National Park (Fig. 1). As the largest slough in the Everglades National Park, the Shark River Slough serves as the primary flow path that carries surface water sheet flow southwestwards into the Gulf of Mexico (Fig. 1). The marshes in the Shark River Slough are flooded throughout the year, while the marshes in the adjacent prairies would dry out during the dry season (from January to May). Ten of the selected tree islands are located in the Shark River Slough, and the other seven are located in the eastern and western prairies adjacent to the slough. The selected tree islands are well preserved and do not suffer from degradation or flood. Shamblin et al. (2008) measured the elevation of 10 out 17 selected tree islands and showed that the head of these islands remain above mean water stage by 0.74 ± 0.11 ($\pm\sigma$, $n = 10$) m.

2.2. Ground measurements

These 17 tree islands were selected following a previous study for ground measurements of foliar δ^{15}N values as proxy for P availability of each island at the community level, as well as soil total P concentration (Wang et al., 2010). The δ^{15}N values were measured for mature leaf samples from the top four most dominant upland hardwood tree species of each tree island, such as *Bursera simaruba*, *Celtis laevigata*, *Coccoloba diversifolia*, *Eugenia axillaris*, *Sideroxylon foetidissimum*. Leaf samples were collected during 4 sampling periods in the wet season (September) and dry season (May) of 2007 and 2008. We collected 4 to 5 mature leaves from 10 individual trees of each sampling species from each selected tree island, making a total of 40 samples per tree island for each sampling period. Ground leaf samples were then processed with a continuous flow isotope ratio mass spectrometer (Isoprime, Elementar, Hanau, Germany) to measure δ^{15}N. We found no significant fluctuation of foliar δ^{15}N values among different sampling periods (Wang et al., 2010). An average δ^{15}N value was then calculated for each tree island to represent the mean foliar δ^{15}N for the two-year time span of ground sampling. In addition, we obtained daily water stage data taken by 18 Everglades water monitoring stations in or near Shark River Slough between 2007 and 2009 from the Everglades Depth Estimation Network (EDEN, http://sofia.usgs.gov/eden/). Monthly average water stage above sea level were calculated for the months that SPOT 4 images were acquired.

2.3. Satellite image processing

We utilized five cloud-free SPOT 4 multispectral images (20 m spatial resolution) representing the mid wet season (28-Oct-2008), the end of the wet season (16-Nov-2007), the beginning of the dry season (29-Jan-2007), the mid dry season (5-Feb-2009) and the end of the dry season (23-Apr-2009) during a three-year-span that partly overlaps the ground sampling periods (Fig. 2a). Because of the difficulty of acquiring cloud-free images over the Everglades, these 5 images were all we could get to best represent the phenology. We also obtained a set of color infrared orthophotos (1 m spatial resolution) taken in 1999 from the South Florida Information Access (SOFIA, http://sofia.usgs.gov/). The 1999 orthophotos were chosen instead of the 2004 orthophotos because they have higher image quality and are more suitable to facilitate georeferencing and classification of the SPOT 4 images. All SPOT 4 images were georeferenced based on the 1999 orthophotos. Using the high-resolution orthophotos, we visually identified the upland hammock communities within the selected tree islands and manually digitized their extents as study areas (Fig. 2b, c). These areas are dominated by broadleaf subtropical tree species that we sampled for measuring foliar δ^{15}N values, and range in size from approximately 100 to 200 m in diameter. Manually classified polygons were used to sample and extract mean values of NDVI and NDWI from the upland parts of tree islands where field sampling was done. Mixed pixels along the edges of digitized polygons were excluded if 50% or more of that pixel fell outside the target area. The size of the digitized polygons range from 6 to 15 pixels (Table 1).

To allow comparison of vegetation index values across time, radiometric calibration and atmospheric correction were performed on the five SPOT 4 images. Calibration coefficients were based on in-flight calibration data supplied with each image. View and solar zenith and azimuth angles were also obtained from SPOT 4 image metadata. Atmospheric correction was done using the Atcor2 radiative transfer

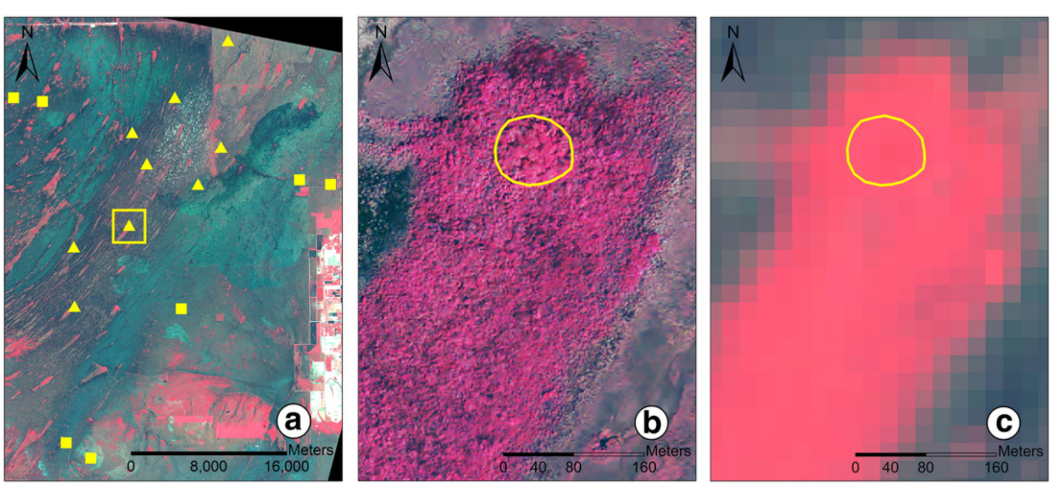

Fig. 2. a. SPOT 4 satellite image (28-Oct-2008) of the Everglades National Park and selected prairie (■) and slough (▲)tree islands. Orthophoto (b) and SPOT 4 image (c) of one tree island marked in the yellow square of a (Panther Island). Yellow circles in b and c mark the areas where leaf samples and vegetation indices were acquired in upland areas on the tree island.

Table 1
Number of pixels (n) within the digitized polygon of the target area used to derive vegetation indices for each tree island. Mixed pixels were not included if 50% or more of that pixel fell outside the target area.

Slough islands	n	Prairie islands	n
Chekika	8	Grossman	12
Gumbolimbo	12	Edge	7
Vulture	10	E4200	6
Satinleaf	8	Ficus	6
Irongrape	10	Mosquito	15
Black	6	NP205	14
SS37	6	A4900	7
Manatee	12		
Panther	14		
SS81	6		

method, which accounts for path radiance, adjacency effects, and reflected radiation from the land surface for multispectral satellite wavebands ranging from 0.4 to 2.5 μm (Richter, 1996). As the terrain in the Everglades is essentially flat, we considered correction for topographic effects unnecessary. Because our images may have contained substantial aerosol and water vapor heterogeneity from nearby maritime and urban influences, we simplified the analysis by assuming a standard atmosphere (mid-latitude, rural conditions) for the five SPOT 4 scenes. Standard atmospheres in Atcor2 are based on climatologies for aerosols, water vapor and absorbing gasses and are obtained from look-up-tables of radiative transfer calculations made with MODTRAN-4 code (Richter, 2005). Visibility was set to be 50 km for all 5 SPOT 4 images during atmosphere corrections.

2.4. Statistical analysis

Mean NDVI and NDWI values were computed for each of the 17 tree islands. Images from some dates only cover 15 (29-Jan-2007) or 16 (28-Oct-2008 and 05-Feb-2009) of the tree islands because of limited extent of the satellite image. NDVI and NDWI values computed from each SPOT 4 image were correlated to the previously obtained foliar δ^{15}N values (Wang et al., 2010). We also used a linear mixed model to analyze the relationship between foliar δ^{15}N and NDVI and NDWI respectively, with image date considered a fixed effect.

A one-way ANOVA was used to compare the average NDVI and NDWI values between the five different image dates respectively, followed by a Tukey's post-hoc test to determine the significant differences among dates. Since the vegetation index values showed non-homogeneity between slough and prairie islands, we used Mann–Whitney U test to compare NDVI and NDWI values between prairie and slough tree islands within each SPOT 4 image. The significance level of the Mann–Whitney U tests among the five different images was adjusted by a Bonferroni correction to $P \leq 0.05/5 = 0.01$ (Sokal & Rohlf, 1995). A one-way ANOVA was also used to compare the average water stage among months during which SPOT 4 images were taken, followed by a Tukey's post-hoc test to determine the significance of differences between each month. A Pearson's correlation analysis was performed between monthly average water stage and average NDVI and NDWI, respectively.

3. Results

Fig. 3a and b shows the results of the atmospheric correction of the NDVI and NDWI values. As expected given the impacts of aerosols on SPOT 4 band 2, the atmospheric effect on NDVI (Fig. 3a) was substantially greater than on NDWI (Fig. 3b) with differences before and after correction ranging from approximately 0.37 to 0.60 NDVI units for the February and October images, respectively. In contrast, the difference between atmospherically corrected and uncorrected NDWI was typically about 0.13–0.16 NDWI units. Although the SPOT 4 images originated from different years, Fig. 3a and b displays the

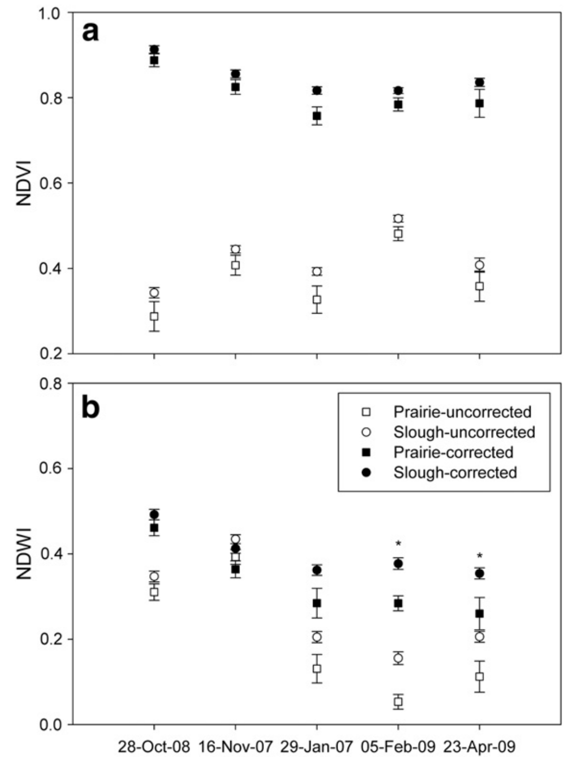

Fig. 3. Atmospherically corrected (closed) and uncorrected (open) NDVI (a) and NDWI (b) values for prairie (squares) and slough (circles) tree islands. Error bars show the standard error of the mean (SEM). Stars (*) indicate statistically significant differences between prairie and slough tree islands at one date by Mann–Whitney U test for atmospherically corrected vegetation indices.

vegetation index sequence by month and thus show how the atmospheric correction produced vegetation index series more consistent with known foliar phenology than uncorrected values. Vegetation index values are expected to decrease from mid wet season (October, November) to dry season (January to April) as water for plant growth and photosynthesis becomes limited.

Despite producing the expected phenological pattern, atmospheric correction did not result in stronger relationships between foliar δ^{15}N values and corrected vegetation index values. In five cases (November NDWI, January NDVI and NDWI, February NDVI and April NDVI) the relationship between foliar δ^{15}N and corrected vegetation index values resulted in very slight increases in Pearson's correlation coefficients versus uncorrected values; whereas in the other five cases, atmospheric correction resulted in slightly reduced correlations between the two variables (Table 2). Below, we present and analyze these relationships as they apply only to the atmospherically corrected vegetation index values.

Average NDVI and foliar δ^{15}N values showed significant correlations only from SPOT 4 images taken on 29-Jan-2007 and 5-Feb-2009 (Fig. 4c and d). On the other hand, NDWI values from all five SPOT 4 images showed significant correlations with foliar δ^{15}N values taken

Table 2
Pearson's correlation coefficient (r) values from correlation analysis between average foliar δ^{15}N values and average uncorrected and atmospherically corrected NDVI (a) and NDWI (b) values of each SPOT 4 satellite image.

Source	28-Oct-08	16-Nov-07	29-Jan-07	5-Feb-09	23-Apr-09
a. NDVI					
Uncorrected	0.52	0.51	0.75	0.61	0.31
Corrected	0.48	0.42	0.78	0.68	0.39
b. NDWI					
Uncorrected	0.57	0.71	0.80	0.83	0.60
Corrected	0.54	0.72	0.81	0.80	0.60

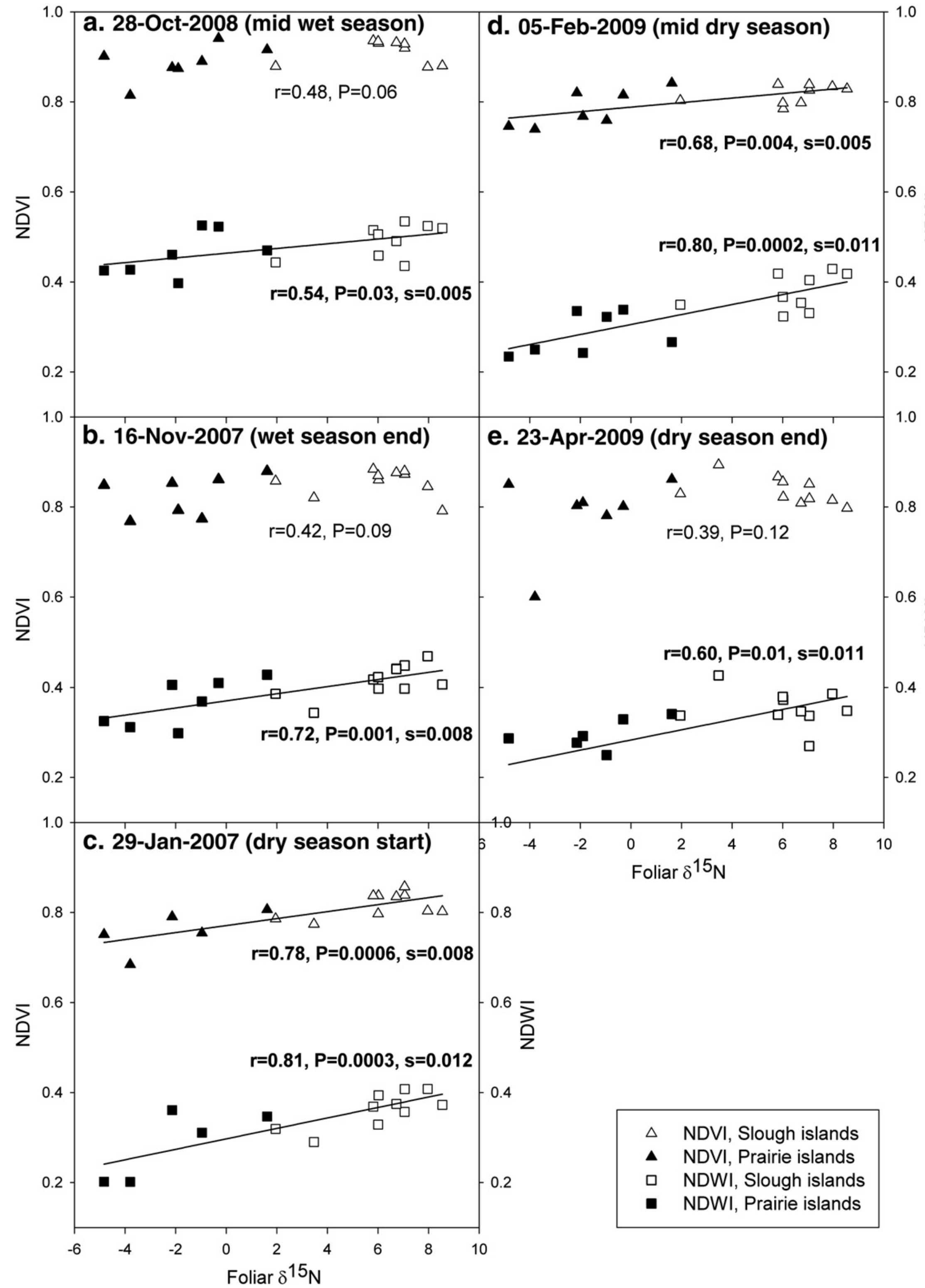

Fig. 4. Average NDVI (triangles) and NDWI (squares) versus average foliar δ^{15}N (‰) for each tree island ($n=15$–17 depending on image extent). Closed symbols represent prairie tree islands, open symbols represent slough tree islands. Lines of best fit represent significant correlation ($P<0.05$). Statistics shown include Pearson's correlation coefficient (r), possibility (P), and slope (s).

from the tree island hammocks (Fig. 4). The linear mixed model showed that NDVI values are affected by both foliar δ^{15}N values ($P<0.05$) and image date ($P<0.0001$), but not by the interaction between these two factors ($P>0.05$, Table 3a). Similarly, the linear mixed model for NDWI also showed significant effects of foliar δ^{15}N values ($P<0.0001$) and image date ($P<0.0001$), but no significant effect of the interaction ($P>0.05$, Table 3b).

Significant differences were found for both NDVI and NDWI between images taken on different dates. The Tukey's post-hoc test showed that the SPOT 4 image taken on 28-Oct-2008 has the highest

Table 3
Results of linear mixed model ANOVAs examining effects of island average foliar δ^{15}N value and date of satellite images on NDVI (a) and NDWI (b).

Source	*d.f.*	*F*	Sig.
a. Dependent variable: NDVI			
Foliar δ^{15}N	1	8.307	0.0114
Image date	4	37.596	<0.0001
δ^{15}N*date	4	0.992	0.4196
b. Dependent variable: NDWI			
Foliar δ^{15}N	1	29.2587	0.0001
Image date	4	46.2453	<0.0001
δ^{15}N*date	4	1.5363	0.2042

NDVI and NDWI values, followed by 16-Nov-2007. No difference was found among the three dry season images for both NDVI and NDWI (Fig. 5a and b). We found significantly lower NDWI in prairie tree islands than in slough tree islands from images taken on 5-Feb-2009 and 23-Apr-2009, but not on the other dates (Fig. 3b). No difference was observed between slough and prairie tree islands for the NDVI index (Fig. 3a). Monthly average water stage was also plotted in monthly sequence regardless of the year (Fig. 5c). Average water stage was found to be significantly different among the five dates, with 28-Oct-2008 being the highest and 23-Apr-2009 being the lowest (Fig. 5c). Moreover, we found a significant positive correlation between average water stage and average NDWI values ($P<0.05$), but no significant correlation between average water stage and average NDVI values (Fig. 6).

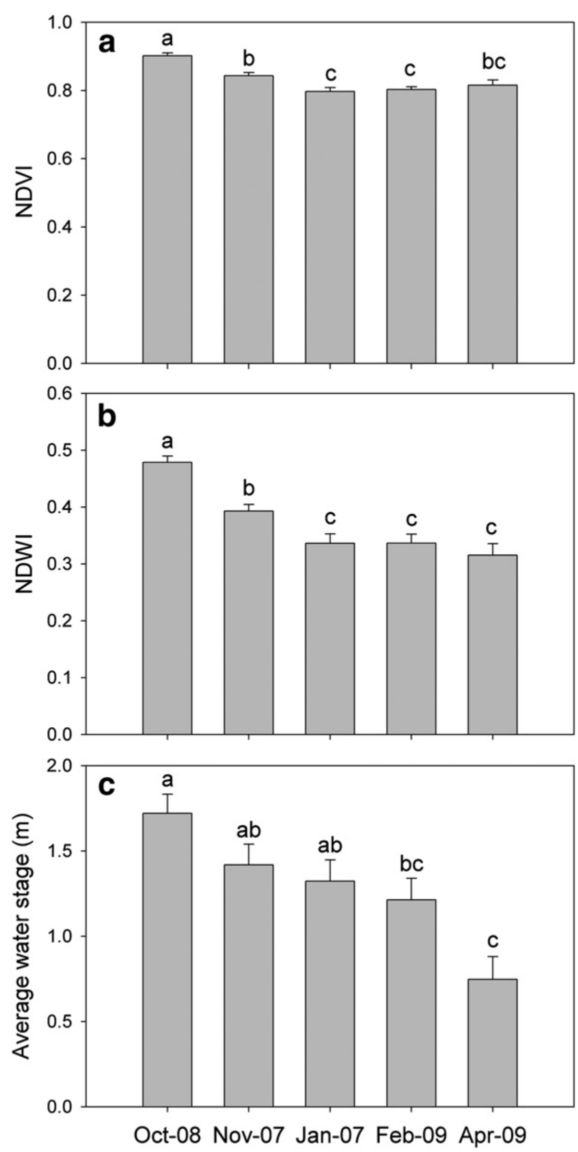

Fig. 5. Average NDVI (a), NDWI (b), and monthly average water stage (c) of each SPOT 4 image. Error bars show the standard error of the mean (SEM). Bars marked with same letters do not differ statistically by Tukey's post-hoc test following a one-way ANOVA.

4. Discussion

Foliar δ^{15}N values were used as a proxy for P availability at the community level. It has been shown that in the generally P-limited Everglades ecosystem, foliar δ^{15}N of plants is an indicator of ecosystem P availability (Inglett & Reddy, 2006; Inglett et al., 2007; Wang et al., 2010). We chose to use island foliar δ^{15}N as the proxy because unlike any direct measurement of plant available P, foliar δ^{15}N value is a stable parameter through time that does not fluctuate with year and season (Wang et al., 2010). Therefore, we could compare it with vegetation indices derived from satellite images taken between 2007 and 2009. The linear mixed models showed that both image dates and island δ^{15}N have significant effects on NDVI and NDWI values (Table 3), indicating that tree island NDVI and NDWI are sensitive to the long term proxy of island nutrient status and to annual hydrology status (dry and wet seasons). However, the NDWI value showed consistently higher image-by-image linear fits with island δ^{15}N than did NDVI, with all five correlations being significant (Fig. 4). This is consistent with our hypothesis and general understanding of NDWI, which is highly sensitive to canopy EWT provided canopy cover is sufficiently high (>80%) (Gao, 1996). On the other hand, significant correlations between NDVI and island δ^{15}N values were obtained for only two dry-season images, (29-Jan-2007 and 5-Feb-2009, Fig. 4c and d). We found no significant interaction between image date and island foliar δ^{15}N value on NDVI and NDWI (Table 3), suggesting that the correlation between δ^{15}N and the vegetation indices is independent of the date. Because NDWI is considered an indicator of canopy water content and the community level foliar δ^{15}N value as a proxy for P availability, the positive relationship between NDWI and island δ^{15}N supports the chemohydrodynamic hypothesis that plant water availability is positively associated with tree island nutrient status.

Wang et al. (2010) showed that prairie tree islands, surrounded by dry marshes during the dry season, experience greater water deficits than slough tree island and, therefore, show reduced transpiration and nutrient accumulation during the dry season relative to slough tree islands. These observations are consistent with the chemohydrodynamic nutrient accumulation model. Here, we

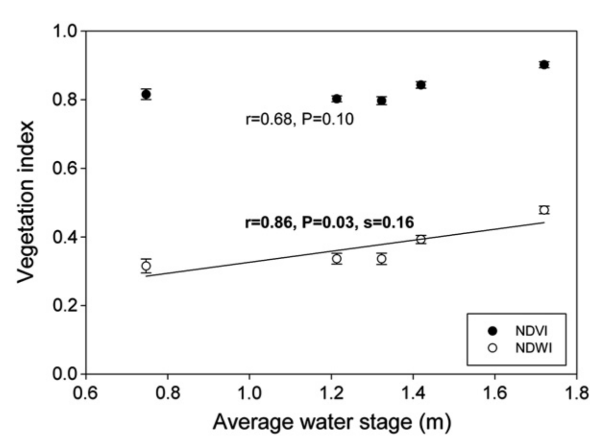

Fig. 6. Monthly average water stage (m) for the months SPOT 4 images were acquired versus average NDVI (●) and NDWI (○) over all sampled tree islands of each date. Water stage data obtained from the Everglades Depth Estimation Network (EDEN, http://sofia.usgs.gov/eden/). Error bars represent standard error of the mean (SEM). Lines of best fit represent significant correlation ($P<0.05$). Statistics shown include Pearson's correlation coefficient (r), possibility (P), and slope (s).

found that both NDVI and NDWI values showed significant decrease through the monthly sequence from October to April as expected (Fig. 5a and b). However, NDWI showed greater variation throughout the seasonal cycle than did NDVI (Fig. 5b), and this seasonal variation showed similar decreasing pattern from wet season to dry season as monthly water stage above sea level (Fig. 5c). The significant positive correlation between average NDWI and average water stage confirmed that the seasonal variation of NDWI follows the variation of water availability (Fig. 6). This result suggests that NDWI is more sensitive in capturing seasonal variation in nutrient and hydrologic status than NDVI. We also found no significant difference in NDVI between slough and prairie tree islands (Fig. 3a); while two out of three dry season images (5-Feb-2009 and 23-Apr-2009) showed significantly lower NDWI in prairie tree islands than in slough tree islands (Fig. 3b), indicating that prairie tree islands have lower canopy water content than slough tree islands during the dry season. Moreover, the only dry season image that did not show significant differences in NDWI between slough and prairie tree islands was taken at the beginning of the dry season (29-Jan-2007), when the marsh water level was still high and not different from the two wet season dates (Fig. 5c). Again, this result is consistent with evidence presented by Wang et al. (2010), supporting the chemohydrodynamic nutrient accumulation model. This result suggests that NDWI, especially the SWIR band, is highly sensitive to canopy-level water status. Overall, our results show that both NDVI and NDWI indices can be used to monitor the geographical and seasonal variation in nutrient and water status for Everglades tree island habitats, but NDWI provides a stronger predictor of water status across different seasons and years. Nonetheless, unexplained variation in relationships between NDWI and foliar δ^{15}N may be attributed to soil background, canopy shadowing and unaccounted for atmospheric effects. The NDWI-foliar δ^{15}N relationships showed somewhat stronger relationships during the dry season when the semi-deciduous trees lost a portion of their leaf canopies, which suggests that soil background effects did not affect our results. However, further investigation of these influences on NDWI may be warranted in our study area. Moreover, the pattern revealed by NDWI and island foliar δ^{15}N values agrees with the chemohydrodynamic nutrient accumulation model, suggesting that prairie tree islands, which have lower dry season water availability than slough tree islands, accumulate less P than slough tree islands.

This study is novel in applying remote sensing techniques specifically on tree island habitats. Previous remote sensing studies in the Everglades ecosystem mostly focused on the freshwater marshes (Rivero et al., 2009). Although Givnish et al. (2008) included tree island habitats in their NDVI survey, NDVI was only used to show the distribution of biomass in the Everglades landscape. This study is one of the first to utilize satellite-derived vegetation indices in combination with stable isotope analysis of leaf tissues. Strong relationships between foliar δ^{15}N and NDWI, in particular, suggest that NDWI can be used to monitor canopy-level P accumulation over large areas in wetland and other communities, when the link between foliar δ^{15}N and P status is supported by ground studies. Although our analysis is limited to a specific wetland habitat type (tree islands), the linearity of the relationship between canopy-level nutrient status and NDWI suggests that many operational, satellite sensor systems can be used to map and monitor available P, which is a critical, limiting nutrient in many terrestrial and wetland ecosystems. Further work is required to extend and test this hypothesis in other terrestrial and wetland ecosystems that are characterized by spatial and temporal heterogeneity of nutrient flux and availability.

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