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

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ABSTRACT

We examined the relationships between two satellite-derived vegetation indices and foliar $\delta^{15}N$ 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 $\delta^{15}N$ 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 $\delta^{15}N$ 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

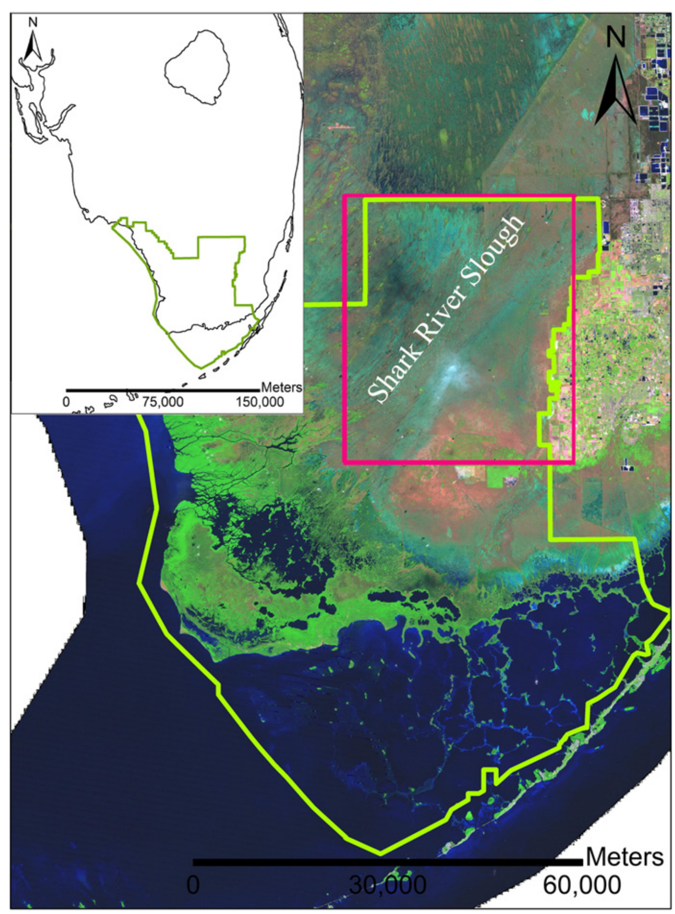

Fig. 1. Map of south Florida and false color Landsat-7 imagery of Everglades. Green lines mark the boundary of Everglades National Park. Pink quadrat marks the study area. Landsat image was taken on 4/18/2004 and bands shown are band 5, 4 and 3. Image obtained from Florida Coastal Everglades Long Term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