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Estimating major ion and nutrient concentrations in mangrove estuaries in Everglades National Park using leaf and satellite reflectance

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ABSTRACT

Coastal mangrove ecosystems are under duress worldwide because of urban development, sea-level rise, and climate change, processes that are capable of changing the salinity and nutrient concentration of the water utilized by the mangroves. This study correlates long-term water chemistry in mangrove environments, located in Everglades National Park, with mangrove spectral reflectance measurements made at both the leaf and canopy scales. Spectral reflectance measurements were collected using a handheld spectrometer for leaf-level measurements and Landsat 5TM data for regional coverage. Leaf-level reflectance data were collected from three mangrove species (i.e., red, black and white mangroves) across two regions; a tall mangrove (~18 m) and dwarf mangrove (1–2 m) region. The reflectance data were then used to calculate a wide variety of biophysical reflectance indices (e.g., NDVI, EVI, SAVI) to determine signs of stress. Discrete, quarterly water samples from the surface water, groundwater, and pore water (20 and 85 cm depths) and daily autonomous surface water samples were collected at each site and analyzed for major anions (Cl^- and SO_4^{2-}), cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}), total nitrogen (TN) and total phosphorus (TP). Mangrove sites that exhibited the highest salinity and ionic concentrations in the surface and subsurface water also had the lowest near-infrared reflectance at both the leaf and satellite levels. Seasonal reflectance responses were measured in the near-infrared (NIR) wavelengths at both the leaf and canopy scales and were strongly correlated with nutrient and ionic concentrations in the surface and subsurface water, even though there was no significant separability between the three mangrove species. Study sites that experienced the greatest variability in surface and subsurface water ionic concentrations also exhibited the greatest fluctuations in NIR spectral reflectance. Landsat 5TM images were able to detect tall and dwarf mangroves by the differences in spectral indices (e.g., NDVI, NDWI, and EVI) because of the variability in the background conditions amongst the environments. In addition, Landsat 5TM images spanning 16 years (1993–2009) were successfully used to estimate the seasonal variability in ionic concentrations in the surface water across the Florida Coastal mangrove ecotone. This study has shown that water chemistry can be estimated indirectly by measuring the change in spectral response at the leaf- or satellite-scale. Furthermore, the results of this research may be extrapolated to similar coastal mangrove systems throughout the Caribbean and world-wide wherever red, black, and white mangroves occur.

1. Introduction

Mangroves are one of the most productive hydrologically controlled ecosystems that support high primary productivity, diverse habitats, and complex interactions between hydrogeology, biogeochemistry, and ecology (Twilley, Chen, & Hargis, 1992). These fragile ecosystems are sensitive to perturbations caused by human developments and both gradual (e.g., sea-level rise, saltwater intrusion) and abrupt (e.g., storms, temperature extremes) natural changes (Brunt, 1992; Mitsch & Gosselink, 2000). Coastal development has been a major cause of mangrove deforestation and coastal erosion, removing between 30 and 50% of the worlds' mangroves over the last half century (Duke et al., 2007; Spalding, Kainuma, & Collins, 2010; Valiela, Bowen, & York, 2001). Human populations along the coast are expected to increase over time and further intensify issues related to water quality and water availability (Lotze et al., 2006; Vorosmarty, Green, Salisbury, & Lammers, 2000). In the Caribbean alone, 10% of the mangrove forests were lost in the 1980s as a result of deforestation, oil spills and other pollutants, and destruction of mangrove lands for urban and agricultural development (Ellison & Farnsworth, 1997). Since then, approximately one-third of mangroves have been lost globally between the 1980s and 2000s (Spalding, Kainuma & Collins, 2010). Moreover,

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mangrove forests continue to disappear quicker than other endangered environments (e.g., coral reefs, tropical forests) and may be lost completely within the next century (Duke et al., 2007).

Changing the hydrology of these tropical and sub-tropical coastal wetlands can affect much of the surrounding ecosystem, from the food web dynamics (Winemiller & Jepsen, 1998; William & Trexler, 2006), community structure (Lugo & Snedaker, 1974; Twilley, Chen & Hargis, 1992; Zedler & Kercher, 2005), and biogeochemical processes (Robertson & Alongi, 1992; Douglas, Bunn, & Davies, 2005). Moreover, changing hydrogeologic and nutrient conditions can affect plant biophysical properties which can be measured remotely using optical sensors (Carter & Young, 1993; Govender, Chetty, & Bulcock, 2007). Some applications using optical remote sensing have included classifying land cover, estimating biophysical factors and plant stress (e.g., leaf area index, light-use efficiency, water-use efficiency, and net ecosystem production), estimating energy balance components and evapotranspiration, and measuring water quality (Curran, 1989; Griffith, Martinko, Whistler, & Price, 2002; Hirano, Madden, & Welch, 2003; Williams & Norris, 2001).

Imaging spectroscopy is useful for calculating spectra-derived biophysical indices that have been related to leaf structure, biochemical content, and plant function (Roberts, Roth, & Perroy, 2011). The biophysical indices are determined using specific wavelengths, or spectral derivatives in the visible (VIS) and near-infrared (NIR) portions of the electromagnetic spectrum that are sensitive to alterations in foliar chemistry (e.g., cellulose, lignin and chlorophyll) and plant membrane structure (e.g., chlorophyll and water content), which have been shown to be altered by many environmental factors such as groundwater level, soil moisture, net radiation, water quality, salinity and nutrient limitations (Campbell, Middleton, McMurtrey, Corp, & Chappelle, 2007; Naumann, Anderson, & Young, 2008). Previous reflectance and biophysical studies have primarily focused on classifying vegetation or relating biophysical indices with other vegetation parameters (e.g., leaf area index, light use efficiency, biomass) and are primarily based in agriculture and temperate forests (Campbell, Middleton, McMurtrey, Corp & Chappelle, 2007; Williams & Norris, 2001) with some studies in mangrove wetlands (Green, Clark, Mumby, Edwards, & Ellies, 1998; Hirano et al., 2003; Kamaruzaman & Kasawani, 2007; Nichol, Rascher, Matsubara, & Osmond, 2006; Ramsey & Jensen, 1996).

The reflectance properties of mangroves are dependent on the leaf structure and chemistry at the leaf-scale; and are dependent on the background and physical conditions such as exposed sediments (e.g., sand, peat), tidal cycles, soil moisture, leaf inclination, branches, and shadows at the satellite-scales (Diaz & Blackburn, 2003; Hurcom, Harrison, & Taberner, 1996; Vaiphasa, Ongsomwang, Vaiphasam, & Skidmore, 2005). Previous studies have addressed the role of water chemistry (e.g., salinity, major ions and nutrients) on leaf reflectance, but have been primarily in agricultural sites (Ayala-Silva & Beyl, 2005; Lauten & Rock, 1992; Poss & Russell, 2010). Other studies have used stepwise linear regressions to fit observed chemical concentrations inside the leaf (e.g., nitrogen and chlorophyll) by using a combination of various spectral bands (Curran, Dungan, & Peterson, 2001; Dawson & Curran, 1998; Kokaly & Clark, 1999). Salinity impacts on leaf spectral patterns were considered in very few studies in coastal areas (Naumann, Anderson & Young, 2008; Zinnert, Nelson, & Hoffman, 2011) and in tropical mangrove communities (Song, White, & Heumann, 2011). Very few researchers have investigated the close-range variation in leaf spectral properties between mangrove species (Diaz & Blackburn, 2003; Vaiphasa, Ongsomwang, Vaiphasam & Skidmore, 2005; Wang & Sousa, 2009). There is a lack of information in the literature regarding the temporal variability in mangrove leaf reflectance and variability caused by changes in major ions and nutrients.

This study seeks to fill a research gap by investigating relationships between plant water source chemistry and mangrove leaf optical properties at both the site-specific and canopy scales along an estuarine and productivity gradient. More specifically this study seeks to 1) characterize mangrove leaf spectral reflectance with varying surface and subsurface water chemistry, 2) identify spectral reflectance signatures between dwarf and tall varieties of mangroves, and 3) identify the best approach to estimate surface and subsurface water chemistry from spectral reflectance data. To address these objectives, a combination of spectral data and water chemistry was collected together at two different mangrove communities along the southern coast of Florida, in Everglades National Park.

2. Study sites

The Everglades sits on top of the Florida Carbonate Platform, which has an exceptionally low topographic gradient (slope of 3 cm km^{-1}; Kushlan, 1989) and is composed primarily of highly permeable carbonate and siliciclastic sediments up to 2000–6000 m thick (Randazzo & Jones, 1997). The flat topography of the Everglades contributes to poorly defined watershed boundaries and a low hydraulic gradient (5×10^{-5}) (Price, Swart, & Fourqurean, 2006). Shark River Slough (SRS) and Taylor River Slough (TS), the two main waterways in the Everglades, occupy underlying bedrock depressions that are ~1.5 m lower than the surrounding uplands (Gleason & Stone, 1994; Obeysekera, Browder, Hornung, & Harwell, 1999) (Fig. 1). The largest freshwater conduit, SRS delivers water directly to the Gulf of Mexico but is only a fraction of its original pre-development size (Flora & Rosendahl, 1982). Taylor River Slough is located to the east of SRS and is separated by a relative topographic high (2–4 m above sea level). Freshwater is delivered from TS to northern Florida Bay by way of a channelized creek system (Olmsted, Loope, & Hilsenbeck, 1980; Sutula, Day, Cable, & Rudnick, 2001) that is restricted by the presence of the Buttonwood Embankment, a 0.35 m high near-continuous natural coastal levee, which restricts overland flow and concentrates water into five major creeks (Orem et al., 1999; Sutula, Day, Cable & Rudnick, 2001).

The Everglades is a hydrologically-controlled subtropical environment, where water levels, flows, and residence times play a crucial role in ecosystem function and structure (Light & Dineen, 1994). Annual precipitation in the southwest region ranges between 1200 and 3000 mm year^{-1} (measured at Flamingo Ranger Station; ID083020, fcelter.fiu.edu), and is unequally distributed throughout the year (Fig. 2). Approximately 75–80% of the annual precipitation falls during the wet season between late May and November, with a bi-modal distribution of peak rains occurring in June and August (Childers et al., 2006; Duever, Meeder, Meeder, & McCollom, 1994). The Florida Peninsula is prone to frequent afternoon thunderstorms and tropical cyclones during the late summer and early fall, and frontal systems with low temperatures and humidity in the later fall through early spring (Obeysekera, Browder, Hornung & Harwell, 1999).

Over the last 100+ years, anthropogenic compartmentalization of the northern Everglades via canals, levees and water conservation areas (Fig. 1) along with increased pressure of urban growth and development have resulted in an almost 50% reduction in the historical size of the Everglades (Walker & Solecki, 2004). Ultimately, these modifications to the Everglades region have not only reduced the natural flow of water into the ENP by approximately 25% into TS and 15% in northeast SRS (Light & Dineen, 1994), but also altered the hydrogeologic and ecohydrologic dynamics of the mangrove ecotone (Rivera-Monroy et al., 2011). For instance, as water levels and flows decreased in ENP, seawater intrusion into the coastal aquifer increased landward along the entire southern Florida coast (Fitterman & Deszcz-Pan, 1998; Price, Swart & Fourqurean, 2006) allowing coastal mangroves to migrate over 1.5 km inland over the last 50 years (Rivera-Monroy et al., 2011; Simard et al., 2006).

3. Methods

3.1. Site description

The coastal mangrove forests of the Everglades consist of three mangrove species; *Avicennia germinans* (black mangroves), *Laguncularia*