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Hyperspectral remote sensing of salinity stress on red (Rhizophora mangle) and white (Laguncularia racemosa) mangroves on Galapagos Islands

CONGHE SONG*,†, BRIAN L. WHITE‡ and BENJAMIN W. HEUMANN†
†Department of Geography, University of North Carolina, Chapel Hill, NC 27599, USA
‡Department of Marine Sciences, University of North Carolina, Chapel Hill, NC 28599, USA

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Mangroves are an assemblage of salt-tolerant woody hydrophytes that are the foundational species along tropical and subtropical coastlines, estuaries, lagoons and rivers. Once covering 75% of the world’s tropical and subtropical coastlines, mangrove forests have been declining rapidly throughout the world in the last few decades. Monitoring and modelling mangrove forest growth are critical for their conservation. Salinity is one of the primary limiting factors for mangrove forest growth. In this letter, we report the potential of using hyperspectral remotely sensed data collected in the field for monitoring the photosynthesis rate of red (Rhizophora mangle) and white (Laguncularia racemosa) mangroves with regard to salinity gradient. Using photochemical reflectance index (PRI) as proxy for photosynthetic rate, PRI for both species are strongly related to salinity gradient, indicating the potential of monitoring mangrove forest growth on a regional scale using hyperspectral remote sensing.

1. Introduction

Mangroves are an assemblage of salt-tolerant woody hydrophytes that are the foundational species along tropical and subtropical coastlines, estuaries, lagoons and rivers (Tomlinson 1986, Hogarth 2007). Mangrove forests have historically covered as much as 75% of the world’s tropical and subtropical coastlines (Alongi 2002) but have suffered dramatic declines in areas because of coastal development, non-renewable resource exploitation (e.g. clear cutting, mining, aquaculture), pollution, high rates of sedimentation, sea level rise and alterations of hydrology (Saenger et al. 1983, Farnsworth and Ellison 1997, Ellison and Farnsworth 2001, Duke et al. 2007). Alongi (2002) estimated that as much as a third of the world’s mangrove forests have been lost in the past 50 years. Mangrove forests sustain productive, biologically unique and economically important ecosystems (Lugo and Snedaker 1974, Tomlinson 1986, Kathiresan and Bingham 2001, Hogarth 2007). Mangroves provide valuable ecosystems goods and services including wood, fibre, food, high primary productivity, linking terrestrial and marine systems, buffering coastline from erosion and supporting biodiversity (Alongi 2008). Mangrove forest composition is often characterized by a strong zonation in community composition based primarily on soil salinity related to tidal inundation (Tomlinson 1986), although

*Corresponding author. Email: song@email.unc.edu
other geomorphic, edaphic, climatic and biotic factors can create more complex patterns (Onuf et al. 1977, Ewel et al. 1998, Lee 1998, Ellison 2002). Protecting and managing mangrove forests are important international conservation objectives (Macintosh and Ashton 2003). Achieving these objectives will require the development of techniques for accurately mapping and monitoring the distribution and health of mangrove forests in an era of accelerated climate change. Mangrove forest monitoring is no easy task. Such forests are notoriously difficult to access and survey on foot because of the flooded, soft sediment environments in which they grow and the typically high densities of stems and prop roots. Remote sensing provides an operational alternative to map and monitor mangrove forest on a timely basis for a wide range of spatial coverage. Numerous studies have utilized remote sensing to delineate, detect change, map species distribution and estimate structural metrics such as leaf area index and above-ground biomass as reviewed by Walters et al. (2008). The remotely sensed data used include aerial photos, satellite images (e.g. Landsat and Satellite Pour L’Observation de La Terre (SPOT)) as well as airborne hyperspectral data (Green et al. 1998, Manson et al. 2001, Held et al. 2003, Vaiphasa et al. 2007, Conchedda et al. 2008, Wang et al. 2008). Few studies explored the potential of using hyperspectral remotely sensed data for monitoring or modelling the growth in relation to the main environmental stressor, salinity.

Salinity is a major factor that influences mangrove forest growth. Although mangroves have several mechanisms to tolerate saline conditions such as ion compartmentation, osmoregulation, selective transport and uptake of ions, maintenance of a balance between the supply of ions to the shoot and capacity to accommodate the salt influx (Parida and Jha 2010), the costs of these mechanisms appear to come at the expense of photosynthesis (Sobrado 2005). The objective of this study is to test the suitability of using hyperspectral remote sensing in monitoring/modelling mangrove forest growth on the Galapagos Islands. Specifically, we test the potential for detecting the salinity-induced stress on photosynthesis for two common mangrove species, the red and white mangroves, on Isla Isabela, Galapagos.

2. Methodologies

2.1. Theory

Photosynthesis is a biological process in which photosynthetically active radiation (PAR) captured by leaf pigments is used to produce hydrocarbon in chlorophyll. Part of the energy absorbed by chlorophyll is always lost as heat or fluorescence. The xanthophyll cycle plays a key role in regulating the energy flow (Bilger and Bjorkman 1990). Under conditions of excess light, the absorbed PAR exceeds photosynthetic capacity. The excessive PAR causes the deepoxidation of violaxanthin to zeaxanthin through antheraxanthin. The process is reversed under limiting light condition (Demmig-Adams 1990). Therefore, the xanthophyll cycle is directly related to photosynthetic radiation-use efficiency. Gamon et al. (1990) identified that the reflectance feature at 531 nm is associated with the conversion of violaxanthin to zeaxanthin. A spectral index, the physiological reflectance index (PRI), was defined to quantify canopy photosynthetic function as in the following:

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PRI = \frac{R_{531} - R_{570}}{R_{531} + R_{570}}
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where \( R_{531} \) and \( R_{570} \) are reflectance at 531 and 570 nm, respectively. PRI was later renamed as photochemical reflectance index by Gamon et al. (1992). Several subsequent studies found that PRI is highly correlated with photosynthetic radiation-use efficiency (Penuelas et al. 1995, Gamon and Surfus 1999, Sims and Gamon 2002). Nichol et al. (2006) examined the radiation-use efficiency with experimental mangrove forests and found that PRI is an effective indicator of photosynthetic activity. In this study, we further test the feasibility of using PRI for monitoring mangrove forest growth in field conditions. Because salinity is a major stress factor for mangrove growth, we hypothesize that there be a statistically significant relationship between PRI and salinity gradient. If this relationship exists, it would serve as theoretical basis for development of new approaches to monitor/model mangrove forest growth using remotely sensed data.

2.2. Study sites

The Galapagos Islands, located 1000 km off the coast of Ecuador, are a volcanically active archipelago consisting of 13 large islands, 4 of which have human populations, and 188 small islands and rocks. The Galapagos Islands were declared a national park in 1959 (the park consists of 97% of land area), a UNESCO World Heritage Site in 1978 and a UNESCO Biosphere Reserve in 1987. The Galapagos Islands lie on the western edge of the Atlantic–East Pacific mangrove complex. Mangrove forests consist of three species common in this region: red (\textit{Rhizophora mangle}), black (\textit{Avicennia germinans}) and white (\textit{Laguncularia racemosa}) mangroves, as well as several mangrove associates. In the Galapagos Islands, mangrove forests form dense but small patches in protected coves and lagoons along an otherwise barren or arid coast. Our study sites are located near Puerto Villamil on Isla Isabela, which is the largest island of the Galapagos archipelago (figure 1). We selected two sites to study the salinity stress on mangrove growth with hyperspectral remote sensing along a protected bay. Site 1 is dominated by red mangroves along an estuary with deep sediment deposits and fed by a landward freshwater spring. The freshwater input creates a strong salinity gradient, particularly at low tide. We identified 10 spots (points to the left in the top panel in figure 1) along the salinity gradient and sampled leaf reflectance and salinity simultaneously. Site 2 is located to the east of Site 1 and is dominated by white mangroves. This site lacks freshwater input and lies on top of a lava bedrock ledge with shallow sediment deposits and tidal pools.

2.3. Hyperspectral reflectance measurements

We used the FieldSpec HandHeld device manufactured by ASD Inc. (at Boulder, CO, USA) to take the hyperspectral reflectance measurements. The spectral range spans 325–1075 nm. The spectral resolution is 3.5 nm with a sampling interval of 1.6 nm. The processing software resamples the reflectance with 1.0 nm resolution. The instrument was calibrated by the manufacturer just before taking to the field. To control for noise in the field, we equipped the FieldSpec HandHeld with a plant probe and a leaf clip, accessories provided by the manufacturer. The plant probe comes with a halogen bulb (2901 K) to provide a constant source of light. The plant probe and the HandHeld device is connected with a fibre optic wire. The leaf clip is specially made to simplify the spectral measurement of leaves with the plant probe. Together they can gently enclose a circular leaf area with 1 cm in diameter. Because of the relatively low temperature from the halogen bulb, we found that reflectance signals below 400 nm are noisy.
Because of the fact that there are significant variations in the spectral signature for different leaves on the same tree depending on its age and physical condition, we selected the mature healthy leaves for the hyperspectral measurements. Leaves were carefully selected such that all were fully grown with no mechanical damage. We found that the second leaf from the top of a shoot best met these requirements. The location of the spectral measurements can also influence the reflectance signal, particularly whether the main leaf vein in the middle is enclosed. Although measurements avoiding the main leaf vein are ideal, it is impossible to avoid the main leaf vein in the spectral measurement with the leaf clip because of the relatively small leaf size of white mangrove. To facilitate comparison between red and white mangroves, we measured the spectral signal at the tip of the leaves across the main vein for both species. To reduce random error, each spectral measurement is an average of five samples.
Measurements were carried out on land because of the difficulty and risk of working with valuable electronic equipment in the intertidal swamp. Gamon et al. (1990) found that leaf reflectance at 531 nm can change within minutes after switching from dark to full light in field conditions without detachment. Because of the difficulty in access, detachment of leaves from the tree is a common practice in hyperspectral measurements of mangrove leaves (Sims and Gamon 2002, Vaiphasa et al. 2007, Wang and Sousa 2009). In our experiment, the light intensity was constant for all leaves as a result of using the plant probe, and the use of a leaf clip maximally reduces noise from other sources. We assume that similar change in PRI among all leaves will occur within minutes after detachment, thus not significantly altering the relationships between PRI and salinity.

2.4. Salinity measurements

Salinity was measured in situ at each of the mangrove sites using a Hydrolab Quanta CTD (Hach Environmental, Loveland, CO, USA) with specific conductivity, temperature and depth sensors. Salinity provided by the instrument is in specific conductivity at 25°C in milliSiemens per centimetre (mS cm−1). Seawater salinity is ~52 mS cm−1. Transects were made at each site during different days and at different times during the tidal cycle, to investigate both spatial gradients and tidal cycle variability. At Site 1, the spring-fed estuary, near-bottom and near-surface water salinity was measured during both high and low tides, along the seaward increasing salinity gradient. Salinity throughout the estuary was the highest during low tide, and these values were used for analysis with PRI.

Salinity was also measured at Site 2, the white mangrove site along the lava rocky shore. At low tide, the white mangroves are above the sea level among tide pools in the lava bedrock. We measured the salinity of the silt close to the root for the individuals from which we took leaf samples. To measure the salinity of silt, we mixed 1 part of silt with 5 parts bottled freshwater in volume (Henschke and Herrmann 2007). We also measured the tide pool water close to the root of the sampled individuals.

3. Results and discussions

The relationship between PRI and salinity gradient is shown in figure 2 for red mangroves at low tide. The relationship is statistically significant (r = 0.69; p = 0.03). Salinity is negatively correlated with PRI, indicating that salinity is a stress factor to red mangrove growth. Given that multiple other environmental factors, such as nutrients and wave impacts, may influence mangrove growth, it is clear that salinity is a major environmental factor controlling red mangrove growth.

The white mangroves found on the lava rocky shore are found in an intertidal region with high variability in tidal inundation, wave forcing and salinity stress. This site is more energetic and temporally variable than the red mangrove site (figure 1). Thus, the relationships between PRI and physical factors are expected to be more complex. The relationship between PRI and silt salinity is negatively correlated (figure 3(a)), but the relationship is weaker (r = 0.53; p = 0.14) than that for the red mangrove. Several factors may contribute to the weaker relationship between PRI and salinity for white mangroves. First, there is a smaller salinity dynamic range in the samples, which may mask the effect of salinity stress. Second, the silts sampled are not uniform as they contain varying proportions of very fine roots and sand. These non-silt components contribute to the salinity noise weakening its relationship with PRI. Third, the sampling
The relationship between pool water salinity and PRI is reversed (figure 3(b)). The pool water salinity is strongly influenced by evaporation and therefore by the time elapsed since the last seawater inundation. Thus, salinity can be highly variable and is a strong function of phase in the spring–neap tidal cycle as well as wave conditions. The pool size and the time of evaporation determine the pool water salinity along the tidal range. In general, the higher the pool is in the intertidal range and the further from the seafront, the longer the evaporation time since the last high tide. Thus, the salinity gradient of pool water on shore is an indirect measurement of height in the intertidal region and distance to the seafront. Thus, we hypothesize that figure 3(b) primarily reflects the impact of waves on the growth of white mangrove, rather than salinity.

Comparing figures 2 and 3(a) suggests that red mangroves are more sensitive to salinity than white mangroves according to the magnitude of the slope of the regression line. This finding is consistent with salinity experiment as reported in the literature (Chen and Twilley 1998). Mangrove forests have several mechanisms to cope with salinity, leading to local accumulation of salt in the root zone. The fact that red mangrove is generally distributed at the seafront is testimony to its lower tolerance of salinity as the frequent wash of tidal water helps dilute the local salt accumulation. The freshwater input from upland further reduces the salinity stress, thus red mangroves generally grow well in estuaries. The capability of identifying the effect of salinity gradient on mangrove forest growth with hyperspectral remotely sensed signals makes it possible to monitor mangrove forest growth on a regional scale.

Salinity is one of the key environmental factors that distinguish upland forests from mangrove forests. The multiple taxa of mangroves indicate multiple independent evolutionary adaptations to saline conditions from terrestrial forests (Duke et al. 2002). Although mangrove forests are among the most productive ecosystems in the world (Clough et al. 1997), salinity is an environmental stressor, not a facilitator (Lin and Sternberg 1993, Ball 2002, Saenger 2002). The gradient of salinity along intertidal coastal areas contributes to the zonation of the mangrove forests. Currently, there are very limited approaches available in modelling and monitoring mangrove forest growth.

Our finding points to a new direction in modelling and monitoring mangrove forest growth using hyperspectral imagery. In general, hyperspectral remotely sensed data are very limited, but the situation will significantly improve given the fact that the United States is planning to launch the Hyperspectral Infrared Imager in the coming years. Realistic modelling of mangrove forest growth in the Galapagos Islands will significantly aid the conservation effort to protect the endemic species that reside in the mangrove forests.

4. Conclusions

This study found that red mangrove forests show a statistically significant salinity stress effect on PRI, an indicator of radiation-use efficiency in plant photosynthesis. White mangrove forests have a reasonably strong relationship between salinity and PRI, but not as strong as the red mangroves. Results from this study point to a new direction to monitor/model mangrove forest growth on a regional scale using hyperspectral remote sensing. Future research is needed (1) to examine the effects of multiple variables, including salinity, wave-action and soil nutrients, on photosynthesis and (2) to scale spectral relationships for satellite-based remote sensing applications.
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