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Quantifying mangrove chlorophyll from high spatial resolution imagery

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ABSTRACT

Lower than expected chlorophyll concentration of a plant can directly limit photosynthetic activity, and resultant primary production. Low chlorophyll concentration may also indicate plant physiological stress. Compared to other terrestrial vegetation, mangrove chlorophyll variations are poorly understood. This study quantifies the spatial distribution of mangrove canopy chlorophyll variation using remotely sensed data and field samples over the Rapid Creek mangrove forest in Darwin, Australia. Mangrove leaf samples were collected and analyzed for chlorophyll content in the laboratory. Once the leaf area index (LAI) of sampled trees was estimated using the digital cover photography method, the canopy chlorophyll contents were calculated. Then, the nonlinear random forests regression algorithm was used to describe the relationship between canopy chlorophyll content and remotely sensed data (WorldView-2 satellite image bands and their spectral transformations), and to estimate the spatial distribution of canopy chlorophyll variation. The imagery was evaluated at full 2 m spatial resolution, as well as at decreased resampled resolutions of 5 m and 10 m. The root mean squared errors with validation samples were 0.82, 0.64 and 0.65 g/m^2 for maps at 2 m, 5 m and 10 m spatial resolution respectively. The correlation coefficient was analyzed for the relationship between measured and predicted chlorophyll values. The highest correlation: 0.71 was observed at 5 m spatial resolution (R^2 = 0.5). We therefore concluded that estimating mangrove chlorophyll content from remotely sensed data is possible using red, red-edge, NIR1 and NIR2 bands and their spectral transformations as predictors at 5 m spatial resolution.

1. Introduction

Mangroves are one of the most productive and biochemically active ecosystems (Suratman, 2008). Their dense root system reduces coastal erosion, and protects the coastline from flood, waves and storms. These roots also filter and trap pollutants, thereby decreasing coastal pollution. Mangrove forests serve as a nursery area for shrimps, fish and crustaceans. On the global scale, high population pressure in coastal areas has converted many mangrove forests into infrastructure, salt and rice production, and aquaculture (Food and Agriculture Organisation, 2007). If these coastal activities are unsustainably planned and managed, the result will be a large scale mangrove degradation or deforestation. Therefore, the maintenance of mangrove ecosystems is important.

Maintenance of mangrove ecosystems requires better knowledge of their physiological processes such as photosynthesis, net primary production and plant health (Flores-de-Santiago et al., 2013). The status of these physiological processes may reflect by the nutrients in vegetation foliage (Filella and Penuelas, 1994). For example, plant stress may affect the plant pigment system, and thus the photosynthesis. More specifically, the chlorophyll content of any foliage is correlated with nitrogen levels, and hence photosynthesis, and developmental stages (Filella and Penuelas, 1994; Haboudane et al., 2002; Wu et al., 2008). Therefore, assessing mangrove chlorophyll content is an important tool for ecosystem management.

Chlorophyll variations can occur at a variety of scales from individual trees to communities, or even broader regions. Variations are affected by soil type, soil nutrients, topography, and daily nutrient intake received from other sources (Williams,

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2012). Compared to other ecosystems, understanding mangrove biochemical variations especially chlorophyll content is relatively limited (Flores-de-Santiago et al., 2013; Williams, 2012; Zhang et al., 2012).

Quantifying spatial variability of mangrove chlorophyll from field observations is time consuming and costly. An intensive sampling scheme is needed throughout the area of interest to capture fine scale spatial variability. As fine scale sampling is often prohibitive over large areas, predictive models are created to extrapolate the information to unsampled regions. Remote sensing is integral in this process.

Remote sensing has been used for decades to measure the chlorophyll content of various natural plant communities (Atzberger et al., 2010; Boegh et al., 2012; Clevers and Kooistra, 2012; Filella and Penuelas, 1994; Joyce and Phinn, 2003). For example, Wu et al. (2008) compared the performances of several vegetation indices derived from hyperspectral data in estimating chlorophyll content, and introduced four new vegetation indices that are highly correlated with canopy chlorophyll. Gitelson et al. (2003) investigated the spectral characteristics of the relationship between reflectance and chlorophyll content of maple, chestnut, wild vine and beech leaves, and developed a technique for non-destructive chlorophyll estimation. These studies commonly related the absorption and reflectance of light in different wavelengths with the presence or absence of photosynthetic pigments. Further, developing statistical relationships between the chemical content extracted from leaf samples and light reflectance in specific wavelengths using airborne or satellite data allows modeling the spatial variations of chlorophyll over a large area.

Chlorophyll absorbs light strongly in the blue and red wavelength regions for the purpose of photosynthesis. Kokaly et al. (2009) described the broad wavelength region of 400–700 nm as the most active region for leaf pigments or chlorophyll. Filella and Penuelas (1994) identified the red edge region (wavelengths of 680–750 nm) as one of the best remote sensing descriptors of chlorophyll concentration. Hunt et al. (2013) developed a triangular greenness index (TGI) considering spectral reflectance at wavelengths: 480, 550, and 670 nm, and confirmed TGI as the best spectral index for low-cost chlorophyll mapping. However, Wu et al. (2008) stated that the blue region should not be used to estimate chlorophyll content due to its overlapping absorption features with carotenoids. Therefore, the chlorophyll prediction indices that provide higher accuracies are mainly based on the reflectance around the 550 nm or 680–750 nm regions. In summary, there are numerous options for revealing canopy pigment concentration from remotely sensed data.

The challenge is to identify the spectral bands of remote sensing data and their transformations with the highest predictive power to model the spatial variation of mangrove chlorophyll. Statistical relationships between field samples and corresponding reflectance values provide numerical estimates for analyzing the best predictor. For example, Flores-de-Santiago et al. (2013) introduced Vog1 index stating that the ratio of reflectance at 740 nm to that of at 720 nm as the best predictor for the south end of the Urias system mangrove forest in Mexico. Zhang et al. (2012) identified the red-edge position as the best predictor for the degraded mangroves of Mexican Pacific during the dry season.

The aim of this study was to model the spatial distribution of mangrove canopy chlorophyll content using remotely sensed data and field samples. Further, the study analyzed the optimal combination of predictor variables and spatial resolution for chlorophyll mapping with the random forests regression algorithm.

2. Materials and methods

2.1. Study area and satellite data

This study focused on the Rapid Creek mangrove forest in Darwin, Northern Territory, Australia (12°22′43″S, 130°51′55″E) (Fig. 1). The extent of the mangrove forest is about 3.8 ha. *Avicennia marina*, *Ceriops tagal*, *Bruguiera exaristata*, *Lumnitzera racemosa*, and *Rhizophora stylosa* are the most common mangrove species in this forest (Heenkenda et al., 2014). There is relatively limited coverage of the additional species *Excoecaria ovalis* and *Aegialitis annulata*.

A WorldView-2 (WV2) 2.0 m spatial resolution, multispectral satellite image was selected as the remote sensing data source for this study. The image was acquired on 26th July, 2013, with eight multispectral bands. The image was radiometrically corrected with the sensor specifications published by DigitalGlobe® (Updike and Comp, 2010). Digital numbers were converted to at-sensor radiance values, and then to top-of-atmosphere reflectance values. The additive path radiance was removed using the dark pixel subtraction technique in ENVI 5.0 software. Finally, the image was geo-referenced using rational polynomial coefficients provided with the image, and ground control points extracted from digital topographic maps of Darwin, Australia (Heenkenda et al., 2014). To avoid the confusion between mangroves and non-mangroves, mangrove areas were extracted using the object-based image analysis method described in Heenkenda et al. (2014). We used contextual information, geometry and neighborhood characteristics of objects at different hierarchical levels to separate mangrove coverage only.

The WV2 multispectral bands were resampled to 5 m and 10 m spatial resolution using the cubic convolution resampling method. This was done to simulate remote sensing images from other satellite missions that provide multispectral images within the same spectral region such as RapidEye and SPOT 5. Green (506–586 nm), red (624–694 nm), red edge (699–749 nm), NIR1

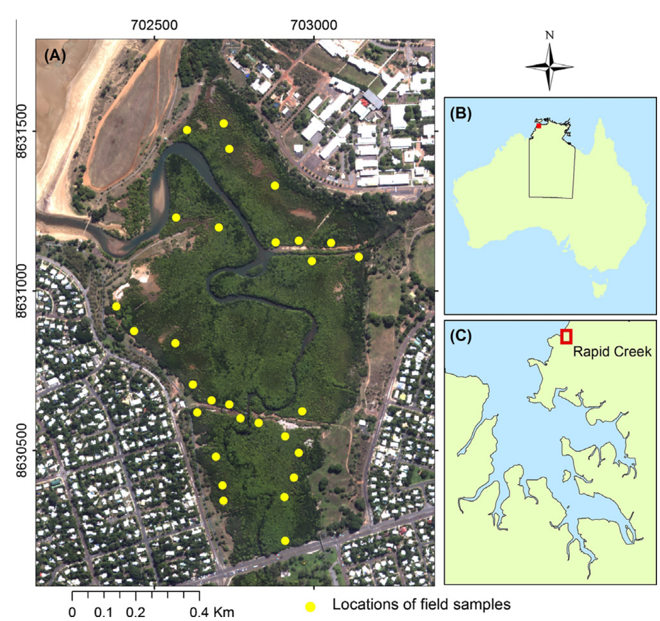

Fig. 1. The study area is located in the coastal mangrove forest of Rapid Creek in Darwin, Northern Territory, Australia; (A) WorldView-2 satellite image and locations of 29 field sampling plots (5 m × 5 m); WorldView-2 images © DigitalGlobe; (B) Australia, the boundary of the Northern Territory, and the study area; (C) The Rapid Creek mangrove forest (study area); *Coordinate system: Universal Transverse Mercator Zone 52 L, WGS84.*