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Evaluating the relationship between the photochemical reflectance index and light use efficiency in a mangrove forest with *Spartina alterniflora* invasion

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ABSTRACT

Mangrove forests, with high productivity, strong carbon fixation ability, and high ecological value, are a critical component of wetland ecosystems. However, in recent years, species invasion is threatening the health of mangrove forests. In order to trace the change and protect them, Light Use Efficiency (LUE) has been used as a significant parameter to estimate the vegetation productivity of mangrove forests. Recent studies have shown that the Photochemical Reflectance Index (PRI) has a strong relationship with LUE. Nevertheless, their relationships undergone significant changes under the influence of vegetation types and external environment. In this paper, we evaluated the relationship between PRI and LUE for different mangrove species (*Avicennia marina* and *Aegiceras corniculatum*) and the effects of *Spartina alterniflora* invasion on the relationship. The results showed that LUE had a strong correlation with PRI. The correlation of *Avicennia marina* was slightly higher than that of *Aegiceras corniculatum*. In addition, LUE values of mangrove forests reduced as a result of *Spartina alterniflora* invasion. The mean LUE value of *Aegiceras corniculatum* decreased by 27.91% which was bigger than the decrease in *Avicennia marina* (23.19%). Furthermore, *Spartina alterniflora* invasion weakened the LUE-PRI relationship of mangrove forests. The coefficient of determination (R^2) of the LUE-PRI relationship of *Avicennia marina* and *Aegiceras corniculatum* dropped by 19.48% in total, and 17% and 25.17% respectively. This research provides an effective approach to estimate the LUE of mangrove forests, which is significant for the evaluation of photosynthetic capacity and productivity of mangrove ecosystems in the future.

1. Introduction

Mangrove forests are the most important forest in tropical and subtropical continental margins (Schmidt, 1995). They grow in intertidal zones, form important intertidal ecosystems with shrubs, connect terrestrial and marine ecosystems, provide habitats for a large number of terrestrial and marine species, and provide valuable ecosystem products and services, including economically and ecologically significant fisheries (Alongi, 2002; Nagelkerken et al., 2008; Jia et al., 2014).

Mangrove ecosystems are the top one productive force in coastal zones. Their productivity is the same with rainforest (Heumann, 2011; Alongi and Mukhopadhyay, 2014). Nevertheless, as the intensification of global communication, species invasion becomes a serious problem in mangrove forests. Invasive species compete with native plants for space and nutrition, leading to a decline in local biodiversity (Zhang et al., 2012; Liao et al., 2018). In order to understand and monitor mangrove changes in global carbon cycle dynamics, quantitative estimation of their primary productivity is important. Models based on LUE theory are major approaches for estimating primary productivity of terrestrial ecosystems using optical remote sensing (Song, 2013). As LUE of vegetation is a key parameter for those models, it is essential to accurately estimate the LUE of vegetation physiology ecology (Chen et al., 2008).

In general, LUE is not directly obtained from remote sensing techniques. It is acquired from the maximum light use efficiency and environmental conditions, such as temperature and moisture (Prince and Goward, 1996; Wang et al., 2009). In recent years, as the development of the CO_2 flux observation technique, analysis of observation data have shown that the relationship between LUE and the environment is very complex. What's more, LUE is not only related to environmental stresses, but also related to vegetation species, leaf area index, nutritional status, and other factors (Potter et al., 1993; Medlyn, 1998;

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Turner et al., 2003). Meanwhile, LUE has obvious diurnal and seasonal variations. It is oversimplified in most models, which may result in serious error in estimating the primary productivity of vegetation. Eddy flux correlation technology provides an effective method for estimating LUE at site scale. However, the estimation accuracy is difficult to improve(Zhang et al., 2015). Thus, how to estimate LUE directly using remote sensing is a key problem to be resolved in the application of LUE models.

In recent years, more and more studies have found that the Photochemical Reflectance Index (PRI) had great potential for the direct estimation of LUE. Gamon et al. (1990, 1992) proposed physiology reflectance index for the first time when observing the physiological and biochemical characteristics of sunflower leaves. He suggested that physiology reflectance index was associated with net photosynthesis. Later, Penuelas et al. (1995) modified and renamed it as the Photochemical Reflectance Index (PRI) to estimate the utilization of light at 531 nm. In fact, the variation of spectra at 531 nm is related to the epoxidation state of the xanthophyll cycle (Demmig-Adams and Iii, 1996). When the absorbed photosynthetic affective radiation (PAR) exceeds the requirement of vegetation, plants will transform violaxanthin to zeaxanthin to consume the excess light in pigment bed. The absorption coefficients of zeaxanthin near 531 nm is higher than that of violaxanthin. So, the change of xanthophyll cycle pigments leads to the change of leaf reflectance near 531 nm (Demmig-Adams, 1990).

Previous studies have described the relationships between PRI and LUE for different plants using linear regression (Gamon et al., 1992; Trotter et al., 2002) or non-linear fitting such as exponential curves (Penuelas et al., 1995; Filella et al., 1996; Stylinski et al., 2002). Through the experiment of grape vine, Evain et al. (2004) revealed a physiological mechanism that PRI changed along with LUE. Hilker et al. (2008) found a strong, nonlinear relationship between LUE and PRI in a Douglas-fir forest. Thus, PRI derived from narrow bands provides a simple and feasible method for evaluating photosynthetic parameters (Nichol et al., 2002; Louis et al., 2005). In addition, the relationship between the PRI and LUE was also extensively studied under environmental changes, such as different temperature, water pressure, and light conditions (Weng et al., 2006; Rascher et al., 2007; Guo and Trotter, 2006 Hmimina et al., 2014). The stress from those environment conditions resulted in the decrease of photosynthesis and the long-term adjustment of pigment pool, leading to a change in the LUE-PRI relationship (Fréchette et al., 2016; Wong and Gamon, 2015 Gitelson et al., 2017).

Although the relationship between the PRI and various photosynthetic parameters has been well demonstrated, it significantly depends on plant type, environmental stress and biological invasion (Garbulsky et al., 2011; Gamon, 2015). What's more, their relationship is still rarely explored in mangrove ecosystems, presumably due to tidal conditions that increase the difficulty of measuring photosynthesis (Huang, 2013). Nichol et al. (2006) studied mangrove forests that were not affected by tides using a hand-held spectrometer at the Biosphere 2 laboratory in Arizona. It was the first time that a good relationship was demonstrated between the PRI and actual photochemical quantum efficiency for mangrove species, showing the PRI's potential for estimating photosynthesis and productivity of mangroves. Additionally, Song et al. (2011) found that there was a significant relationship between PRI and soil salinity in the mangrove plantation area, further demonstrating the potential of PRI for the detection of productivity and stress in mangroves.

In this paper, we evaluated the relationship between the PRI and LUE in a mangrove forest with *Spartina alterniflora* invasion. More specifically, this study was designed with the following aims: (1) to assess the relationship between PRI and LUE for different mangrove species (*Avicennia marina* and *Aegiceras corniculatum*); (2) to explore the effects of *Spartina alterniflora* invasion on the LUE-PRI relationship for the two mangrove species. These issues are important for future assessments of photosynthetic capacity and productivity of mangrove ecosystems, as well as the analysis of the disturbance of invasive species to mangrove forests.

2. Materials and methods

2.1. Study area

The study area is located in ShanKou Mangrove Nature Reserve, Beihai Hepu County, Guangxi Zhuang Autonomous Region in China (21°29′–21°37′N, 109°37′–109°43′E). The area experiences a subtropical monsoon climate. The average annual temperature is 23.4 °C, and the average annual precipitation is 1816 mm. The tides are diurnal in the coast of Guangxi (Jia et al., 2015). Four mangrove species dominate in the study area: *Avicennia marina* (AM), *Aegiceras corniculatum* (AC), *Kandelia candel* (KC), and *Rhizophiora stylosa* (RS). However, the growth of mangroves there is seriously threatened by an invasive species (*Spartina alterniflora*) (Tian et al., 2017). The *Spartina alterniflora* (SA), a perennial herb, originated on the Atlantic coasts of North America and the Gulf of Mexico, was introduced to China in 1979 for coast protection (Chung, 2006). However, this kind of plant grows fast and competes with native plants for space and nutrition, leading to a decline in local biodiversity (Zhang et al., 2012; Liao et al., 2018). In recent years it has spread rapidly along the coastline from Liaoning Province to Guangxi Province. Thus, SA becomes a plant that negatively affect mangrove growth in China (Wang, 2007).

2.2. Plant material

In this study, two mangrove species including AM and AC were selected. In addition, the interference of SA was considered. Therefore, the study focused on four different types of research objects: *Avicennia marina* (AM), *Avicennia marina* affected by *Spartina alterniflora* (AM_{SA}), *Aegiceras corniculatum* (AC), and *Aegiceras corniculatum* affected by *Spartina alterniflora* (AC_{SA}).

The data was collected with sunny days in April and May in 2017. We selected five sites to study the LUE of mangrove with hyperspectral remote sensing in an island (Fig. 1). The total number of each type of mangroves was 10. The number of specific measurement points is shown in Table 1. Every day two trees (for example, one AM and one AM_{SA}) were measured in the observation area during 9 a.m. to 4 p.m. However, due to the tidal events, sometimes, the collection should be shift for one hour before or after the schedule. The distance between the two sampling trees was about 0.6–1 m, with an open space in the middle. The two samples were relatively close in order to ensure that the environmental factors of the trees were generally consistent.

2.3. Hyperspectral measurement

The spectral data of mangrove leaves were obtained by the ASD FieldSpec4 Spectrometer (Analytical Spectral Devices, Boulder, CO, USA). At the top of each tree canopy, two typical healthy and mature leaves were selected. Mangrove leaves were measured once every hour from 9 a.m. to 4 p.m. The spectral measurement was repeated 5 times and take the average as leaf spectral data for each leaf. The spectral range of the spectrometer is 350–2500 nm. From 350 nm to 1050 nm, band sampling interval is 1.4 nm and spectral resolution is 3 nm. In the rest of the spectral range, 1050–2500 nm, band sampling interval is 2 nm and spectral resolution is 10 nm. The instrument was calibrated before measuring. The experiment used the 99% Lambert body Whiteboard as the reference board.

The spectral data were used to calculate the PRI according to the following equation (Peñuelas et al., 1995):

$$PRI = \frac{R_{531} - R_{570}}{R_{531} + R_{570}} \tag{1}$$

It is a comparison between the reflectance at 531 nm(R_{531}) and the