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Potential ecosystem service values of mangrove forests in southeastern China using high-resolution satellite data

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ABSTRACT

Mangrove forests provide a large number of important ecological, economic, and social benefits. This study proposes a pixel-based method for estimating the spatial variability of mangrove ecosystem services (coastal protection, carbon sequestration, nutrient retention and heavy metal retention) in the Jiulong River Estuary using a combination of high-resolution satellite data with market price and replacement cost approaches. The results indicated that there was a considerable variability in the ecosystem service values caused by the distance of mangroves to the coast and the different growth phases of mangrove forests. The total estimated value of the four selected ecosystem services was US$ 287,993/year for 174.58 ha (approximately US$ 1650/ha/year). Coastal protection was estimated to provide the highest value (US$ 239,683/year), amounting to 83.23% of the total value of the ecosystem services, followed by nutrient retention (US$ 25,283/year), contributing 8.78% of the total value of the ecosystem services and accounting for up to 52.33% of the total value of regulating services. Heavy metals retention (US$ 10,289/year) and carbon sequestration (US$ 12,738 in 2015/year) had relatively low values in comparison to those of coastal protection and nutrient retention. However, there was an underestimation of mangrove ecosystem services because we did not consider other services, such as fisheries, biodiversity, recreation, education and tourism, mainly due to the lack of primary data. Nevertheless, the estimated economic value of mangrove ecosystem services in this area is meaningful to raise awareness of the benefits provided by mangroves to local communities and policy makers.

1. Introduction

Mangrove forests occur in the intertidal zone of estuaries and open coastlines in the tropics and subtropics of the world (Barbier et al., 2011; Saenger, 2002; Viswanathan, 2016). This coastal vegetation not only provides direct economic benefits to local communities (Bennett and Reynolds, 1993; Brander et al., 2012; Vo et al., 2015), such as fishery products and timber products, but also provides a large number of indirect benefits (Barbier, 2016; Clough, 1998; Huxham et al., 2015; Kuenzer et al., 2011; Mazda et al., 2006; Vo et al., 2015), including coastal protection (e.g., coastal erosion control and wave attenuation), water filtration, carbon sequestration, recreation, education and research. However, many mangrove forests are disappearing or are in danger of disappearing mainly due to rapid land-use change and environmental degradation (Giri et al., 2007; Valiela et al., 2001; Vo et al., 2015). This is in large part because the local communities and policy makers are not well aware of the values of ecosystem services provided by mangroves (Vo et al., 2015).

Many previous studies have attempted to estimate the economic value of mangrove ecosystem services around the world (Barbier, 2016; Brander et al., 2012; Kuenzer and Tuan, 2013; Salem and Mercer, 2012; Vo et al., 2012). In these studies, different valuation approaches were used to assess the value of different mangrove ecosystem services, such as market price, replacement cost (RC) and contingent valuation. However, using various approaches to evaluate ecological services provided by mangroves often leads to considerable discrepancy among the values of ecosystem services. For example, the results of Salem and Mercer (2012) showed that the RC method generated higher values compared with market price approach in carbon sequestration valuations. Additionally, the values reported for coastal protection and stabilization were higher when the RC method was used rather than the contingent valuation method. Similarly, Kuenzer and Tuan (2013) reported that coastal protection and sediment stabilization by mangrove forest were higher using a RC approach compared with a contingent valuation method. In addition to the valuation approaches used, several other determinants, such as the development degree of the economy and the society, geographical specificity and perceptions of people on ecosystem services, can impact the monetary value of mangrove

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ecosystem services (Barbier, 2016; Groot et al., 2012; Salem and Mercer, 2012; Vo et al., 2012). Therefore, the value of mangrove ecosystem services is closely associated with socio-economic factors and should be valued at a specific site for a specific time frame.

Estimating the spatial variability in the values of mangrove ecosystem services is more useful for policy making than the valuation of the mangrove ecosystem services as a whole. However, the geographic coverage of valuation studies remains limited (Barbier, 2016). This might be because mangrove forests grow in the intertidal zone which is not easily accessible to humans (Giri et al., 2010). Obtaining mangrove ecosystem service values using field surveys is a difficult, time-consuming, and expensive task. One effective way to evaluate mangroves ecosystem service values is to use satellite imagery, such as using remote sensing to map mangrove cover and thus calculate the distance of mangroves to the coast for a valuation of coastal protection by mangroves (Vo et al., 2015). In addition to distance to the coast, there are several natural factors that can impact the valuation of mangrove ecosystem services, including mangrove biomass, width, morphology and integrity of mangroves (Barbier, 2012, 2016; Koch et al., 2009; Massel et al., 1999; Vo et al., 2015). To accurately estimate the heterogeneity of mangrove service values, these factors must be taken into consideration during the valuation process.

This study focused on the Jiulong River Estuary (JRE) and estimated the values of mangrove ecosystem services and their spatial distributions. Mangrove cover and carbon stocks should be carefully mapped before the value of mangrove ecosystem services are evaluated, because they can be used as spatial variability information (e.g., weighting factor) for the valuation of ecosystem services. In this study, high-resolution PLEIADES imagery and objected-based method were primarily used in the mangrove classification processing and subsequently we utilized a PLEIADES image and field measurements to further estimate the mangrove above-ground carbon (AGC) in the JRE. The objectives of this study were to establish an effective approach in linking remote sensing data with field survey data to estimate the pixel-based values of mangrove ecosystem services. Four services of mangrove forests in the JRE, including coastal protection and three regulating services (carbon sequestration, nutrient retention and heavy metal retention) were selected to estimate the benefits provided by mangroves to the local communities. The four services of mangrove forests were selected for the following reasons: 1) This area is erosion-prone due to the sandy coast (Liu, 2010; Luo et al., 2013). Moreover, the JRE is an area that is frequently hit by typhoons, which result in large wave surges that erode the coastline (Yu et al., 2017); 2) The JRE has serious environmental pollution problems, including nutrient and heavy metal pollution (Yan et al., 2012; Zheng et al., 1996a,b); 3) Mangroves play a critical role in carbon sequestration due to the high primary productivity and low decomposition rate in mangrove sediments, and therefore, mangrove forests can mitigate global climate warming (McLeod et al., 2011). Carbon sequestration of mangroves is gaining more and more attention in the world.

2. Materials and methods

2.1. Study area

This study was conducted within the JRE (24°21′-24°27′N, 117°50′-117°59′E) located in southeastern Fujian Province of China (Fig. 1). The vegetation in this estuary is dominated by mangrove forests, which consist mostly of *Kandelia candel* (more than 90%) (Xue, 2005). The mangroves in this region are some of the best-protected *Kandelia candel* mangrove forests in the world. The mangrove forests that existed historically in this area declined due to mounting population pressure and the rapid development of offshore fisheries. To restore the function of mangrove forests in this area, a plantation program for *Kandelia candel* has been implemented since the 1960s. Moreover, a provincial natural conservation area for mangrove in the JRE was established in 1988. Hence, the felling of mangrove trees in this area now prohibited. To date, the mangrove forest area has markedly increased and the mangroves are mainly 0–50 years old. Mangrove forests are expected to provide a large number of benefits to local communities, such as coastal protection provided by the dense mangroves (Liu, 2010; Luo et al., 2013).

2.2. Field data collection

To estimate mangrove above-ground biomass (AGB), thirty field sample plots (10 × 10 m) were measured from 14 to 17 July 2016 (Fig. 1). Within each 10 × 10 m plot, the diameter at 1.3 m in height (diameter at breast height, DBH) (above the ground) was measured. If the trees were multi-stemmed, each individual stem was measured (Aziz et al., 2008; Cienciala et al., 2013; Clough et al., 1998). To generate regressions for the allometric equations, the heights of trees were measured using a laser range finder. The allometric equations for the assessment of AGB for *Kandelia candel* have been discussed in a previous study (Tam et al., 1995). AGC is closely related to AGB and a conversion factor of 0.45 was used to convert AGB to AGC in our study (Cartus et al., 2014; Lal and Singh, 2000; Manhas et al., 2006; Twilley et al., 1992). The location of each quadrat's centre was recorded using a global positioning system.

2.3. Satellite data collection and processing

A geo-corrected PLEIADES satellite image (2.0 m spatial resolution with an RMSE of 2.5 m) of the study site was acquired for 29 January 2015. The image was subsequently processed using satellite sensor radiometric calibration and FLAASH atmospheric correction with ENVI 5.2 software. The imagery provides reflectance values in four spectral bandwidths: Band 1 (blue) 430–550 nm; Band 2 (green) 500–620 nm; Band 3 (red) 590–710 nm; and Band 4 (near infrared) 740–940 nm.

2.4. Mangrove classification

In this study, an object-based method was employed to classify the processed image using eCognition Developer 8.7 (®Trimble Gmbh, Munich, Germany). The object-based classification method has been widely proven to be more accurate and robust than the traditional pixel-based method (Aguirre-Gutiérrez et al., 2012). Four types of land use/land cover in the intertidal zones including mangroves, grasses, bare flat and water were classified. The object-based method used for image classification was composed of two main steps, including image segmentation and image classification. Segmentation was the first step of the object-oriented method, which is the process of segmenting an image into groups of homogeneous pixels so that the variability within the object would be minimized (Jia et al., 2014). Images segmentation parameters include scale, shape and compactness. In this study, the parameters (by constantly testing) were set as follows: the scale parameter of segmentation was 15, the shape factor was 0.1, and the colour factor was 0.5; then the typical object was sampled and the nearest neighbouring classification function was used to classify this image. This study used a total of 857 field observed points from 14 to 17 July 2016 for accuracy assessment of the classification results. The extent of mangroves (i.e., PLEIADES satellite image, pixel-based) was further extracted by the vector mask of mangroves from the object-based classification and then used to calculate the mangrove carbon and spatial variability of mangrove ecosystem services.

2.5. Model development

In the process of AGC model establishment, in addition to the four spectral bands ($Band_{BLUE}$, $Band_{GREEN}$, $Band_{RED}$ and $Band_{NIR}$), we also examined six band combinations (see Table 1) and elevation. For all the ten independent variables, including the spectral bands and the ratio