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Temporal patterns in species zonation in a mangrove forest in the Mekong Delta, Vietnam, using a time series of Landsat imagery

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ABSTRACT

Time-series analysis of Landsat imagery was used to evaluate trends in species zonation in a restored mangrove forest in the Mekong Delta, Vietnam. Dating back throughout the primary expansion of the forest, the Landsat archive provides a unique opportunity to examine the evolution of a restored forest in all stages of maturity. Through temporal trend analysis, areas of the forest were divided into four development stages: Pre-mangrove water, initial mangrove colonization, a period dominated by *Sonneratia* spp., and the arrival and zonation of secondary species. Field inventory data was used in conjunction with satellite data to investigate the geomorphic and hydrologic influences behind the species zonation. We hypothesize that the development of *Sonneratia* spp. facilitates initial sedimentation. The trees mature at higher soil elevations and a region develops with low forest density, high light availability, and reduced tidal inundation. Multi-species zonation then develops through the timely exploitation of the geomorphic conditions suitable for the establishment of secondary species.

1. Introduction

Mangrove forests are among the most productive yet vulnerable ecosystems in the world. In coastal habitats, mangroves are essential in erosion prevention, nutrient cycling, and habitat provision. Mangroves are also a vital resource for coastal communities by providing fuel, lumber, fishing grounds, and storm protection (Gebhardt et al., 2012; Vo et al., 2015). Extensive root systems and high concentration of organic matter in the soil allow mangroves to have one of the highest amounts of carbon storage of any ecosystem (Richards and Friess, 2015; Warner et al., 2016). Because of their ecosystem services, the economic value of mangroves is estimated to be in the billions of dollars (Brander et al., 2012).

While mangroves are globally distributed in the tropics between 30°N and 40°S, no other region matches the abundance and variety found in Southeast Asia (Giri et al., 2011). Southeast Asian mangroves are part of a larger grouping of species commonly referred to as 'Old World', or Eastern Hemisphere mangroves. Those in the Western Hemisphere are consequentially referred to as 'New World' mangroves. Southeast Asian mangrove forests exhibit higher levels of species diversity than those in Africa and the Americas, and also have the highest rate of deforestation (Kuenzer et al., 2011; Gebhardt et al., 2012). From 1950–2000, an estimated one third of the world's mangroves were destroyed, of which almost half occurred in Southeast Asia (Alongi, 2002; Gebhardt et al., 2012). Aquacultural conversion, harvesting for local use, and in some countries war, have all contributed to this dramatic decrease in mangrove forests in the region over the last century.

Mangroves grow in intertidal environments and are often found in distinct zones of individual species (Tomlinson, 1986). While undoubtedly important for ecosystem structure and functionality, the causes of mangrove zonation and distribution are still not well understood (Snedaker, 1982). Currently, the dominant forces thought to control mangrove zonation are succession, geomorphology, external disturbances, ecophysiology, and competition (Lugo and Snedaker, 1974). Early studies utilized ecological succession to explain zonation patterns, with a natural progression from a 'primary' or 'pioneer' species, to one or multiple 'secondary' species (Watson, 1928; Davis, 1940; Tomlinson, 1986; van Loon et al., 2007). However, succession by land building implies that the primary species promotes sediment accumulation and facilitates the arrival of new species, which is not always the case for mangroves. In fact there is evidence that mangroves are merely responding to shoreline progradation without causing it (Thom, 1967). Geomorphology influences the interaction between species develop-

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ment and sedimentation. Thom (1967) showed that mangrove species in the Grijalva-Usumacinta Delta in Mexico are segregated according to landform type. Mangrove zonation is thus induced by delta morphodynamics, such as the abandonment of a distributary triggering subsidence or the shifting of the active center of deposition. The influence of landform type is also in part due to the associated changes in hydrodynamics of the landscape, including varying levels of tidal inundation, wave power, and salinity (Woodroffe, 1992). External disturbances include storm surges, extreme winds, droughts, increasing sea level, and anthropogenic influences. Piou et al. (2006) determined that hurricane destruction and subsequent mangrove regeneration was a factor influencing horizontal zonation patterns in Belize. Ecophysiology is based on the physical responses of species to changes in the environment. McKee (1993) indicates that spatial and temporal variations in soil redox potential can affect the distribution of mangrove species. Interspecific competition can also explain mangrove zonation. Cardona-Olarte et al. (2006) showed that some mangrove species have competitive advantage over others within a range of salinity and hydroperiod.

The fast growth and numerous ecosystem services of mangroves have led regions to invest in reforestation efforts over large areas (Lewis, 2005). Restoration projects have had varying levels of success resulting in a range of economic and ecological benefits. While there are often multiple primary objectives, one of the major aims of mangrove restoration is returning to the original levels of biodiversity and ecological functions (Ellison, 2000). Being able to monitor these dynamic systems over large areas would improve our understanding of the processes leading to mangrove zonation as well as improve management and planning of mangrove restoration sites. Restoration sites offer a unique opportunity to study the development of the forest while the zonation is first occurring. This study investigates the use of time-series of remote sensing data to track changes in species zonation of a restored mangrove forest in the Mekong Delta, Vietnam. The same fringe forest was studied by Nardin et al. (2016a, 2016b), who focused on the encroachment of pioneer mangrove species. In this paper we instead study vegetation zonation and the arrival of secondary species.

Through time-series analysis in combination with a high-resolution canopy survey, clear patterns in the expansion and zonation of the forest can be detected. These patterns can then be used to make inferences about the underlying causation of the zonation that has helped the restored forest develop into a mixed-species environment.

1.1. Remote sensing of mangrove forests

The dramatic decrease in the global abundance of mangroves has led to an urgent demand to detect and assess their distribution, composition, and health. Since the locations of mangrove forests are often remote and inaccessible, remote sensing offers the only feasible means of monitoring them over large areas (Kuenzer et al., 2011). Applications of remote sensing for mangrove management can broadly be grouped into two categories. The first category includes attempts to quantify their extent and detect natural and anthropogenic land cover changes. Many of these efforts have utilized high-to-medium resolution optical sensors such as Landsat and SPOT. These sensors offer consistent measurements over time that allow for change detection at spatial resolutions adequate for mangrove classification. The Landsat series of sensors has provided continuous and global data availability at 30-meter spatial resolution since 1982 and 60-meter data since the first launch in 1972. Since then, it has been widely used to assess the distribution (Giri et al., 2011; Long and Giri, 2011) and change in distribution (Béland et al., 2006; Binh et al., 2005; Bui et al., 2013; Dahanayaka et al., 2013; Son et al., 2016; Tran Thi et al., 2013; Tong et al., 2004; Van et al., 2015) of mangroves in Southeast Asia.

The second category includes the assessment of within-stand forest characteristics, such as species composition and nutrient content. There have been a limited number of attempts at mangrove species mapping in Southeast Asia using Landsat. Myint et al. (2008) used object-based analysis of Landsat imagery for mangrove species classification in Thailand, and Kasawani et al. (2010) tested various spectral indices for use in species delineation in Malaysia. While these studies have demonstrated the feasibility of species classification, the subtle differences in the spectral responses of the different plant traits and unrelated “noise” in the images - such as changing tides - make analysis of specific mangrove traits difficult at this spatial resolution (Gao, 1998).

Time-series analysis is often used to address image quality issues, such as noise and fluctuating tidal water-surface elevation, which inhibit the estimates of vegetation characteristics. By calculating the average trend over time, the day-to-day variability can be removed, and what is left is a clearer signal of what is happening on the ground. Landsat has been widely used for time-series analysis due to its long and continuous data archive (Kennedy et al., 2010; Verbesselt et al., 2010; Zhu et al., 2012). Since time-series analysis utilizes the temporal trajectory of a pixel rather than merely its spectral response, subtle changes or trends can be characterized. This information can give added insight into gradual changes in land cover conditions in addition to reducing classification errors due to image noise.

1.2. Study site

The Mekong Delta is located in the southernmost portion of Vietnam where the Mekong River reaches the sea. The Mekong Delta has a tropical monsoon climate with high precipitation between May and October. The Delta is home to over 17 million people, many of them living in coastal communities (Nguyen, 2007). While the climate is ideal for mangroves, years of war and land conversion have left Southern Vietnam with the highest rates of mangrove deforestation in the country. Recently, the primary driver of mangrove loss has been conversion of land to shrimp aquaculture (Gebhardt et al., 2012). To counteract mangrove destruction, policies were established in the 1980s to begin reforesting the seacoast (San, 1993). Since then, an estimated 1300 km^2 of mangroves have been reforested (Blasco et al., 2001).

The specific area of interest for our study is a fringe forest on Cù Lao Dung Island at the mouth of the Sông Hậu River. The river is one of the major distributaries of the Mekong River into the South China Sea. The mangrove forest of interest is fronted by a sand and mudflat with the adjacent land being heavily farmed and modified. Between 1993 and 2007 Sóc Trăng Province (where Cù Lao Dung is located) restored 1400 ha of *Sonneratia* (Wyatt et al., 2012). Starting in the 1990's, *Sonneratia* trees were planted at a rate up to of 70 ha per year in Cù Lao Dung, mostly along the southwest forest edge (Wolcke et al., 2015). *Sonneratia* is commonly used as a ‘pioneering’, or introduced species due to its resistance to tropical storms and flooding, ability to grow in high-salinity environments, fast root establishment and growth, and high biomass accumulation (Ren et al., 2008). *Sonneratia* spp. are the natural pioneer species near the distributary mouths of the Mekong Delta, while *Avicennia alba, Avicennia marina and Rizophora apiculata* are also present along the coast farther from the mouths. The mangrove forest is nowadays considered a healthy ecosystem with high biodiversity (Wolcke et al., 2015).

While regeneration is occurring all along the seaward shoreline, its increase is more noticeable in the southwestern part of the island where the planting effort has been focused. The mangroves are then naturally expanding into areas and during time periods in which no planting is occurring. When geomorphic and ecophysiological conditions allow it, other plants can establish on these mudflats (San, 1993; Li et al., 2012). In addition to an abundance of aquatic species, a large number of insects, such as bees, birds and even macaques (crab eating macaque - *Macaca fascicularis*) live in the mangrove forest. The vast amount of available aquatic species leads to high anthropogenic pressure as people from both Trà Vinh and Sóc Trăng Provinces travel