Remote Sensing of Environment 205 (2018) 71–84

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Remote sensing of mangrove forest phenology and its environmental drivers

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ARTICLE INFO

Keywords:
Phenology
Mangrove forest
MODIS

ABSTRACT

Mangrove forest phenology at the regional scale have been poorly investigated and its driving factors remain unclear. Multi-temporal remote sensing represents a key tool to investigate vegetation phenology, particularly in environments with limited accessibility and lack of *in situ* measurements. This paper presents the first characterisation of mangrove forest phenology from the Yucatan Peninsula, south east Mexico. We used 15-year time-series of four vegetation indices (EVI, NDVI, gNDVI and NDWI) derived from MODIS surface reflectance to estimate phenological parameters which were then compared with *in situ* climatic variables, salinity and litterfall. The Discrete Fourier Transform (DFT) was used to smooth the raw data and four phenological parameters were estimated: start of season (SOS), time of maximum greenness (Max Green), end of season (EOS) and length of season (LOS). Litterfall showed a distinct seasonal pattern with higher rates during the end of the dry season and during the wet season. Litterfall was positively correlated with temperature ($r = 0.88$, $p < 0.01$) and salinity ($r = 0.70, p < 0.01$). The results revealed that although mangroves are evergreen species the mangrove forest has clear greenness seasonality which is negatively correlated with litterfall and generally lagged behind maximum rainfall. The dates of phenological metrics varied depending on the choice of vegetation indices reflecting the sensitivity of each index to a particular aspect of vegetation growth. NDWI, an index associated to canopy water content and soil moisture had advanced dates of SOS, Max Green and EOS while gNDVI, an index primarily related to canopy chlorophyll content had delayed dates. SOS ranged between day of the year (DOY) 144 (late dry season) and DOY 220 (rainy season) while the EOS occurred between DOY 104 (mid-dry season) to DOY 160 (early rainy season). The length of the growing season ranged between 228 and 264 days. Sites receiving a greater amount of rainfall between January and March showed an advanced SOS and Max Green. This phenological characterisation is useful to understand the mangrove forest dynamics at the landscape scale and to monitor the status of mangrove. In addition the results will serve as a baseline against which to compare future changes in mangrove phenology due to natural or anthropogenic causes.

1. Introduction

Mangroves are a taxonomically diverse assemblage of tree species which have common morphological, biochemical, physiological and reproductive adaptations that allows them to colonise and develop in saline, hypoxic environments (Alongi, 2016). These assemblages form intertidal forests which are one of the most carbon rich ecosystems (Donato et al., 2011) because of their high productivity (Twilley and Day, 1999), rapid sediment accretion (Bouillon et al., 2008) and low respiration rates (Barr et al., 2010). Vegetation phenology, defined as the growing cycle of plants and involving recurring biological events such as leaf unfolding and development, flowering, leaf senescence and litterfall (Njoku, 2014), regulates the timing of plant photosynthetic activity and influences directly the annual vegetation carbon uptake. Vegetation phenology has been a focus of attention in recent years due to a strong and measurable link between biological events and climate (Cleland et al., 2007; Richardson et al., 2013; Dannenberg et al., 2015).

Historically, vegetation phenology was based on field records of key biological events such as budburst, flowering, seed set and leaf senescence (Fitter and Fitter, 2002). Recently, a network of fine-resolution digital cameras installed in the field known as “phenocams”, emerged as a new method to monitor vegetation phenology (Richardson et al., 2007). While this method reduces the subjectivity of human observations, it is limited by its relatively small spatial extent across the globe (Mizunuma et al., 2013; Klosterman et al., 2014). Alternatively, as the reflectance properties of vegetated land varies seasonally in relation to vegetation phenology, the systematic, multi-temporal data collected by optical satellite sensors offer a unique mechanism to monitor vegetation

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https://doi.org/10.1016/j.rse.2017.11.009
Received 11 January 2017; Received in revised form 30 October 2017; Accepted 10 November 2017

dynamics as this approach allows monitoring of an entire ecosystem rather than individual trees (Reed et al., 2009; White et al., 1997, 1999). This has led to the rise of a new field known as land surface phenology (LSP) (Hanes et al., 2014).

In the last few decades, LSP, which uses time-series of satellite-derived vegetation indices, has received considerable attention given its potential to characterise the interactions between vegetation and climate at broad geographical scales. Pioneer work in the temperate latitudes of the American continent showed that the start of vegetation greening was controlled by pre-season temperature (White et al., 1997). Moulin et al. (1997) conducted one of the first attempts to map global vegetation phenology using the Advanced Very High Resolution Radiometer (NOAA/AVHRR) at 1° × 1° resolution. The study revealed patterns in the global vegetation phenology related to seasonal variation in climate. For example, the start of vegetation greenness in temperate deciduous forests was strongly influenced by temperature, whereas savannahs were more influenced by rainfall. The capability to study global vegetation dynamics increases as more advanced sensors and new algorithms become available. Zhang et al. (2006) mapped global vegetation phenology at a finer spatial resolution (1 km × 1 km) achieving more realistic results using the Enhanced Vegetation Index (EVI) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS). In the last decade, numerous studies have been carried out to analyse patterns in vegetation phenology at continental and regional scales at a variety of latitudes including the boreal ecosystem (Xu et al., 2013; Jeganathan et al., 2014), Europe (Stöckli and Vidale, 2004; Rodriguez-Galiano et al., 2015a), India (Dash et al., 2010) and the Amazon Forest (Xiao et al., 2005b).

Despite increasing interest in the use of remote sensing to characterise vegetation phenology, most studies of mangrove phenology rely on traditional field methods consisting on *in situ* collection of different components of litterfall (*e.g.* leaves, branches, flowers and propagules) (Leach and Burgin, 1985). Studies of this nature were documented in mangrove forests across the globe (see Table 1), and those studies have indicated that litterfall dynamics and reproductive phenology of mangroves is driven by a complex interaction of ecological (species composition, competition, reproductive strategy), climatic (air temperature, precipitation, evaporation, hours of sun, wind speed) and local environmental factors (fresh water inputs, tides, flooding, soil salinity, soil nutrients) and natural disturbances (*e.g.*, hurricanes). Moreover, these studies revealed that although mangroves are evergreen species that produce litterfall and replace old leaves continuously throughout the year they generally present a peak of leaf fall, leaf emergence and reproductive structures in the wet season. There are cases, however, where this pattern can be bimodal, with one leaf fall peak in the dry season and one in the wet season.

Although the above studies provide a local perspective of the interaction between mangroves and physical drivers, there are some limitations. For instance, mangroves are often distributed across hundreds of kilometres of coastlines. Thus, spatially restricted studies do not support observation of the phenology phases over the complete extent of the forest. In addition, a common characteristic of those studies is the limited time span, ranging between 1 and 4 years. This relatively short period prevents observing inter-annual variation and trends in phenological metrics and how they are driven by any climatic factors. Spatially continuous and temporally rich information on mangrove phenology would be useful to characterise mangrove forest dynamics at the landscape scale and understand their contribution to biogeochemical cycles.

Table 1
Field studies addressing mangrove forest phenology.

Country	Reference
Australia	Coupland et al., 2005; Duke, 1990
Borneo	Sukardjo et al., 2013
Brazil	Mehlig, 2006; Fernandes, 1999
India	Upadhyay and Mishra, 2010; Wafar et al., 1997
Japan	Kamruzzaman et al., 2016; Sharma et al., 2014
Kenya	Slim et al., 1996
Malaysia	Hoque et al., 2015; Akmar and Juliana, 2012
Mexico	Agraz-Hernández et al., 2011; Utrera-López and Moreno-Casasola, 2008; Aké-Castillo et al., 2006; Arreola-Lizárraga et al., 2004; Day et al., 1987; Lopez-Portillo and Ezcurra, 1985
Panama	Cerón-Souza et al., 2014
South Africa	Rajkaran and Adams, 2007
United States of America	Castañeda-Moya et al., 2013

To date there has been no characterisation of mangrove forests phenology using remote sensing data. In this paper, we estimate and map phenological metrics from time-series of medium resolution satellite sensor imagery in a mangrove forest in the SE of Mexico and investigate their relationship with environmental drivers. The objectives of this research were to (i) estimate phenological parameters using a time-series of MODIS vegetation indices to explore the consistency among them, (ii) map the spatial distribution of phenological metrics (start of growing season, time of maximum greenness, end of growing season and end of season), and (iii) characterise the relationship between phenology dynamics and environmental drivers.

2. Methods

2.1. Study area

Yucatan Peninsula is located in SE Mexico (Fig. 1). To the west and north the Yucatan Peninsula is bordered by the Gulf of Mexico and to the east it is bordered by the Caribbean Sea. The area comprises the states of Campeche, Yucatan and Quintana Roo. Except for a narrow fringe of dry climate in the north west (see Figs. S1–S3), the climate of the Yucatan Peninsula is predominantly hot and humid with little precipitation all year and a distinct rainy season in summer (Roger Orellana et al., 2009). The region experiences three seasons: a dry season from March to May, a rainy season from June to October and a cold season from November to February (Herrera-Silveira et al., 1999). The mean annual temperature ranges from 26.5 to 25.5 °C and mean annual precipitation ranges from 600 mm to 1100 mm (Roger Orellana et al., 2009). Mangrove forest in the Yucatan Peninsula is found on a flat karstic substrate that facilitates the infiltration of rainfall resulting in the absence of runoff and the lack of important streams above the surface (Pope et al., 1997). The vertical and horizontal range of the tides is variable across the study area as the tide depends on the morphology of a particular location. For the Yucatan Peninsula the tidal range is estimated to be between 0.06 m to 1.5 m (Herrera-Silveira and Morales-Ojeda, 2010). The mangrove forest is separated from the sea by a sand barrier and it extends in a fringe of varying widths parallel to the coast covering an area of approximately 423,751 ha which represents 55% of Mexico's mangrove cover (CONABIO, 2009). Four species of mangrove dominate the landscape: *Rhizophora mangle*, *Laguncularia racemosa*, *Avicennia germinans and Conocarpus erectus*. The National Commission for Knowledge and Use of Biodiversity (CONABIO) has a programme for mapping and monitoring mangrove forest based on aerial photography and fine spatial resolution satellite sensor imagery which is updated every five years.

2.2. Data processing

Four major steps were followed in this research as summarized in Fig. 2: (i) remote sensing data pre-processing and computation of vegetation indices, (i) time-series smoothing and estimation of phenological metrics, (iii) *in situ* data collection and comparison of *in situ* data with mangrove phenology.

Although there is a phenology product readily available it was not