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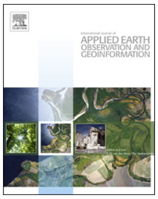

Identifying and forecasting potential biophysical risk areas within a tropical mangrove ecosystem using multi-sensor data

Shanti Shrestha[a,f], Isabel Miranda[c,f], Abhishek Kumar[b,f], Maria Luisa Escobar Pardo[c,f], Subash Dahal[e,f], Taufiq Rashid[d,f], Caren Remillard[b,f], Deepak R. Mishra[b,*]

[a] *Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA*
[b] *Department of Geography, University of Georgia, Athens, GA 30602, USA*
[c] *Department of Geography, Clark University, Worcester, MA 01610, USA*
[d] *College of Engineering, University of Georgia, Athens, GA 30602, USA*
[e] *Department of Crop and Soil Sciences, University of Georgia, Athens, GA 30602, USA*
[f] *NASA DEVELOP Program, University of Georgia, Athens, GA 30602, USA*

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ABSTRACT

Mangroves are one of the most productive ecosystems known for provisioning of various ecosystem goods and services. They help in sequestering large amounts of carbon, protecting coastline against erosion, and reducing impacts of natural disasters such as hurricanes. Bhitarkanika Wildlife Sanctuary in Odisha harbors the second largest mangrove ecosystem in India. This study used Terra, Landsat and Sentinel-1 satellite data for spatio-temporal monitoring of mangrove forest within Bhitarkanika Wildlife Sanctuary between 2000 and 2016. Three biophysical parameters were used to assess mangrove ecosystem health: leaf chlorophyll (CHL), Leaf Area Index (LAI), and Gross Primary Productivity (GPP). A long-term analysis of meteorological data such as precipitation and temperature was performed to determine an association between these parameters and mangrove biophysical characteristics. The correlation between meteorological parameters and mangrove biophysical characteristics enabled forecasting of mangrove health and productivity for year 2050 by incorporating IPCC projected climate data. A historical analysis of land cover maps was also performed using Landsat 5 and 8 data to determine changes in mangrove area estimates in years 1995, 2004 and 2017. There was a decrease in dense mangrove extent with an increase in open mangroves and agricultural area. Despite conservation efforts, the current extent of dense mangrove is projected to decrease up to 10% by the year 2050. All three biophysical characteristics including GPP, LAI and CHL, are projected to experience a net decrease of 7.7%, 20.83% and 25.96% respectively by 2050 compared to the mean annual value in 2016. This study will help the Forest Department, Government of Odisha in managing and taking appropriate decisions for conserving and sustaining the remaining mangrove forest under the changing climate and developmental activities.

1. Introduction

Mangroves are one of the most productive ecosystems with unique morphological, biological, and physiological characteristics that help them to adapt extreme environmental conditions including high salinity, high temperature, strong winds, high tides, high sedimentation, and anaerobic soils (Giri et al., 2011; Kuenzer et al., 2011). They can sequester large amounts of carbon estimated to be around 22.8 million metric tons each year, which is 11% of the total terrestrial carbon (Giri et al., 2011). They help in accumulation of sediments, contaminants and nutrients (Alongi, 2002), thus acting as biological filters and maintain water quality. In addition, mangroves provide a buffer against erosion and storm damage, thus protecting coastal communities from adverse oceanic dynamics (Mazda et al., 1997; Blasco et al., 2001). Besides providing provisioning and cultural services, they are also rich biodiversity hotspots (Manson et al., 2005; Nagelkerken et al., 2008). Despite numerous ecosystem services provided by mangroves, current extent of mangroves is declining rapidly, especially in Southeast Asia, where it is declining at a rate of 3.58%–8.08% (Hamilton and Casey, 2016). Besides natural disturbances like hurricanes, tsunami, storms, and lightning, numerous anthropogenic factors like landuse conversion for aquaculture, agriculture, urban development; overexploitation; and pollution have been found to destroy millions of mangroves (Reddy et al., 2007). Recently, several studies have identified climate change as

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[*] Corresponding author.
E-mail address: dmishra@uga.edu (D.R. Mishra).

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the largest global threat to mangrove in the coming decades (Blasco et al., 2001; Alongi, 2002). It is predicted that climate change is going to intensively alter atmospheric and water temperature; timing, frequency and amount of rainfall; magnitude of sea-level rises; wind movements and frequency and severity of hurricanes (Solomon, 2007). Though mangroves possess resistive capacity to withstand and recover from these changes, mangroves extent, composition and health may undergo changes when coupled with anthropogenic disturbances (Kandasamy, 2017). Hence, an increasing need has been identified for global monitoring system of mangrove response to climate change (Field, 1994). In this context, satellite based remote sensing has the potential to provide cost-effective, reliable and synoptic information to examine mangrove habitats and frequent monitoring over a large area. Particularly, in developing countries where geoinformation is rare, its use is immensely valuable.

Availability of open source historical and near real-time satellite data, increased range of datasets at varying spatial, temporal and spectral resolutions and recent developments in the hardware and software used for processing a large volume of satellite data have helped increase the usefulness of remotely sensed data in environmental monitoring (Kamal et al., 2015). Many scientific studies have been published regarding the potential of remote sensing to detect, map and monitor areal extent, species differentiation, density changes, carbon stock estimation, productivity and health assessment of mangroves throughout the world (Giri et al., 2011; Kamal and Phinn, 2011; Bhar et al., 2013; Giri et al., 2015; Patil et al., 2015; Khairuddin et al., 2016; Sari and Rosalina, 2016; Sanderman et al., 2018; Satyanarayana et al., 2018). Many studies have used moderate resolution satellite data to produce a long-term phenology and identify hotspots for early stages of mangrove degradation (Ibharim et al., 2015; Pastor-Guzman et al., 2015; Ishtiaque et al., 2016; Pastor-Guzman et al., 2018). For example, Pastor-Guzman et al. (2015) assessed spatio-temporal variation in mangrove chlorophyll concentration using Landsat 8. Another study by Ishtiaque et al. (2016) has shown the applicability of utilizing MODIS products to monitor biophysical health indicators of mangroves in order to analyze degradation in the Sundarbans. Studies have also shown the potential of synthetic aperture radar (SAR) data for mangrove mapping, especially to address the issue of data gap due to cloud coverage (Cougo et al., 2015; Kumar et al., 2017).

While many past studies have assessed the status, and changes in mangrove forest cover, very few have explored biophysical parameters of mangroves. Moreover, studies on forecasting mangrove spatial extent and biophysical parameters are non-existent. While space and ground-based observations are useful in monitoring ecosystems, and assessing change-detection, they only consider past or current conditions or trends. Being able to assess an ecosystem in the future is important as it allows decision-makers to take precautionary steps and prepare for adverse future conditions (Nemani et al., 2007). Within the past decade climate forecasting capabilities of coupled ocean-atmosphere global circulation models (GCMs) have improved allowing for future climate trends to be applied on the ecosystem to forecast biophysical and land-cover conditions (Zebiak, 2003; Nemani et al., 2007). Advent of tools like TerrSet Land Change Modeler have now allowed prediction of future land-cover transitions (Rodríguez Eraso et al., 2013; Weber et al., 2014). Also, availability of data such as NASA's Giovanni derived meteorological parameters and WorldClim projected spatial data have provided avenues for predicting how mangrove ecosystems will change in the future in response to environmental factors. These tools and resources were utilized in this study to develop a framework to forecast mangroves areal extent and their biophysical parameters.

This study aims at integrating data from multiple satellite sensors with projected meteorological variables to achieve forecasting of mangrove biophysical characteristics of Bhitarkanika Wildlife Sanctuary to predict future risk to mangrove extent as well as their ecological health status. Specific objectives of this study are to i) calibrate and validate the models to predict biophysical parameters (GPP and LAI) using surface reflectance data obtained from MODIS for 17 years (2000–2016), ii) analyze spatio-temporal variability in the biophysical parameters, iii) to forecast and map biophysical parameters at year 2050 using hydro-meteorological data, and iv) to perform land use-land cover (LULC) classification and forecast of mangrove land cover. To the best of our knowledge, this is a novel study in terms of ecological forecasting based on biophysical parameters using multi-sensor multi-source data. The study was carried out to investigate the land cover and biophysical characteristics of mangroves in Bhitarkanika Wildlife Sanctuary that harbors the second largest mangrove ecosystem of India.

A large population depends on these mangroves for livelihood including food, raw materials, medicinal and ornamental products (Hussain and Badola, 2010). Mangroves in this region are dynamic and threatened because of many drivers including over-exploitation and conversion to agricultural land (Reddy et al., 2007), overfishing, firewood extraction, and climatic changes. Few studies have assessed vegetation composition, phenology and areal extent of mangroves in Bhitarkanika (Reddy et al., 2006; Upadhyay and Mishra, 2010; Behera and Nayak, 2013). However, information on the temporal behavior of mangrove forests and their biophysical parameters is limited. This study attempts to not only understand the dynamism but also predict how mangrove ecosystem of this region will change in future in response to climatic factors. This study would provide environmental managers with ecological data for informed national and international management of mangrove ecosystems.

2. Materials and methods

2.1. Study area

Bhitarkanika is the second largest mangrove ecosystem in India situated on the east coast of the country, between 20°33′–20°47′N latitude and 86°48′–86°03′E longitude. It lies in the estuarine region of Brahmani, Dhamra and Baitarani rivers in the northeastern corner of Kendrapara District in the state of Odisha. With an extensive area of 672 km^2, the wetland was declared as Wildlife Sanctuary in 1975 and a core area of 145 km^2 has been declared as Bhitarkanika National Park in 1992. It falls under tropical monsoon climate with three distinct seasons- winter (October–January), summer (February–May) and rainy (June–September) and frequently experiences tropical cyclones. The wetland is a habitat for large populations of salt water crocodiles, turtles, many endangered mammals and avian population. Additionally, it supports an exceptional floral diversity with around 62 species of mangroves (Chauhan and Ramanathan, 2008). Being a wetland with rich biodiversity, this mangrove habitat has been designated as a Ramsar site of international importance in year 2002. Fig. 1 shows the location and areal extent of mangroves of Bhitarkanika Wildlife Sanctuary.

2.2. Data acquisition

*Satellite data from multiple sensors were acquired from April 1995 to May 2017 (Table 1). Cloud-free Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI), surface reflectance (ρ) products were downloaded from the United States Geological Survey (USGS) EarthExplorer website corresponding to Bhitarkanika Wildlife Sanctuary for LULC classification. Sentinel-1 products were downloaded from the European Space Agency (ESA) Scientific Data Hub website to achieve high spatial resolution (10m) and improve the accuracy of LULC classification. Terra MODIS 500 m Level-2G 8-day average products including surface reflectance (MOD09A1.006), LAI (MOD15A2H) and GPP (MOD17A2H) products were downloaded from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS) website for biophysical (LAI and GPP) model calibration and long-term (2000–2016) seasonal and annual trend analysis.