Doctoral Dissertation

Remote Sensing of Mangrove Forest Dynamics in the Sundarbans

(Summary)

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Mangroves are vital ecosystems despite their smaller areal coverage compared to other types of tropical forests. They sequester and store a massive amount of carbon as known as one of the most productive ecosystems, and have attracted attention of various conservation and management initiatives. A considerable amount of literature on various aspects of mangrove ecosystems have been published. However, mangrove studies are yet to fully utilize long-term satellite remote sensing (SRS) data.

The Sundarbans is the largest single-tract mangrove forest of the world. The Sundarbans mangrove forests are threatened by climate change stressors like sea-level rise and tropical cyclones. Long-term studies on dynamics and phenology of the forests is crucial for predicting responses of mangrove forests to climate change in Sundarbans. However, existing remote sensing (RS) studies on the Sundarbans generally used dataset of low-temporal resolution and mainly focused on mapping and classification of the extent of mangrove forests and its changes over time. Without using dense-temporal data, it is not possible to extract forest phenology information. Canopy greenness indices derived from RS data such as normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) can be used as a proxy of leaf biomass and photosynthetic activity in the canopy. Thus, these indices allow us to evaluate the ability of carbon sequestration of ecosystems.

Therefore, the primary goal of this study is to depict the long-term canopy dynamics of mangrove forests harnessing long-term SRS data. The dynamics of canopy greenness is driven by internal factors such as seasonality in leaf flushing and shedding, and external factors such as canopy disturbance by cyclones, storms, forest fires and deforestation. Leaf phenology, cyclone disturbance and following canopy recovery after cyclones would play a major role in the temporal changes in canopy greenness in the Sundarbans. In contrast, anthropogenic disturbances such as deforestation and forest fires are not common after designated as a protected area. Therefore, this study focused on elucidating the relationship of dynamics of canopy greenness with leaf phenology, cyclone disturbance and regeneration dynamics in the Sundarbans.

Chapter 2 introduced the study area, Sundarbans mangrove forest, and briefly describes its history, ecology and existing RS studies. The Sundarbans spreading across two neighboring countries, Bangladesh and India, is part of UNESCO World Heritage Site and Ramsar site for wetland conservation. Communities living nearby the forest depend on it directly or indirectly. Despite being the focus of many ecological studies, information on forest phenology at the landscape scale is rare, which can be valuable information for identifying drivers of mangrove forest dynamics and elucidating the impacts of climate change on the Sundarbans.

Chapter 3 aimed to elucidate the phenology of the Sundarbans using NDVI and EVI time-series data derived from 18 years of 16-day MODIS composite images and GEE. Time-series analyses indicated that there was a clear annual seasonality in canopy greenness in the Sundarbans mangrove forests at the landscape scale. Based on the EVI, canopy greenness increased in late May to mid-June, peaked in mid-August to mid-September and decreased in mid-October to early November. Estimates of seasonal changes derived from EVI and NDVI data differed somewhat; EVI-based estimation was probably more accurate because estimates were more consistent with ground-level information. This implies that careful consideration of forest phenology is needed for change detection analyses; comparing forest status between two different seasonal periods might be influenced by the seasonal dynamics. As canopy greenness is directly related to the level of photosynthetic activity of the forests, changes in climatic conditions (e.g., temperature and solar radiation) around the peak period (July–October) will strongly affect carbon uptake by the forest ecosystem. The results of this study will be baseline information for future phenological changes in the Sundarbans.

Chapter 4 assessed long-term patterns of forest disturbances by the tropical cyclones. The extent and pattern of forest disturbances caused by cyclones in the Sundarbans remain poorly understood. Using GEE and Landsat images, changes in the NDVI before versus after 21 cyclones that occurred between 1988 and 2016 were evaluated. Images for observation was selected from the same months of each year to minimize seasonal differences in NDVI values. Classification and Regression Tree (CART) classification successfully classified the forest area with an overall accuracy of 86% and Kappa coefficient 0.80. The percentage of affected forest area (i.e., the area that exhibited negative changes in NDVI values following a cyclone) ranged from 0.5 to 24.1% of the total forest area. Of the 21 focal cyclones, 18 affected less than 10% of the forest area, while two cyclones, Sidr in 2007 and a cyclone in 1988 (category 5 and 3 in Saffir-Simpson Hurricane Index), affected 24.1% and 20.4%, respectively. Among the cyclone parameters (i.e., maximum wind speed, distance from the Sundarbans and river water level), the wind speed was significantly and positively correlated with the affected forest area. Piecewise linear regression and cubic regression suggested that the relationship between wind speed and affected forest area was non-linear. Also, piecewise model suggested that wind speed had little effects below a breakpoint of 101.9 km h-1. This study finds that, based on a 29-year dataset, although the region experienced cyclones almost every year, only the most significant cyclones (i.e., in the category 3 or higher) affected 20% or more of the mangrove forest area, and these occurred around once per 7 to 12-year period.

Chapter 5 focused on assessing the long-term dynamics in forest regeneration and the impact of tropical cyclone Bulbul in 2019 on the Sundarbans using Synthetic Aperture Radar (SAR) and optical satellite data. L-Band SAR Global JERS-1 Mosaic data of the year 1996 was downloaded from the JAXA website. L-Band SAR Global PALSAR-2/PALSAR data of the years 2007, 2008, 2009, 2010, 2016 and 2017 were accessed in GEE. Horizontally emitted-vertically received (HV) polarization was used as a proxy for above-ground biomass of mangrove forest, and changes over the years were recorded. Landsat images of TM, ETM+ and OLI sensors between 1987-2019 (33 years) were harmonized and generated as time-series dataset of 33 years. Recovery patterns of NDVI were examined in the affected areas by cyclones in 1988 and 2007. Results showed that mangrove forests recovered to the NDVI values before the cyclone in 1-3 years. Based on SAR data, mangrove extent reduced considerably from 1996 to 2007 in the Indian part of the Sundarbans, and most of these changes were higher near the coast than inland. Between 2007-2017, amount of vegetation gain was greater than that of vegetation loss. Regeneration was observed throughout the Sundarbans while erosion was dominant on the coastal edges. Forest disturbances by tropical cyclone Bulbul estimated based on NDVI was much lower (1.33%) than that predicted by cubic and piecewise model (5.39% and 7.57%, respectively) developed in Chapter 4. Overall, the total amount of erosion was less than that of regeneration in recent years.

Chapter 6 summarized the main findings of this study and further proposed future study directions to overcome limitations of this study. First, the phenological calendar maps estimated in this study were the first to be developed for the Sundarbans at the landscape level. When these data are coupled with biophysical parameters such as temperature, rainfall, salinity, storm surge and wind, it is possible to predict phenological changes of the forest in response to future climate change. Second, this study found that only the strongest cyclones affected the Sundarbans considerably. The methodology in this study can be used for quick assessment of future cyclone impacts in the Sundarbans. It will be further improved by including more detailed and comprehensive parameters on cyclones and forests. Third, recovery time (1-3 years) in terms of vegetation indices after the strongest cyclones was faster than occurrence interval of these cyclones (7-12 years). Loss in vegetation cover was high at the coastal edges. However, regeneration of vegetation was greater than the loss of vegetation in recent years. Overall, the forest is regenerating, and the quick recovery process may explain the high resilience of the Sundarbans against cyclones.

Future study should address how various factors and their interactions affect the dynamics of Sundarbans mangrove forests. Moreover, tropical cyclone disturbances can have a long-term impact, even after seeming recovery, the forest might still undergo degradation. Thus, future studies should address how sedimentation and cyclone surges affect the forest dynamics in a longer period. Remote sensing can be a valuable tool for long-term monitoring of huge mangrove forests like the Sundarbans. However, lack of sufficient and accurate ground-truth data is often the limitation of RS studies on mangrove forests. Therefore, development of permanent forest plot for systematic long-term forest monitoring will greatly improve accuracy of RS analyses on mangrove forests. But if this is unrealistic, as is the case for many developing countries, newly developed RS technologies such as SAR, unmanned aerial vehicle (UAV) and hyperspectral data might be able to provide a range of surrogates on forest parameters, which are close to or even more detailed than ground data. SRS studies incorporating with those new technologies may realize the systematic long-term monitoring of extensive mangrove forests.