Geoid
Journal of Geodesy and Geomatics

Geoid Vol. 20, No. 1, 2025, 47-52

P-ISSN: 1858-2281; E-ISSN: 2442-3998

Estimation of Total Carbon Stock and Mangrove Health Index in Sidoarjo using Machine Learning Spectral Analysis Method of Sentinel-2A Satellite Imagery

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Received: 2 January 2025; Revised: 27 January 2025; Accepted: 24 February 2025; Published: 30 April 2025

Abstract:
The mangrove ecosystem has the potential ability to absorb carbon dioxide better than other forest ecosystems. It is noted that mangrove forests have an important role in reducing the concentration of carbon dioxide in the air. Changes in land cover conditions, massive development of urban areas, and the large need for housing in the Sidoarjo are the main causes of the decline in the area of mangrove forests which have been converted into fish ponds and residential areas. This triggers a decline in the quality of mangroves and will directly impact on reducing the capacity to store carbon reserves in Sidoarjo Regency. Biomass estimation calculations were carried out using the NDVI algorithm from remote sensing results using Sentinel Imagery – 2A. Apart from that, the mangrove health index was also calculated using the GCI (Green Chlorophyll Index), SIPI (Structure Insensitive Pigment Index), NBR (Normalized Burn Ratio), and ARVI (Atmospherically Resistant Vegetation Index). Based on the calculation results, the value obtained for the coastal area of Sidoarjo Regency the TCS or total carbon stock ranged from 1.1679468503445e-09 to 84.3344 TonC/hectares. Meanwhile, the results of the mangrove health index calculation show that the condition of mangroves in the coastal area of Sidoarjo Regency has a sufficient mangrove health index, with the highest area being 637.77 hectares, while only 10.80 hectares are available has a good health index. The results of this study are expected to be one of the bases for decision-making and policies in the rehabilitation and conservation of mangrove in Sidoarjo.

Keywords: carbon stock; mangrove; MHI; NDVI; remote sensing

How to cite: Alina, A.N., Yahya, F., Safitri, D.A., Sanjaya, H., & Rahmawaty, M.A. (2025). Estimation of Total Carbon Stock and Mangrove Health Index in Sidoarjo using Machine Learning Spectral Analysis Method of Sentinel-2A Satellite Imagery. *Geoid*, *20*(1), 47-52.

Introduction

Coastal ecosystems are essential for maintaining human well-being and global biodiversity. Coastal ecosystems also contribute to storing and absorbing large amounts of carbon from the ocean atmosphere, called coastal blue carbon. Since carbon emissions are currently considered to be the largest contributing factor to global warming, vegetation that has the ability to absorb and store carbon reserves is very crucial in reducing the impact of climate change. Mangrove ecosystems have the potential to absorb carbon dioxide better than other forest ecosystems because of their ability to grow faster than other forest vegetation. It is noted that mangrove forests have a crucial role in reducing the concentration of carbon dioxide in the air. Mangrove forests are one of the highest carbon storage forests in the tropics and the amount is very high compared to the average carbon storage of other types of forests in the world (Alongi, 2022). In addition to environmental functions, mangroves also have economic and social functions, especially for coastal communities (Wahyuning Hastuti et al., 2017) stated that the existence of mangroves provides economic benefits in the form of obtaining wood and increasing catches with high value. Mangroves also have a coastal ecotourism function which is also a source of income for the community.

Sidoarjo Regency is one of the administrative areas in East Java Province which is a buffer zone for Surabaya City which functioning as the Capital City of East Java Province. The Regency is also known as a delta city and is the final estuary of several rivers that flow through Sidoarjo Regency. The existence of the Lapindo mudflow geological disaster resulted in the emergence of mud disposal deposits which later developed into a mangrove ecosystem. (Hidayah, 2011) stated that development in the coastal areas of East Java, especially in the areas of Surabaya and Sidoarjo, is currently facing major challenges, namely the change in the function of mangrove land into ponds, settlements, and industrial areas. In addition, coastal area planning is still not based on accurate information regarding the condition of the ecosystem in the area. This situation will certainly complicate efforts to prevent damage and conserve the mangrove ecosystem. Changes in land cover conditions, massive urban development, and the large need for settlements in the Sidoarjo Regency area are the main causes of the decline in the area of mangrove forests which have changed function into ponds and settlements. This triggers a decline in the quality of mangroves and will directly impact the decline in the ability to store carbon reserves in Sidoarjo Regency.

According to Lu et al., 2016 and Wahyuning Hastuti et al., 2017 terrestrial surveys or measurements are accurate methods in collecting biomass data, but this technique is usually very expensive, time-consuming, requires a lot of manpower, and is difficult to apply in remote and large areas. Therefore, this study uses passive remote sensing technology that utilizes spectral values as an alternative to provide information on the estimation of mangrove biomass that plays a role in absorbing carbon dioxide. Pandapotan Situmorang et al., 2016 found that there was a high correlation (R^2=0.729) between the vegetation index generated by satellite data and the carbon stock estimate calculated using the allometric equation. This high coefficient of determination shows that satellite data is suitable for use in estimating carbon stocks.

Hidayah et al., 2022 calculated the Above Ground Biomass (AGB) and Below Ground Biomass (BGB) parameters with allometric equations from field survey results with a combination of Normalized Difference Vegetation Index (NDVI) bands that were cross-linked with field data to find the correlation between NDVI results and AGB from allometric equations. Meanwhile, (Hidayah et al., 2023) stated that the MHI (Mangrove Health Index) analysis is an approach that can be used to measure the condition and quality of the ecosystem environment in mangrove forests. In general, the calculation of the MHI value is designed to determine the level of mangrove health at the ecosystem level using three parameters as the main input from the mangrove stand structure, namely stem diameter, crown cover and stem density. The MHI value can be predicted from several vegetation index values, namely GCI (Green Chlorophyll Index), SIPI (Structure Insensitive Pigment Index), NBR (Normalized Burn Ratio), and ARVI (Atmospherically Resistant Vegetation Index). Based on the description, the aim of this study is to map the distribution of mangroves in Sidoarjo Regency so that the potential size of mangrove carbon reserves can be obtained and the level of mangrove health can be determined using the Mangrove Health Index (MHI). The results of this study are expected to be one of the bases for decision-making and policies in the rehabilitation and conservation of mangrove forest ecosystems in Sidoarjo.

Data and Method

Study Area and Satellite Image

This research was conducted in Sidoarjo Regency and focused on the mangrove area in the coastal area with the following coordinates: 112° 45’ 3” East Longitude ; 7 ° 29’ 47” South Latitude and 112° 50’ 43” East Longitude ; 7 ° 19’ 18” South Latitude (Figure 1). The expanse of the mangrove area was obtained from the results of unsupervised classification of Sentinel level 2A satellite imagery with the best recording results with a time span of 01-01-2022 to 31-12-3022. Sentinel level 2A satellite imagery is satellite imagery that has undergone a surface atmospheric correction process and has been orthorectified so that it is ready to be carried out the spectral analysis process. This Sentinel satellite imagery was obtained by utilizing the Google Earth Engine (GEE) cloud dataset.

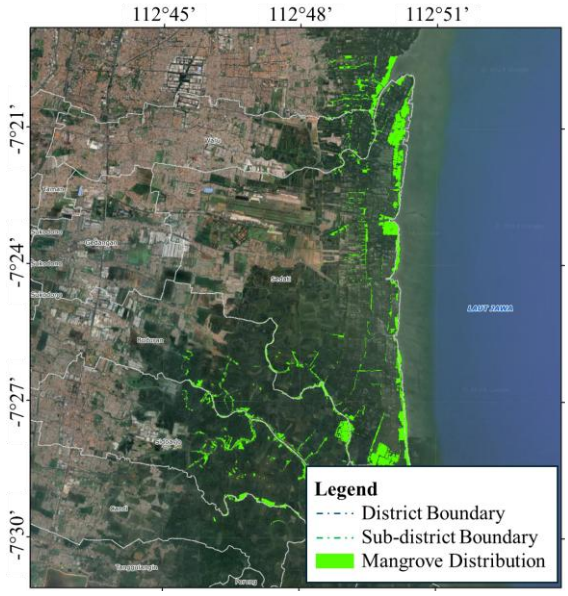


Figure 1. Mangrove distribution in Sidoajo Regency. The RGB display is obtained from the base map of satellite image processing software.

The satellite imagery that has been obtained is then subjected to the Shortwave Infrared band combination process. The selection of this spectral band is based on the ability of the NIR, SWIR, and RED spectral bands which have higher sensitivity to vegetation, soil types, and to distinguish the stages of vegetation development. The results of the image combination or composite are then input into the mangrove landscape classification process using the Machine Learning Unsupervised Classification method with area of mangroved derived is 768.80 hectares.

Ground Biomass Derivation

The next stage is the calculation of the estimation of above ground biomass (AGB) and below ground biomass (BGB) based on the normalized difference vegetation index (NDVI) approach. The index is used to analyze the vegetation index based on the density of vegetation. NDVI is calculated from the reflectance of red ($\boldsymbol{\rho}_{\mathbf{red}}$) and near-infrared ($\boldsymbol{\rho}_{\mathbf{NIR}}$) bands (Jiang et al., 2006). The calculation of NDVI is as follow:

$$\mathbf{NDVI} = \frac{(\boldsymbol{\rho}_{\mathbf{NIR}} - \boldsymbol{\rho}_{\mathbf{red}})}{(\boldsymbol{\rho}_{\mathbf{NIR}} + \boldsymbol{\rho}_{\mathbf{red}})}. \tag{1}$$

Then, the AGB and BGB (both in unit of ton/ha) are derived from the calculated NDVI following the formulation of Jha & Singh (2015) and Cairns et al. (1997), respectively, as below:

$$\mathbf{AGB} = \mathbf{305.9} \times \mathbf{NDVI}^{\mathbf{4.9}}, \tag{2}$$

$$\mathbf{BGB} = \boldsymbol{e}^{-\mathbf{1.1}+\mathbf{0.9}\times\mathbf{ln}(\mathbf{AGB})}. \tag{3}$$

The two biomass parameters are summed to obtain the total accumulated biomass (TAB). The TAB is then used to derive the estimated total carbon stock (TCS) following the study of Westlake (1963). The equation is shown below:

$$\mathbf{TCS} = \mathbf{TAB} \times \mathbf{C}, \tag{4}$$

where C represents the carbon stock percentage value. The value is set to 0.47 in this study. In addition, the TCS value is in the unit of ton/ha.

After obtaining the carbon stock estimate and CO_2 absorption value, analysis can be carried out by calculating the Mangrove Health Index (MHI). The MHI value is determined through a combination of four vegetation indices, namely Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI). According to Dharmawan (2021), the Sentinel image pixel value obtained from the combination of these four vegetation indices showed a high correlation (r = 0.831) with the ecological status of mangroves which was assessed using the parameters of canopy cover, seedling density, and mangrove vegetation stem diameter. The equation for the vegetation index used and the calculation of MHI with Sentinel satellite imagery is explained in the following equations below:

$$\mathbf{NBR} = \frac{(\boldsymbol{\rho}_{\mathbf{NIR}} - \boldsymbol{\rho}_{\mathbf{SWIR}})}{(\boldsymbol{\rho}_{\mathbf{NIR}} + \boldsymbol{\rho}_{\mathbf{SWIR}})}, \tag{5}$$

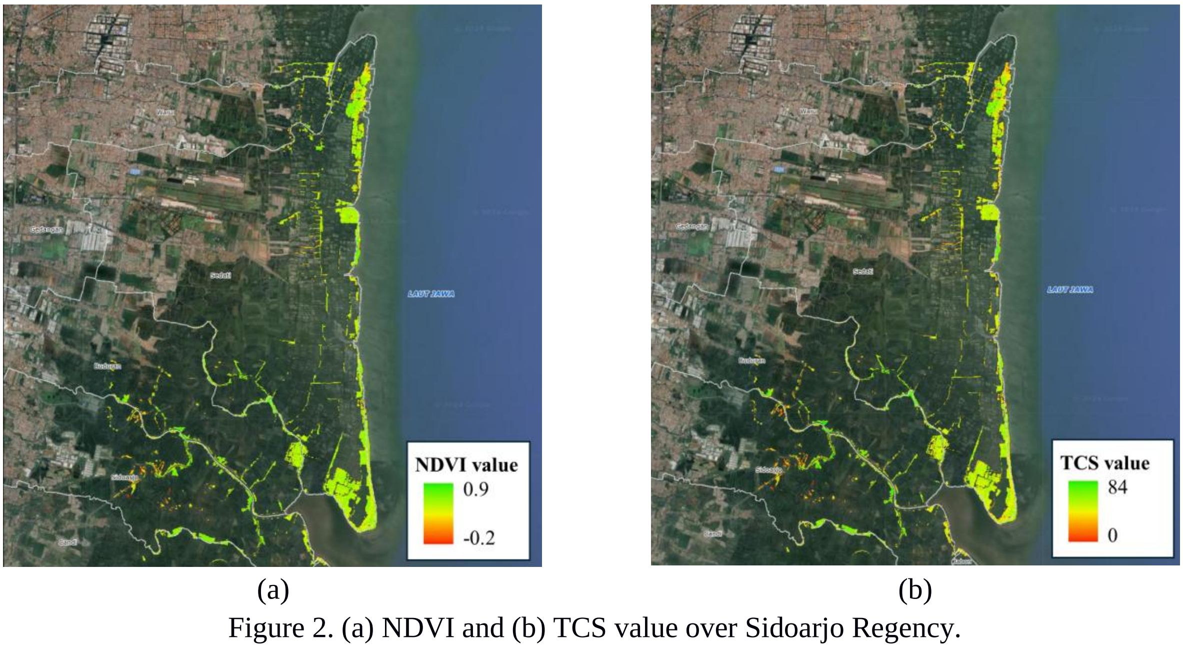
$$\mathbf{NBR} = \frac{(\boldsymbol{\rho}_{\mathbf{NIR}})}{(\boldsymbol{\rho}_{\mathbf{green}} - \mathbf{1})}, \tag{6}$$

$$\mathbf{SIPI} = \frac{(\boldsymbol{\rho}_{\mathbf{NIR}} - \boldsymbol{\rho}_{\mathbf{blue}})}{(\boldsymbol{\rho}_{\mathbf{NIR}} + \boldsymbol{\rho}_{\mathbf{red}})}, \tag{7}$$

$$\mathbf{ARVI} = \frac{(\boldsymbol{\rho}_{\mathbf{NIR}} - (\mathbf{2} \times \boldsymbol{\rho}_{\mathbf{red}}) + \boldsymbol{\rho}_{\mathbf{blue}})}{(\boldsymbol{\rho}_{\mathbf{NIR}} + (\mathbf{2} \times \boldsymbol{\rho}_{\mathbf{red}}) + \boldsymbol{\rho}_{\mathbf{blue}})}, \tag{7}$$

$$\mathbf{MHI} = \mathbf{102.1} \times \mathbf{NBR} - \mathbf{4.6} \times \mathbf{GCI} + \mathbf{178.2} \times \mathbf{SIPI} + \mathbf{159.6} \times \mathbf{ARVI}, \tag{8}$$

where $\boldsymbol{\rho}_{\mathbf{red}}$ and $\boldsymbol{\rho}_{\mathbf{NIR}}$ have been introduced previously, while $\boldsymbol{\rho}_{\mathbf{blue}}$, $\boldsymbol{\rho}_{\mathbf{green}}$, and $\boldsymbol{\rho}_{\mathbf{SWIR}}$ indicate the reflectance value in blue, green, and short-wave infrared bands. The condition of mangrove forests based on MHI values can be classified into 3 classes, namely poor (MHI value <33.3%), moderate (33.4% <MHI value <66.7%) and good (MHI value> 66.8%). For MHI with a negative value, it can be interpreted as a deeper water column.



(a) (b)

Figure 2. (a) NDVI and (b) TCS value over Sidoarjo Regency.

Results and Discussion

The results of the NDVI classification for the study area show that the condition of the mangroves in Sidoarjo Regency is predominantly dense with the highest NDVI value in the range of 0.3 - 0.864 as the highest value.

Once derived, the TCS is estimated using Eq. (2-4). For summary, the highest obtained AGB, BGB, and TAB are 150.337 ton/ha, 29.098 ton/ha, and 179.435 ton/ha, in respective order. The TCS value or total carbon stock is the total value of biomass accumulation multiplied by the percentage value of carbon stock of 0.47, which is the estimated value of carbon emitted based on laboratory measurement results. TCS ranged from $\mathbf{1.167 \times 10^{-9}}$ ton/ha ~ 84.334 ton/ha. Figure 2 (a) and (b) shows the NDVI value and TCS distribution.

After obtaining the estimated carbon stock value and the amount of CO_2 absorption value, analysis can be done by calculating the Mangrove Health Index (MHI). The MHI calculation is determined using an algorithm calculation of 4 vegetation indices, namely NBR, GCI, SIPI, and ARVI. The MHI map can be seen in Figure 3. The results of the calculation of the mangrove health index show that the condition of the mangroves in the coastal area of Sidoarjo Regency has a fairly high mangrove health index with the highest area of 637.77 hectares, while only 10.80 hectares have a good health index (see Table 1).

Table 1. Mangrove Health Index Value per Class

Mangrove Health Indeks per Class	**Area (Ha)**
Potential Rehabilitation Area	49.50
Poor	70.74
Moderate	637.77
Good	10.80

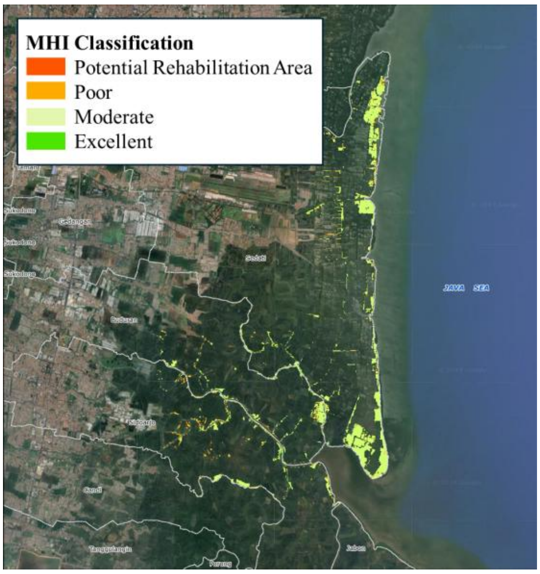


Figure 3. MHI classification over Sidoarjo Regency.

Conclusion

For the coastal area of Sidoarjo Regency, the highest TCS or total carbon stock value was obtained at 84.3344 hectares. Meanwhile, the results of the calculation of the mangrove health index show that the condition of the mangroves in the coastal area of Sidoarjo Regency has a fairly high mangrove health index with an area of 637.77 hectares, while only 10.80 hectares have a good health index. Furthermore, research needs to be developed by utilizing satellite image classification methods based on segmentation or deep learning. It is hoped that by using segmentation and deep learning, mangroves can be classified better.

Acknowledgment

Thank you to the Faculty of Engineering, Dr. Soetomo University for the research assistance provided.

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