JURNAL geografi

https://jurnal.unimed.ac.id/2012/index.php/geo/article/view/62343
https://doi.org/ 10.24114/jg.v17i1.62343 - (Vol 17, No 1 – 2025)
available at http://jurnal.unimed.ac.id/2012/index.php/geo
e-issn (2549-7057) & p-issn (2085-8167)

MODIS Satellite Imagery for Monitoring Carbon Sequestration Potential and Its Drivers in Jambi Province, Indonesia

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ARTICLE INFO
Article History:
Received: August 04, 2024
Revision: February 22, 2025
Accepted: March 29, 2025

Keywords:
Carbon
MODIS
Net Primary Productivity (NPP)

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ABSTRACT
Jambi Province is a province in Indonesia whose land use is dominated by forests and plantations. Threats to land conversion and forest fires in the region have reduced vegetation and will threaten carbon absorption in the future. This study aims to map and assess the potential for carbon absorption and triggering factors by evaluating the spatiotemporal Net Primary Productivity (NPP) pattern to estimate Jambi Province's carbon absorption. This study uses remote sensing data to obtain NPP values and several variables that will be assessed for their influence on NPP. MODIS satellite imagery is used to obtain NPP data, forest cover, Normalized Data Vegetation Index (NDVI) and Land Surface Temperature (LST). Shuttle Radar Topography Map (SRTM) imagery obtains topography and slope data. Population data in the form of the Human Development Index, total population and population in urban areas were obtained from the Central Statistics Agency of Jambi Province. The average NPP value 2003 in Jambi Province was 0.911 kgC/m/year, then the average NPP decreased to 0.754 kgC/m/year in 2023. Based on statistical analysis, there is a correlation between NPP and NDVI, slope, and topography.

INTRODUCTION

Jambi Province is located in the central part of Sumatra Island. To the north, Jambi borders Riau Province; to the east, it borders the South China Sea and Riau Islands Province; to the south, it borders South Sumatra Province; and to the west, it borders West Sumatra Province. The position of Jambi Province is very strategic because it directly faces the IMS-GT economic growth area (Indonesia, Malaysia, Singapore Growth Triangle). According to Government Regulation Number 26 of 2008 concerning National Regional Spatial Planning, National Strategic Areas are areas whose spatial planning is prioritised because they have a nationally significant influence on the State's sovereignty, State's defence and security, economy, social life, culture, and/or environment, including an area recognised as world heritage. National strategic areas in Jambi Province are determined based on environmental function and carrying capacity considerations. The National Strategic Areas included in the Jambi Province area include : (1) Kerinci Seblat National Park Area (Jambi Province, West Sumatra, Bengkulu and South Sumatra); (2) Berbak National Park Area (Jambi Province); (3) Bukit Tigapuluh National Park Area (Jambi and Riau Provinces; (4) Bukit Duabelas National Park Area (Jambi Province).

Jambi Province is one of the Sumatra provinces famous for its tropical climate, rich natural resources, and biodiversity. However, this province is also vulnerable to climate change. The problems in Jambi Province are that the management of natural resources is not optimal and does not consider environmental sustainability. Exploiting natural resources is only oriented towards profit without considering social and ecological aspects (FAO, 2020). Jambi Province is one of the forest asset barns in Indonesia, with 60% of its area still covered by forest. This makes Jambi one of the provinces that receives special attention from the government because of its significant forest area (Sari et al., 2014). In 2001 and 2022, forests in Jambi emitted 61.7 $MtCO_2e$/year and absorbed -25.1 $MtCO_2e$/year with a net carbon source of 36.6 $MtCO_2e$/year (figure 1) (GFW, 2021).

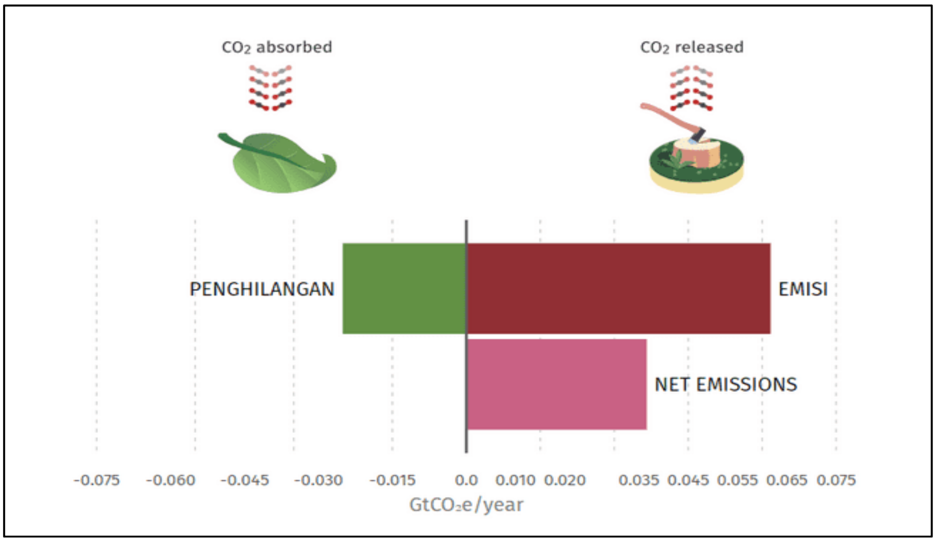


Figure 1. Carbon exchange information in Jambi Province
(Source: Global Forest Watch, 2021)

Kerinci Seblat National Park (TNKS) covers a large area in Jambi and every year; the land is converted from forest land to plantations (Kerinci Seblat National Park Main Office, 2023). Land conversion changes can affect the carbon balance in the atmosphere (Houghton & Goodale, 2004). Assessment of the potential for carbon absorption in this area is important to identify areas with a strategic role in mitigating climate change. Net primary productivity (NPP) is one of the important indicators for measuring environmental change; good NPP will reflect relatively high ecosystem productivity and vice versa (Das et al., 2023). In ecosystem processes and ecological management, measuring net primary productivity (NPP) is very important because NPP represents important energy fluxes in the ecosystem (Pachavo & Murwira, 2014).

Climate change causes disasters that can threaten humans, and this is an environmental challenge for researchers to be able to support efforts to reduce the impacts caused by climate change. One effort to mitigate climate change is mapping the potential for carbon absorption. Healthy forests, plants, and land have great potential to absorb carbon through photosynthesis. In addition to mapping the potential for carbon absorption, it is also necessary to assess the triggers of change that can affect the ability of an ecosystem to absorb and store carbon. This can include forest fires, changes in land use, or anthropogenic activities that change the landscape and can also affect the carbon balance in the ecosystem.

Using remote sensing imagery datasets is essential for broader forest monitoring, from local to global scales. Field data acquisition to estimate primary productivity requires a lot of time and resources. Integrating field survey data with remote sensing data is an efficient method to evaluate changes in forest succession at local scales in forest ecosystems with high efficiency compared to conventional field surveys. The impact of climate change on carbon sequestration can be assessed by analysing changes in the spatiotemporal pattern of NPP obtained from remote sensing data extraction. This study was designed to calculate the spatiotemporal pattern of NPP with a more detailed resolution to produce regional-scale NPP information that can be used to mitigate climate change in Jambi Province.

This study aims to map and assess the potential for carbon sequestration and triggering factors by assessing NPP's spatiotemporal pattern to estimate Jambi Province's carbon sequestration. Understanding these dynamics can provide a basis for developing sustainable and effective environmental policies. Remote Sensing provides an effective, efficient, and accurate approach in monitoring the dynamics of vegetation health and estimating NPP at regional and global scales (Das et al., 2023; Pachavo & Murwira, 2014). Das et al. (2023) have conducted research on assessing carbon sequestration potential and its triggering factors in the Eastern Himalayan Region of India. Arrafi et al (2024) researched NPP in Moaro Jambi Regency using the CASA model but did not assess the factors that influence carbon sequestration temporally. Pacavo and Murwira (2014) assessed NPP using remote sensing and GIS data in the Southern African Savanna. Chen, H., Li, J., & Liu, Z. Y. (2010) researched Spatial and seasonal characterisation of net primary productivity and climate variables in southeastern China using MODIS data. Based on previous research both in Jambi and outside Jambi, research related to MODIS Satellite Imagery for Monitoring Carbon Sequestration Potential and Its Drivers in Jambi Province has never been conducted using spatiotemporal analysis.

RESEARCH METHOD

MODIS imagery as the main data was obtained from the United State Geological Survey (USGS) official website https://earthexplorer.usgs.gov/. MODIS Satellite Imagery with product code MOD17A3HGF as the Global NPP estimation data received from the page https://urs.earthdata.nasa.gov/home. Topographic Map of Indonesia Scale 1: 50.000 from the Geospatial Information Agency. Suttle Radar Topography Mission (SRTM) data was obtained from NASA's earth data and population data from the Central Statistics Agency of Jambi Province. A set of computers with R and QGIS software was used for data processing. Research on the potential for carbon absorption and its triggers is in Jambi Province, as shown in Figure 1.

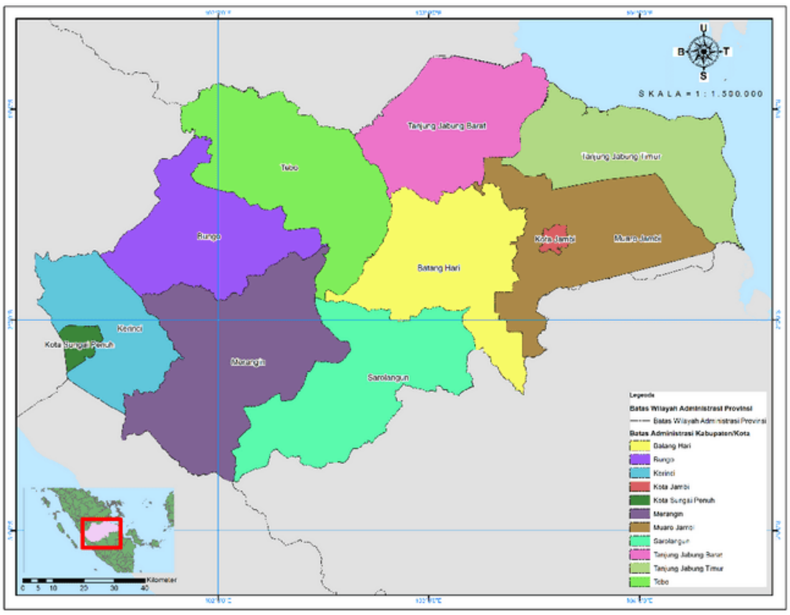


Figure 1. Jambi Province Map
(Source: Topographic Map of Indonesia Scale 1: 50.000 from the Geospatial Information Agency, 2024)

NPP is an important component in the carbon cycle and indicates ecosystem quality controlled by solar radiation and influenced by light, rainfall, and air temperature. Therefore, NPP is a key ecological variable for measuring energy input from the biosphere and terrestrial CO2 assimilation (Peng et al., 2010). NPP measurements can provide a basis for comparison to measure more aerodynamic ecosystem carbon exchange so that it can indicate changes or disturbances that disrupt ecosystem balance. Remote sensing data in MODIS satellite imagery is used to obtain NPP values. Factors influencing vegetation carbon are seen from the Normalized Different Vegetation Index (NDVI), Land Surface Temperature (LST), and percentage of forest cover data.

Other factors related to vegetation loss are the Human Development Index (HDI), Population, and urban population. The social data were obtained from the Jambi Province Central Statistics Agency. The HDI is related to community welfare, and population is associated with converting land from forest to non-forest land. Urban population data indicates the area of built-up land that can affect the conversion of forest land. Suttle Radar Topography Mission (SRTM) data creates topographic and slope maps.

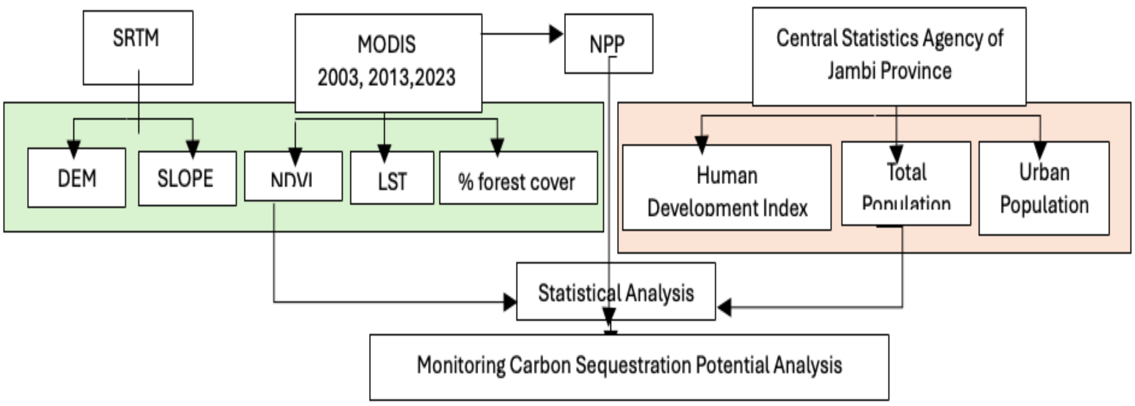


Figure 2. Research Flowchart

RESULT AND DISCUSSION

Topographic and Slope

The topographic data in this study were obtained from Shuttle Radar Topography Mission (SRTM) imagery with a spatial resolution of 500 meters (Figure 4). SRTM collected topographic data on almost 80% of the Earth's land surface, creating the first land elevation dataset that approaches a global scale. SRTM consists of two radar antennas, each SRTM radar assembly contains two antenna panels: C-band and X-band. The C-band radar data is used to create a topographic map of the Earth called a Digital Elevation Model (DEM). Based on the results of the SRTM imagery in Jambi Province, different slopes and topography are found in the western part of Jambi Province, namely Sungai Penuh City, Kerinci Regency, Merangin Regency, Sarolangun Regency, and Bungo Regency. In Jambi Province, there is Mount Kerinci, the highest mountain on the island of Sumatra and the highest volcano in Southeast Asia. Mount Kerinci is part of the Bukit Barisan Mountains, which stretch from the northern tip to the southern tip of Sumatra Island. The slope gradient in Jambi Province has a range of 0°- 39°, while the topography of Jambi Province has a range of values up to 3672 meters, which is the height of Mount Kerinc

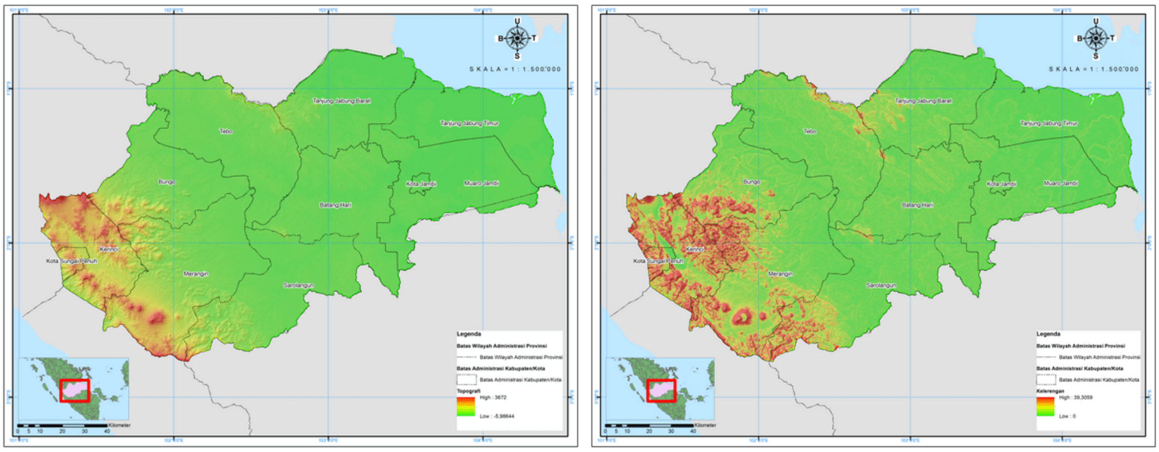
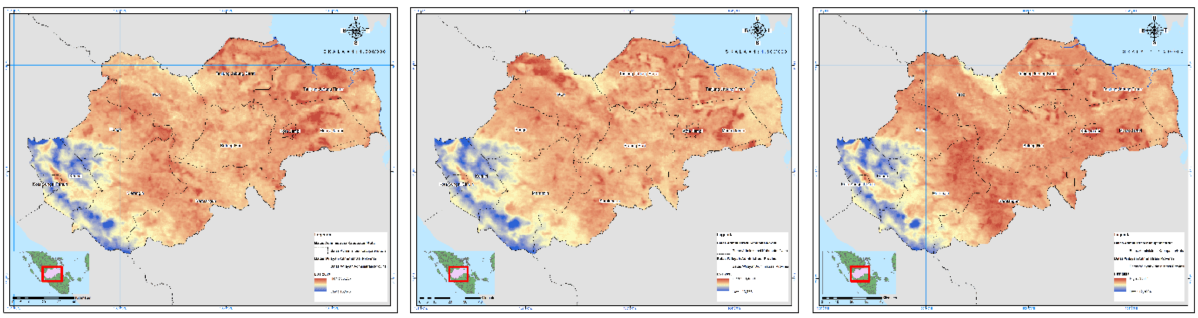


Figure 4. Topographic and Slope Map
(Source: Shuttle Radar Topography Mission (SRTM) imagery, 2024)

Jambi Province has a tropical climate rich in natural resources and biodiversity. Symptoms of climate change, such as rising temperatures, changes in intensity and periods of rain, shifts in the rainy/dry seasons, and rising sea levels, can occur if there is continuous land conversion. The average rainfall in 2019 reached 2,500 mm, while the amount of sunlight was 3.8 hours per day, with an average humidity of 97%. The average air temperature reached 27.11 degrees Celsius, while for the highlands in the West, it reached 22 degrees Celsius. According to observations from the BMKG climatology station, annual rainfall in Jambi Province ranges from 1000 - 3000 mm/year, dominated by the 1500 - 2000 mm/year class. Sarolongun Regency has the highest annual rainfall in Jambi Province, with a yearly rainfall of 2000 - 3000 mm/year (Kurniadi et al., 2018).

Land Surface Temperature (LST)

The results of MODIS image observations show that surface temperatures in Jambi Province vary from 12 °C – to 39°C, as seen in Figure 5. The areas symbolised in blue are highland or mountainous regions with relatively lower temperatures than other districts/cities in Jambi Province. During the 20 years from 2003 – 2023, surface temperatures in Jambi Province tended to increase, especially in urban areas, which may indicate land changes in Jambi Province that occurred within 20 years (Pramudiyasari et al., 2021).

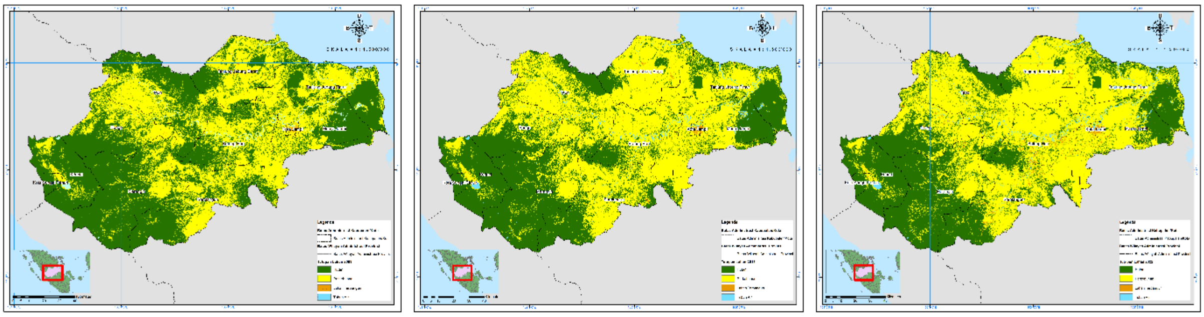


2003 2013 2023

Figure 5. Land Surface Temperature (LST) Map
(Source: MODIS Satellite Image Data Processing, 2024)

Forest Cover

Based on forest cover mapping from Modis imagery (Figure 6), it can be seen that from 2003 to 2022, there was a decline in forest cover. In 2003, forest cover in Jambi Province reached 55.87% of the total area of Jambi Province, then decreased in 2013 to 44.75%, and in 2022 it decreased again to 40.84%. Over 20 years, forest cover in Jambi Province decreased by 15.03%. Changes in forest area were seen in the north of Jambi Province, namely Tebo Regency and West Tanjung Jabung Regency. Jambi Province has rubber plantations with an area of 26.20%. The location of oil palm plantations is 19.22% of the area of Jambi Province. Most of the land in Jambi Province is used for agricultural cultivation activities, both rice field farming and non-rice field farming (Putra et al., 2019).

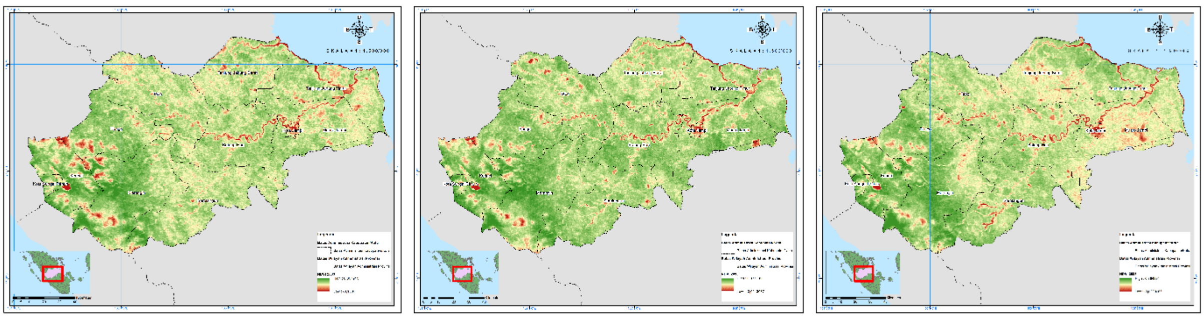


2003 2013 2023

Figure 6. Forest Cover Map of Jambi Province
(Source: MODIS Satellite Image Data Processing, 2024)

Normalized Difference Vegetation Index (NDVI)

NDVI is an index used to measure the health and density of vegetation on the earth's surface (Zhang et al., 2019). This index is obtained from MODIS MOD13A1 satellite imagery using data from the red and near-infrared spectrum. Normalized Difference Vegetation Index (NDVI) is a continuity index for the existing National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) derived NDVI. NDVI values range from -1 to +1, where values closer to +1 indicate healthy and dense vegetation. In contrast, values closer to -1 indicate surfaces with no vegetation, such as water, snow, or bare soil (Ganie & Nusrath, 2016). The results of MODIS image monitoring (Figure 11) show a decrease in NDVI over 20 years. In 2003, NDVI in Jambi Province had an average value of 0.653 and decreased in 2023 to 0.430, which is in line with the decrease in forest cover in Jambi Province.



2003 2013 2023

Figure 7. NDVI Map of Jambi Province
(Source: MODIS Satellite Image Data Processing, 2024)

Population and Human Development Index

Population is both the subject and the object of development because development is carried out by the population and is aimed at the population's welfare. Rapid population growth over time is caused by a decrease in the death rate and an increase in births and migration. According to Statistics Indonesia (2023), the population of Jambi Province in 2023 was 3,679,200 people with an average density of 62 people/km² except for Jambi City at 3,695 people/km² and Sungai Penuh City at 273 people/km². As with the character of the provincial capital in general, namely as a center of government, industry, and trade, Jambi City is also a destination for migration flows. Judging from the position of the western and eastern regions, the percentage of population distribution in the two areas looks relatively balanced, 52% for the eastern region (Batanghari, Muaro Jambi, West Tanjung Jabung, East Tanjung Jabung and Jambi City), and 48% for the western region (Kerinci, Sungai Penuh, Merangin, Sarolangun, Bungo and Tebo).

The human development index is one of the benchmarks for assessing the success of development in a region. Table 1 shows the human development index data in Jambi Province. The progress of human development, in general, can be measured through the Human Development Index (HDI). The index reflects achievements in education, health, and the economy. Based on the development of the HDI figures from year to year, the progress achieved by Jambi Province in human development is quite significant.

Based on data from the Central Statistics Agency, such as the table above, it can be seen that the Human Development Index in the regencies/cities of Jambi Province has increased from 2021 to 2023. The highest average HDI occurred in Jambi City, 79.61 in the high category. The high HDI in Jambi City is indicated by the high average length of schooling, life expectancy, and decent standard of living in this area. Meanwhile, the lowest HDI was recorded in Tanjung Jabung Timur Regency, with an HDI of only 65.77. In the moderate category, the low HDI in Tanjung Jabung Timur Regency was due to the low quality of education and low community welfare.

Table 1. Population and Human Development Index (HDI) in Jambi Province

Location	2021		2022		2023	
	Population	HDI (%)	Population	HDI (%)	Population	HDI (%)
Jambi Province	3,585,100	71.63	3,631,100	72.14	3,679,200	72.77
Kerinci Regency	251,900	71.45	253,900	71.99	255,100	72.54
Merangin Regency	355,700	69.53	357,600	69.98	368,400	70.81
Sarolangun Regency	293,600	70.25	298,100	70.89	302,200	71.29
Batang Hari Regency	306,700	70.11	313,200	70.51	312,700	71.02
Muaro Jambi Regency	406,800	69.55	412,800	70.18	418,800	71.04
Tanjung Jabung Timur Regency	231,800	64.91	234,200	65.77	236,700	66.65
Tanjung Jabung Barat Regency	320,600	68.16	324,500	68.79	330,500	69.35
Tebo Regency	340,900	69.35	344,800	69.78	350,800	70.63
Bungo Regency	367,200	70.15	373,300	70.55	376,400	71.06
Jambi City	612,200	79.12	619,600	79.58	627,800	80.15
Sungai Penuh City	97,800	75.70	99,200	76.17	99,800	76.65

Source: Central Statistics Agency of Jambi Province, 2024

Jambi City and Sungai Penuh City have achieved the "high" status in human development since 2010. In the last one-year period, West Tanjung Jabung Regency, Sungai Penuh City, and East Tanjung Jabung Regency recorded the fastest progress in human development, driven by improvements in decent living standards.

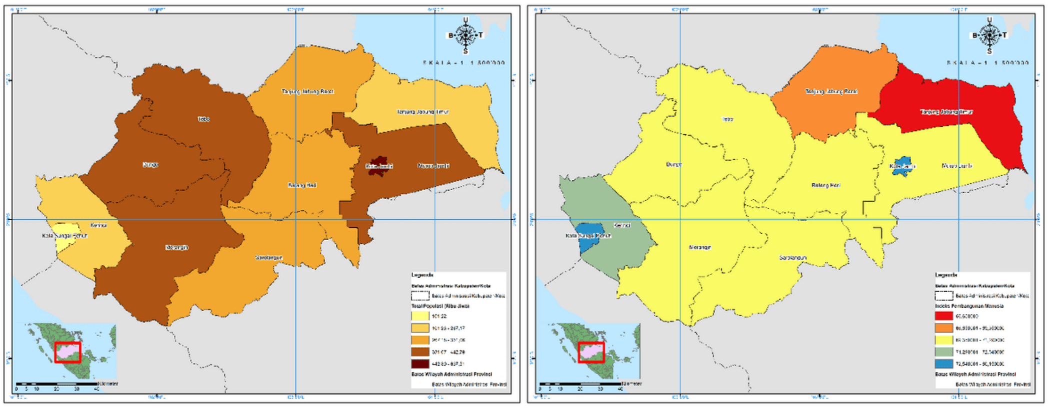


Figure 8. Population and Human Development Index Map of Jambi Province 2023
(Source: Population Data Processing, 2024)

Urban Population

The city's population used to see the effect of carbon changes on the population of Jambi City. Based on Table 1, there was a population increase from 2010-2023 of 15,600 people. Jambi City, as the capital of Jambi Province, experienced significant economic growth; this can be seen from the Gross Regional Domestic Product (GRDP) of Jambi City, which continues to increase (Parmadi et al., 2020). Jambi City is the centre of government, trade, and main service services in Jambi Province. Jambi City is also a potential business centre for several leading economic sectors. The location of Jambi City is very strategic, namely on the East Sumatra Cross-Island route; Jambi City provides opportunities for investors to invest, especially in the trade and hospitality sectors, which has an impact on increasing population migration to Jambi City.

Figure 9 is a map of settlements in Jambi City in 2016 and 2020. For 4 years, there has been an increase in settlements, as indicated by the red circle. The increase in settlements indicates population growth in Jambi City. The increase in population in urban areas will increase the need for land for settlements, resulting in a change in land use from vegetated to non-vegetated land. This condition causes a decrease in carbon storage.

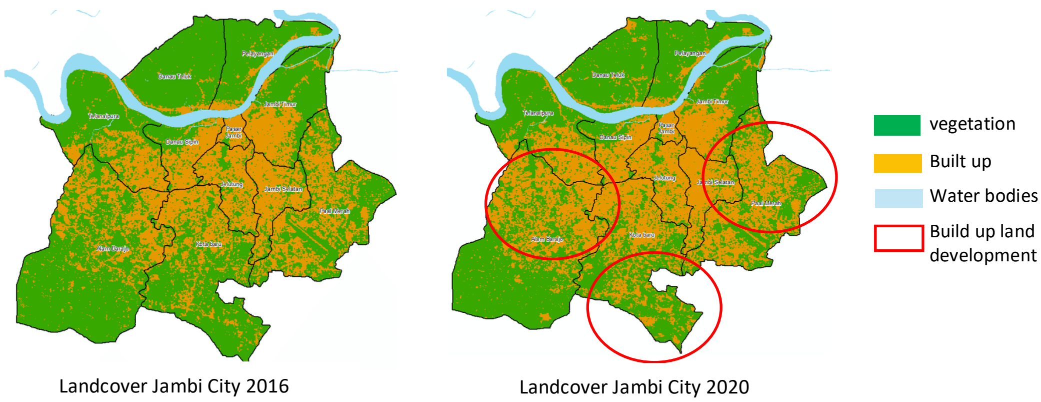


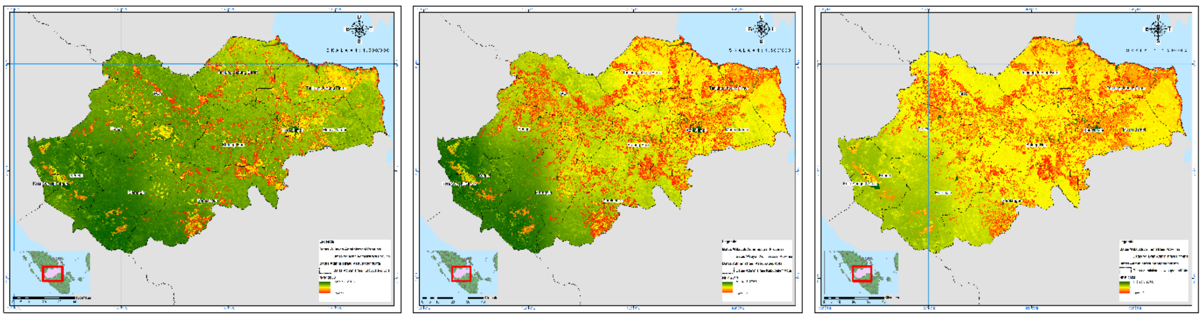
Figure 9. Landcover Map of Jambi City 2016 and 2020
(Source: MODIS Satellite Image Data Processing, 2024)

Net primary productivity (NPP)

NPP measures vegetation's net biomass production rate through photosynthesis after subtracting the autotrophic respiration (Potter et al., 1993). NPP reflects the amount of carbon an ecosystem accumulates and is an important indicator in studying carbon cycling and ecosystem productivity (Gonsamo & Chen, 2017; June et al., 2006). NPP is usually expressed in units of carbon mass per unit area per unit time (e.g., grams of carbon per square meter per year, $gC/m^2/yr$). The CASA (Carnegie-Ames-Stanford Approach) model often estimates NPP using remote sensing data, such as data from the MODIS satellite. This model integrates information on photosynthetically active radiation, air temperature, soil moisture, and vegetation variability (e.g., through NDVI) (Huang et al., 2022; Ma et al., 2020).

This study used MODIS MOD17A3GF imagery data. MODIS imagery is often used in NPP-related studies, as shown by (Huang et al., 2022; Jiang et al., 2015). Moderate Resolution Imaging Spectroradiometer (MODIS) is one of the main instruments used for global monitoring on the Earth Observing System (EOS) Terra and Aqua satellites. The MOD17 product results from this instrument, which provides worldwide GPP and NPP monitoring data. The MOD17 algorithm is developed based on the BiomeBGC ecosystem model that adopts the Light Use Efficiency (LUE) logic, as explained by (Arrafi et al., 2024; Indiarto & Sulistyawati, 2013; Pei et al., 2018).

In the monitoring of NPP using MODIS imagery (figure 10), there is a difference in the 20 years. In 2003, it was dominated by green, which had a high NPP; in 2013, it decreased, and in 2023, it changed further towards a low NPP. The average NPP value 2003 in Jambi Province was 0.911 kgC/m/year, then the average NPP decreased to 0.754 kgC/m/year in 2023. Changes in NPP from 2003 to 2023 can be seen in Figure 11. The NPP range is from red to green with a value of -3.246 - 2.669 kgc/m/year. The red on the map indicates a decrease in NPP in Jambi Province, while the green indicates an increase in NPP values in Jambi Province. The reduction in NPP during 2003 - 2023 caused a reduction in the ability of vegetation to absorb carbon (Yan et al., 2018)



2003 2013 2023

Figure 10. Net Primary Productivity Map of Jambi Province
(Source: MODIS Satellite Image Data Processing, 2024)

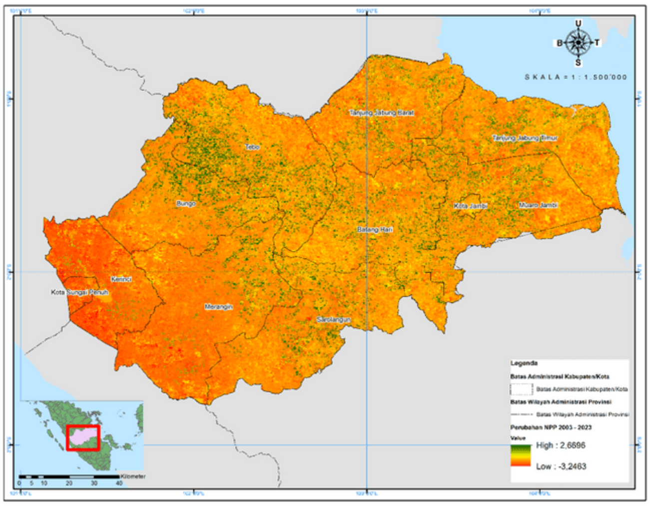


Figure 11. Map of NPP changes from 2003 to 2023 in Jambi Province
(Source: Overlay from map of NPP 2023, 2013 and 2023)

Statistical Analysis of Carbon Absorption Potential in Jambi Province

Statistical analysis was conducted by normalizing the factors used to determine carbon absorption potential in Jambi Province. All variables were converted into interval data with a value range of 0-1, which aims to align the data dimensions. Spearman correlation was conducted to determine variables closely related to NPP in Jambi Province, and this correlation is a non-parametric measure used to assess the strength and direction of monotonic relationships between variables. The relationship between variables is monotonic if, when one variable increases, the other variable tends to increase or decrease, but not necessarily at a constant level. The relationship can be linear or non-linear as long as the direction of the relationship is consistent.

Table 2. Spearman Correlation Results of Physical and Social Variables of Carbon Absorption Factors in Jambi Province

		NDVI	LST	TotPop	HDI	Slope	DEM	CH
NPP	Correlation Coefficient	0.565**	-0.290	0.015	-0.218	0.463**	0.688**	-0.250
	Sig. (2tailed)	0.001	0.120	0.937	0.248	0.010	0.000	0.183

(Source: Data Processing With Statistical Analysis)

Three of the seven variables used as input data correlate with NPP. NDVI has a correlation coefficient 0.565 with NPP and a p-value <0.05, indicating a significant positive relationship between vegetation and primary productivity. The slope has a correlation coefficient of 0.463 with NPP and a p-value <0.05, indicating a significant positive relationship between slope and primary productivity. Finally, DEM data has a correlation coefficient of 0.688 and a p-value <0.05; this indicates a significant positive relationship between topography and primary productivity.

Multi-linear regression (MLR) analysis was conducted to understand the impact of correlated factors on NPP, so the input used were variables that met the p-value significance value. The main purpose of MLR is to understand the linear relationship between the dependent variable and one or more independent variables and to predict the value of the dependent variable. Based on the analysis using Spearman correlation, three variables were obtained that were positively correlated with NPP, which were then used as input in the regression analysis. NPP is the front variable, and

NDVI, Slope, and DEM are independent variables.

The ANOVA results to test the significance of the entire model showed a p-value of 0.043 or p-value <0.05, which stated that the whole model was significant.

As represented by NPP data, slope gradient, topography, and Normalized Difference Vegetation Index (NDVI) correlate with carbon sequestration. Slope gradient and topography are factors that affect the environmental conditions where vegetation grows, while NDVI affects the process of photosynthesis, biomass accumulation and carbon sequestration. Slope gradient affects the physical and hydrological conditions of an area. Steep slopes can affect the level of soil erosion, water drainage, and the availability of nutrients for plants. Flat slopes tend to support more biomass accumulation because plants can absorb more sunlight and water. On flat slopes, there will be little erosion that can damage plants. Topography, such as elevation and slope orientation, affects microclasts and accessibility to water and nutrients. Higher areas may have lower temperatures and higher rainfall. Complex topography can create microclast variations that support better biodiversity and plant growth.

NDVI is a quantitative indicator of vegetation and photosynthetic activity. High NDVI values indicate healthy and active vegetation, which is correlated with adequate water and nutrient availability. The relationship between NDVI and NPP is close because NDVI reflects the amount of green and photosynthetic activity. Based on this, NDVI is related to plant productivity and carbon sequestration.

CONCLUSION

The results of MODIS satellite image analysis from 2003 to 2023 showed a decrease in the average NPP value in the Jambi Province area. The average NPP value 2003 in Jambi Province was 0.911 kgc/m/year, then the average NPP decreased to 0.754 kgc/m/year in 2023. The decrease in the NPP value can be interpreted as a decrease in carbon absorption. Based on statistical analysis between physical variables and social variables on carbon sequestration potential in Jambi Province, it was found that three variables correlate, namely Slope Gradient, Topography, and NDVI. The correlation between slope gradient, topography, and NDVI with NPP illustrates the complexity of the interaction between environmental factors and ecosystem productivity. Understanding this relationship is important to identify potential areas for sustainable resource management, including efforts to increase carbon sequestration and maintain ecosystem health in Jambi Province and other regions.

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