Estimating Atmospheric Forest Carbon Loss in East Baton Rouge Parish Using Satellite Remote Sensing: A Critical Tool for Climate Change Mitigation

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ABSTRACT:

Forests play a crucial role in the global carbon cycle, primarily by absorbing carbon dioxide (CO_2) during photosynthesis. However, it is often overlooked that forests also release CO_2 into the atmosphere at night through respiration or degradation, processes that can significantly contribute to atmospheric carbon levels. This study therefore focuses on estimating atmospheric forest carbon loss in East Baton Rouge Parish using satellite remote sensing as a critical tool for climate change mitigation. By employing Sentinel satellite data, the Gross Primary Productivity (GPP) of the forested areas will be obtained using the Normalized Difference Vegetation Index (NDVI), Photosynthetically Active Radiation (PAR), and Light Use Efficiency. The Net Primary Productivity (NPP) will then be estimated by subtracting Autotrophic Respiration from the GPP to determine the overall carbon balance of the forests. The research highlights the irony that while forests are expected to act as carbon sinks, they also contribute to CO_2 emissions. Understanding this dual role is essential for accurate carbon accounting and for informing climate policies. The results from this study will provide valuable insights into the temporal dynamics of forest carbon loss in East Baton Rouge Parish, helping to refine climate models and develop more effective climate change mitigation strategies. By integrating these findings into local and national policies, better forest resource management can be practiced contributing to the global efforts in reducing atmospheric carbon levels, ultimately mitigating the adverse effects of climate change.

1. INTRODUCTION

Over the years, changes observed in the earth's climate have primarily been caused by both natural and human activities contributing to greenhouse gases in the atmosphere. Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Fluorinated gases, solid and liquid aerosol, as well as water vapor and ground-level ozone are greenhouse gases that trap heat in the atmosphere thereby impacting the climate (EPA, 2024). As a phenomenon known as global warming, these gases result in long-term heating near the earth's surface thereby increasing the earth's average surface temperature. It is also well known that carbon dioxide plays an important role in the natural greenhouse warming of the Earth's atmosphere whereby an increase in its concentration might enhance the warming effect on earth (Haigh, 2013).

Agreeably, atmospheric CO_2 levels are the highest they've been in 650,000 years and are continuing to increase (Smith, 2017). Particularly human activities including the burning of fossil fuels for transportation, electricity generation and industrial activities have significantly increased CO_2 emissions. As highlighted in Chapter One (1) of the Intergovernmental Panel on Climate Change (IPCC) 2022 report, the main sources of CO_2 were attributed to that of power and industry sectors combined, dominating the current global CO_2 emissions, accounting for about 60% of total CO_2 emissions (Gale, et al., 2022). On the other hand, there are natural processes that contribute to carbon concentrations in the atmosphere. For instance, while plants are primarily noted for absorbing CO_2 from the atmosphere through photosynthesis, plants also release CO_2 through natural processes. This process by which plants release carbon they have absorbed back into the atmosphere or soil is known as Carbon Loss.

According to Csillik et al, (2004), the vulnerability of tropical forests to climate change, including more frequent and severe droughts, as well as increased susceptibility to fires, further intensifies the degradation of these forests, resulting in accelerated carbon losses (Csillik, et al., 2024). Also, through the processes of respiration, carbon is released into the atmosphere. Thus, solar energy conserved during photosynthesis and stored as chemical energy in organic molecules is released in a regulated manner. Consequently, a quantitatively important by-product of respiration, CO2 is released implying that plant and ecosystem respiration play a major role in the global carbon cycle. (Gonzalez-Meler & Trueman, 2004).

More so, CO_2 enters the atmosphere naturally through volcanic eruptions, as well as vegetation degradation and decomposition of organic matter. In other words, carbon returns to the atmosphere when the plants decay, are eaten and digested by animals, or burn in fires (Thome, 2024). With wildfires rapidly converting plant biomass into atmospheric CO_2, other natural disturbances from storms also contribute to carbon concentration in the atmosphere. Notably, as humans continually remove vegetation for agricultural and other developmental needs, there is a removal of biomass and subsequent decomposition which in turn releases carbon into the atmosphere. Essentially, the scarcity or absence of

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vegetation and other biological processes of plants are attributed to carbon loss with an impact on the carbon cycle.

Based on this, the rate at which land plants take up and release CO_2 through photosynthesis and respiration, respectively, will significantly influence the trajectory of atmospheric CO_2 change in the future (Smith, 2017). This also implies that the presence of vegetation, determines the amount of carbon to be sequestered from the atmosphere as well as subsequent environmental impacts. For instance, in 2010, East Baton Rouge had 45.4 kha of natural forest, extending over 43% of its land area (GFW, 2024). However, by 2023, it lost 272 ha of its natural forest, equivalent to 136 kt of CO_2 emissions (GFW, 2024). Knowing this, spatially explicit quantification of tropical forest carbon loss and its trajectory greatly helps reduce uncertainties and ascertain the contribution of tropical forest ecosystems to the global carbon budget over time (Yu Feng, et al., 2024).

Hence, this research seeks to employ sentinel satellite data to estimate atmospheric forest carbon loss in East Baton Rouge Parish. Over the years, as mentioned by Diana et al, (2022) for instance, urban areas in the East Baton Rouge parish have increased exponentially from 10.48% in 1991 to 24.92% in 2021 due to urban expansion and population increase. This translates into East Baton Rouge parish witnessing a large amount of agricultural land converted into settlements and other urban development activities, with vegetation and agricultural lands decreasing from 79.93% in 1991 to 67.81% in 2021 (Frimpong, et al., 2022). This reduction in green cover not only decreases the amount of CO_2 absorbed through photosynthesis but also contributes to the release of stored carbon, exacerbating carbon emissions in the region. As a result, the diminishing vegetation in East Baton Rouge Parish not only impacts local ecosystems but also plays a role in increasing atmospheric carbon levels, highlighting the importance of sustainable land management practices.

Even though attributing the sources of carbon loss to forest degradation and natural disturbances remains a challenge due to the difficulty of classifying disturbances and simultaneously estimating carbon changes (Csillik, et al., 2024), this research focuses on the loss of vegetation in East Baton Rouge Parish, primarily due to urban expansion, deforestation, and land development accounting for increased carbon loss.

2. RESEARCH METHODOLOGY

2.1 Research Study Area

East Baton Rouge (EBR) parish as seen in figure 1 is one of the populous parishes in Louisiana which has the state's capital, Baton Rouge city. According to the demographic report in the BREC Strategic Plan, East Baton Rouge Parish is the third most populated Parish in Louisiana, after Orleans Parish and Jefferson Parish (BREC, 2004). However, in the 1990s it was also one of the fastest growing Parishes in the State of Louisiana adding about 38,000 people, second only to St. Tammany Parish which added 46,760 people. This parish has a total area of 470 sq mi (1,200km^2), of which 15 sq mi (39km^2) are covered by water (United States Census Bureau, 2021). East Baton Rouge parish also contains a mixture of urban and natural environments, with substantial green spaces that support rich plant biodiversity. In relation to the vegetation, the city of Baton Rouge has a tree cover that is estimated at 44.6% as at 2012 (Abdollahi, Ning, Legiandenyi, & Khanal, 2012).

Notably, East Baton Rouge is home to bottomland hardwood forests, wetland areas, and riverine systems that contribute significantly to the region's ecological diversity. Typical vegetation that grows in the state and particularly in east baton parish includes a variety of hardwood species, such as oak, cypress, gum, and pine trees (USFS, 2019).

In terms of the climate condition in East Baton Rouge Parish, Loh et al, cited that the general climate is a humid subtropical climate with mild winters, hot and humid summers and moderate to heavy rainfall (Loh, et al., 2023) and (Peters, 2022). Due to the parish's position as a heartland of industrial activities in the Southeast, EBR has a long-standing history of air pollution issues and high temperatures (Frimpong, et al., 2022). That is, East Baton Rouge Parish, with its combination of industrial sectors and urban development, has experienced significant carbon emissions, which are primarily driven by petrochemical plants, transportation, and residential energy use, which collectively contribute to the parish's environmental footprint.

Generally, Louisiana is also noted for its major industrial facilities, emitting more greenhouse gases than almost every other state. For instance, even though emissions for 2023 were a 2.21% reduction from 2022, this was still enough to rank the state as the second among U.S states (Schleifstein, 2024). Therefore, the vegetation cover, coupled with extensive industrial activities, and threatening climate conditions necessitate the critical need to monitor forest carbon dynamics in regions like East Baton Rouge Parish.

2.1.1 Study Area – East Baton Rouge Parish

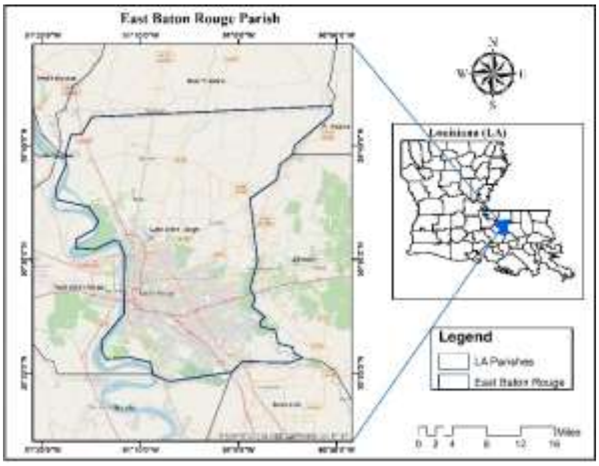

Figure 1. Map of East Baton Rouge Parish

2.2 Data Acquisition

For this study, data acquisition involved using Landsat 5 Level 2 imagery from 1994 and Landsat 9 Level 2 imagery from 2024 to compute the NDVI for both years. This provided the basis for assessing vegetation changes over the stipulated period. To estimate the observed carbon loss between 1994 and 2024, productivity data was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Gross Primary Production (GPP) and Net Primary Production (NPP) datasets. MODIS was used because it enables data to be used in studies across numerous disciplines, including vegetative health, changes in land cover and land use, oceans and ocean biology, sea surface temperature, and cloud analysis (Baynes, 2024). The forest carbon loss was derived by using the GPP (MOD17A2H Version 6) which represents the total carbon fixed by plants through photosynthesis. This MOD17 GPP is a cumulative 8-day composite of values with 500-meter (m) pixel size based on the radiation use efficiency concept that can be potentially used as inputs to data models to calculate processes such as carbon and water cycle processes as well as the biogeochemistry of vegetation (Running, 2018).

Similarly, the NPP, which is the net amount of carbon accumulated by vegetation after accounting for autotrophic respiration (Ra) was also used in deriving the carbon loss for both years. Agreeably, this Net Primary Production is an important component of the global carbon cycle as it provides a measure of the amount of CO, removed from the atmosphere through net carbon exchange (Goetz & Prince, 1999). NASA's MOD17 data product documentation provides a comprehensive guide on deriving Gross Primary Productivity (GPP) and Net Primary Productivity (NPP) from satellite data, offering insights into carbon cycling in terrestrial ecosystems.

2.3 Data Processing

The data acquired represents the observed carbon loss in East Baton Rouge Parish over a three-decade period using remote sensing datasets to obtain the vegetation dynamics. For the vegetation analysis, the Normalized Difference Vegetation Index (NDVI) was used, which is a vegetation index used in remote sensing to estimate the vegetation density and productivity (Shailendra & Taylor, 2018). The NDVI is derived from the red: near-infrared (NIR) reflectance ratio where NIR and RED are the amounts of near-infrared and red light, respectively, reflected by the vegetation and captured by the sensor of the satellite (Pettorelli, et al., 2005). For the 1994 data, this was calculated in ArcGIS Pro by using the near-infrared (NIR) band (Band 4) and red band (Band 3), following the formula below as highlighted by (Pettorelli, et al., 2005).

$$\mathbf{NDVI} = \frac{\boldsymbol{NIR\ Band - Red\ Band}}{\boldsymbol{NIR\ Band + Red\ Band}}$$

For the 2024 data, the NDVI was computed using the NIR band (Band 5) and red band (Band 4), still using the same formula above. Subsequently, the data processing involved comparing the two NDVI raster values by subtracting the 1994 NDVI values from the 2024 values, which yielded a ΔNDVI raster to capture the vegetation change over 30 years. To assess the forest carbon loss, data from the MODIS MOD17A2H Version 6 Gross Primary Productivity (GPP) and MODIS Net Primary Production (NPP) datasets were transferred to ArcGIS for further analysis, sourced from NASA’s Earth Observing System Data and Information System (Running, 2018). The forest carbon loss was calculated by using the formula below.

$$\textbf{Carbon Loss} = \mathbf{a \times \Delta NDVI + b},$$

$$\text{where } \mathbf{a} = \frac{\boldsymbol{max\ carbon\ loss}}{\boldsymbol{maximum\ NDVI\ change}}$$

ΔNDVI is the change in NDVI raster and **b** is the baseline carbon stock intercept value.

This raster represents changes in vegetation density over the 30-year period, facilitating further analysis related to carbon dynamics and forest health. Therefore, MODIS plays a vital role in the development of validated, global and interactive Earth system models able to predict global change accurately enough to assist policy makers in making sound decisions concerning the protection of the environment (Vincent & Saatchi, 1999).

2.4 Map Validation Assessment

An accuracy assessment or validation is a key component of any project employing spatial data (Congalton, 2001). To validate the carbon loss data, the observed carbon loss values were extracted into 100 strategically placed points, resulting in a set of precise locations with known carbon loss values. This comparison between ground-based observations and remotely sensed estimates ultimately refines the model’s capacity to represent actual conditions accurately and strengthens the overall confidence in the carbon loss assessment. More so, to ensure map accuracy, Congalton (2001) highlights that it is essential to follow a progressive assessment process, including visual inspection, non-site-specific analysis, difference image creation, error budgeting, and quantitative accuracy assessment. Therefore, the validation points for this study were grounded in field measurements of biomass and land cover changes, which provided essential ground-truth data for comparing remote sensing results with real-world observations. Notably, data validation has been essential in remote sensing since the very first days of aerial photogrammetry. Thus, positional accuracy has been assessed by comparing the coordinates of sample points on a map against the coordinates of the same points derived from a ground survey or some other independent source deemed to be more accurate than the map. (Congalton & Green, 2009). Hence, for this study a rigorous evaluation of the satellite-derived and model-based carbon loss estimates was ensured which enhanced the accuracy and reliability of the data.

3. RESULTS AND DISCUSSION

3.1 Normalized Difference Vegetation Index (NDVI) Analysis – 1994 & 2024

The Normalized Difference Vegetation Index (NDVI) is a widely used indicator for measuring vegetation health and density in remote sensing applications. The formula for calculating the NDVI is based on the fact that chlorophyll absorbs RED whereas the mesophyll leaf structure scatters NIR (Pettorelli, et al., 2005). NDVI values therefore range from -1 to +1, where negative values correspond to an absence of vegetation (Pettorelli, et al., 2005). The observations for this study were calculated by comparing the difference between the near-infrared (NIR) and red light reflected from vegetation, as plants strongly absorb visible red light for photosynthesis while reflecting NIR light due to their cell structure.

As shown in figure 2, the NDVI in 1994 depicts most parts of East Baton Parish had more vegetation areas (green areas) ranging between 0.3 and 0.9, representing relatively high vegetation. As compared to the other major features that were classified, the light brown areas representing built-up areas are relatively less ranging between 0 and 0.2 just as the blue areas, representing waterbodies have lower values, thus no vegetation.

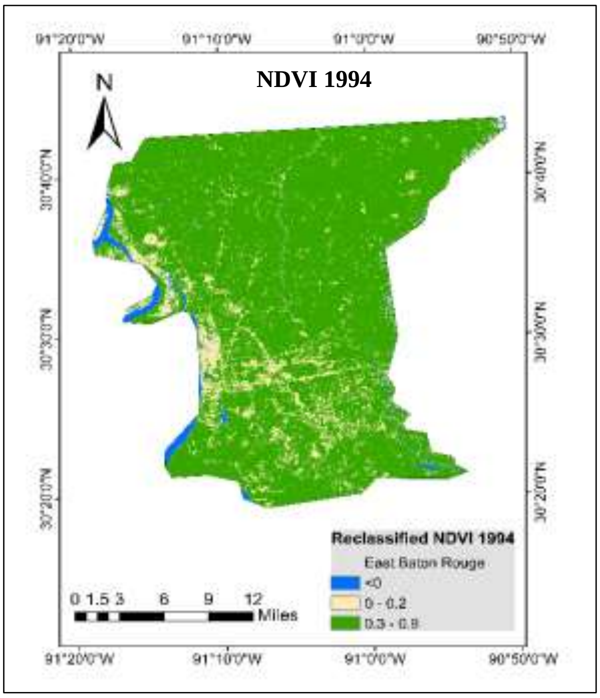

Figure 2. NDVI Map (1994)

Comparatively, the NDVI map of 2024 as seen in figure 3 below shows more light brown areas are encroaching green areas (vegetation), signifying an expansion in the development activities which translate into the clearance of vegetation for built-up areas. Thus, over the 30-year span between 1994 and 2024, the observed changes in vegetation coverage in East Baton Rouge Parish, as shown in both NDVI maps, can be attributed to both natural and human-influenced factors. The encroachment of light brown areas (representing built-up zones) into green areas (indicating vegetation) also highlights the ongoing urbanization process.

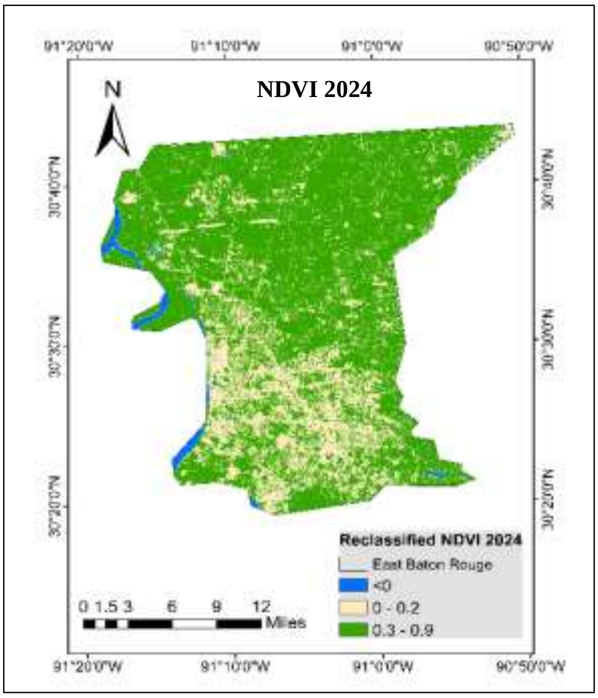

Figure 3. NDVI Map (2024)

3.2 Carbon Loss Analysis – 1994 & 2024

Understanding carbon loss as it relates to East Baton Rouge parish refers to the release of carbon stored in natural systems, particularly in forests and soils, into the atmosphere in the form of carbon dioxide (CO_2). This process occurs when carbon that has been sequestered by plants and soil over time is released back into the atmosphere through various activities or disturbances. Thus, the carbon stored in wood can last for decades or centuries, keeping it out of the atmosphere. However, when roots, leaves, or branches fall off, or when trees die, animals, fungi, and bacteria break down the material which returns some carbon to the atmosphere and moves the remaining carbon to the soil (USDA, 2024). Also, when plants and trees conduct photosynthesis, they take carbon from the atmosphere and turn it into sugars and other organic compounds. During this process, trees use most of these sugars to keep their cells alive, which releases some carbon back into the atmosphere through respiration (USDA, 2024). Based on this process, figure 4 below shows an estimation of carbon loss in East Baton Rouge parish that occurred in the past 30 years. Possibly, a combination of respiration and other forest degradation processes may have contributed to this high amount of carbon loss in East Baton Rouge Parish. Notably, most of the red and orange areas shown on the map below recorded high values of carbon loss. That is, these areas correspond to the dense vegetation areas depicted in the NDVI maps, indicative of the vegetation's contribution to carbon loss.

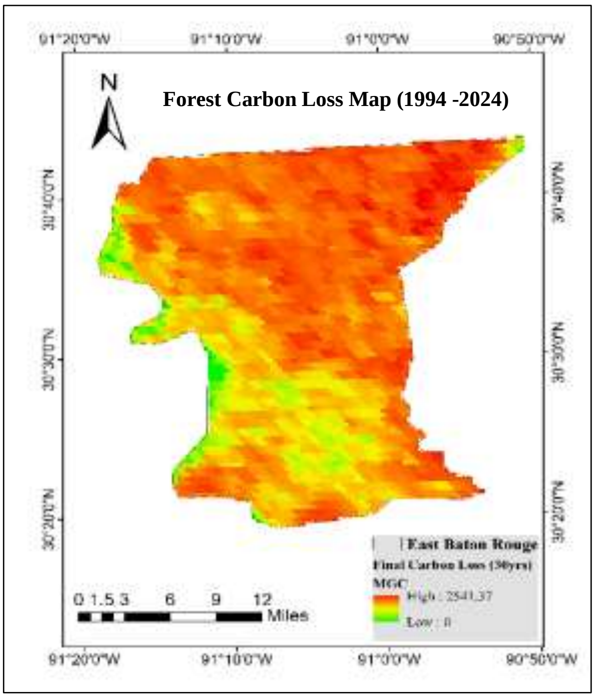

Figure 4. Carbon Loss Map

3.3 Carbon Loss Validation Map

Several methods are employed in validating geospatial data as well as conducting an accuracy assessment. For instance, accuracy and error in spatial data can be assessed progressively through visual inspection, non-site-specific analysis, difference image creation, error budgeting, and quantitative accuracy assessment (Congalton, 2001). For this study, an aspect of quantitative accuracy assessment was used whereby specific data points, 100 in total, with known values were used to assess the accuracy of the carbon loss map. This allowed for comparison of observed values as against the model-derived estimates. Considering this, the carbon loss validation map as seen in figure 5 below confirms that most of the extracted points from the carbon loss values were reflected within East Baton Rouge Parish.

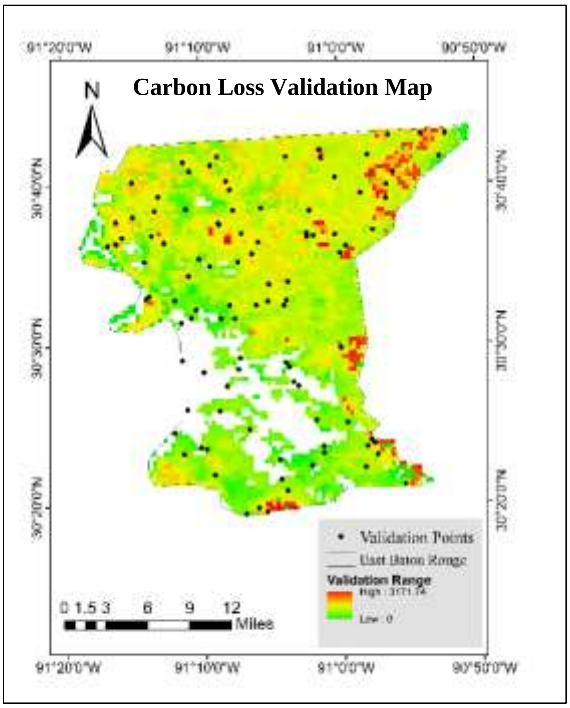

Figure 5. Carbon Loss Validation Map

3.4 Impacts of Carbon Loss on Climate Change – East Baton Rouge Parish

Carbon dioxide, although toxic at high levels, plays a crucial role in regulating the earth's temperatures and maintaining a suitable climate for life. According to Lindsey (2024), without carbon dioxide, Earth's natural greenhouse effect would be too weak to keep the average global surface temperature above freezing. However, adding more carbon dioxide to the atmosphere is supercharging the natural greenhouse effect, causing global temperature to rise (Lindsey, 2024). For instance, from 2001 to 2023, East Baton Rouge lost 9.37 kha of tree cover, which is equivalent to a 15% decrease in tree cover since 2000, and a 3.54 Mt of CO_2e emissions (GFW, 2024).

Unfortunately, with East Baton Rouge being the most populous parish, it has accumulated the most burdens related to climate change (CIVIX, Associates, & SSG, 2024). This is because, an increase in carbon emissions in East Baton Rouge Parish translates into heightened environmental and health risks, including poorer air quality, accelerated climate change impacts, and potential strain on local ecosystems and public health infrastructure. More so, most scientists attribute the global warming trend observed since the mid-20th century to the human expansion of the greenhouse effect, caused majorly by carbon dioxide (Bolles, 2024). In East Baton Rouge Parish, rapid urbanization and infrastructure development have also led to significant forested area reductions, increasing CO_2 emissions and impacting air quality and temperatures.

Every year, approximately 4.8 billion tons of carbon dioxide are released into the Earth's atmosphere as a result of deforestation (Sergieieva, 2023). This has particularly intensified global climate change, contributing to a range of climate-related disasters in Louisiana. An instance is the precipitation totals (inches) from August 2016 recorded which was over two feet of rain observed in parts of southeastern Louisiana which led to catastrophic flooding, especially in areas around Baton Rouge (Liberto, 2016). This tends to pose life-threatening challenges as twelve parishes in Louisiana including Acadia, Ascension, East Baton Rouge, were declared major federal disaster areas (Liberto, 2016). Therefore, beyond industrial CO2 emissions, the release of carbon from natural carbon sinks, such as forests, plays a critical role in elevating atmospheric carbon concentrations and subsequently having an effect on climate change.

4. CONCLUSION

Human activities like fossil fuel use and deforestation, combined with natural processes such as plant respiration and decomposition, have significantly increased atmospheric carbon dioxide (CO_2), driving climate change. In East Baton Rouge Parish, urban expansion and deforestation have drastically reduced vegetation cover, diminishing carbon absorption and releasing stored carbon into the atmosphere. For instance, between 2010 and 2023, the parish lost 272 hectares of forest, emitting 136 kt of CO_2. Based on these phenomena, this study utilized Landsat 5 imagery from 1994 and Landsat 9 imagery from 2024 to compute Normalized Difference Vegetation Index (NDVI) and assess the vegetation changes that occurred over 30 years in East Baton Rouge. The NDVI measured vegetation health by comparing near-infrared (NIR) and red-light reflectance whereby values ranging from -1 to +1, indicate sparser to denser vegetation respectively. In 1994, East Baton Rouge Parish showed significant vegetation coverage (NDVI 0.3–0.9), while built-up areas were minimal (NDVI 0–0.2). However, by 2024, the NDVI analysis revealed substantial vegetation loss due to urbanization, with green areas replaced by built-up zones. To estimate the carbon loss, productivity data was derived from MODIS Gross Primary Production (GPP) and Net Primary Production (NPP) datasets. MODIS, known for its broad spectral range and global coverage every 1–2 days was used to account for net carbon accumulation after plant respiration, which was key in estimating forest carbon loss. These observed changes over 30 years reflect the combined effects of natural factors and human activities, emphasizing the impact of development on vegetation coverage. Interestingly, while trees sequester carbon during photosynthesis, they also release CO_2 back through respiration, while additional carbon is emitted when plant material decomposes through natural or human influenced means. Over 30 years, areas with dense vegetation, as identified in the NDVI maps, showed significant carbon loss, highlighted in red and orange colors on the carbon loss map. Hence, by utilizing satellite data, this research was able to quantify vegetation loss and its contribution to carbon emissions in East Baton Rouge Parish. Carbon loss in East Baton Rouge Parish over 30 years can be attributed to forest degradation and natural processes like respiration and decomposition, releasing CO_2 from vegetation and soils, thereby contributing to the concentration of CO_2 in the atmosphere. Understanding and addressing these patterns are therefore essential to mitigating climate change and promoting sustainable development.

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