Mapping and Estimation of Carbon Dioxide (CO_2) Emissions in Selangor Using Remote Sensing and GIS for Sustainable Urban Development

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Abstract

Rapid urbanization and land use transformation are major agents of rising carbon dioxide (CO_2) emissions, which compromise natural carbon sinks and exacerbate climate concerns. Selangor, Malaysia's most urbanized and industrialized state, is the prime example, whereby population growth, industrialization, and deforestation fuel emissions while reducing biomass storage. This study employs remote sensing and Geographic Information Systems (GIS) to map and quantify CO_2 emissions across Selangor for 2015 and 2025 using Landsat 8 Operational Land Imager (OLI) data. Land cover and land use (LULC) were derived through supervised classification, with the aid of Normalized Difference Vegetation Index (NDVI) in helping with Above Ground Biomass (AGB), carbon stock, and emission level estimation. Findings show extensive land cover alterations, where urban land cover expanded from 38% to 42% between 2015 and 2025, while forest cover reduced from 32% to 28%. High NDVI areas (>0.6) reduced from 27% to 23%, as well as high AGB (>100 t/ha) from 24% to 20% and carbon stock (>24 t C/ha) from 25% to 20%. Concurrently, high-emission zones (>100 tCO_2/ha) expanded from 22% to 28%, and carbon sequestering zones (<0 tCO_2/ha) declined from 15% to 12%, particularly in Hulu Selangor and Sabak Bernam. This indicates a net reduction in carbon sequestration capacity, raising doubt as to whether Selangor is likely to achieve its Low Carbon City 2030 target. The integration of remote sensing and GIS is effective in monitoring spatial carbon dynamics and provides actionable information for interventions such as urban greening, sustainable land use, and forest conservation, directly aiding Malaysia's efforts for SDG 11 and SDG 13.

Keywords: Carbon Emission, Carbon dioxide (CO_2), Remote sensing, GIS , Low Carbon `

Introduction

Climate change has emerged as one of the most critical challenges facing humanity in the

21st century. Among the various greenhouse gases (GHGs), carbon dioxide (CO_2) remains the most significant contributor to global warming (Habib & Al-Ghamdi, 2021) accounting for more than three-quarters of total emissions worldwide (Olivier, 2020). Rapid urbanization, industrial activity, and land use changes accelerate CO_2 emissions, especially in developing regions experiencing fast-paced economic growth. If left unchecked, these emissions will intensify global warming, environmental degradation, and threaten sustainable development.

In Malaysia, Selangor represents a major focal point in the country's carbon footprint (Unit Perancang Ekonomi Negeri (UPEN) Selangor, 2022). Located on the west coast of Peninsular Malaysia, it is the most urbanized and economically active state, hosting major industrial hubs such as Shah Alam, Klang, Petaling Jaya, and Sepang. Rapid expansion of built-up areas (Mohd Zaini et al., 2020**;** Ribeiro et al., 2016) coupled with deforestation (Li et al., 2022; Habib & Al-Ghamdi, 2021) and transportation growth (Mohd Shafie & Mahmud, 2020), contributes substantially to the state's CO_2 emissions (International Energy Agency, 2025). According by (Global Forest Watch, 2023), reports indicate that Selangor's forests alone have emitted an average of 3.13 million tonnes CO_2e annually between 2001 and 2023 due to land conversion and forest loss. This trend underscores the urgent need for efficient monitoring and mitigation strategies, particularly as the state has committed to reducing its carbon footprint under the Selangor Low Carbon City 2030 Challenge.

Conventional ground-based carbon assessments, such as forest inventory plots and biomass surveys, are accurate but constrained in scalability. They require significant manpower, are costly, and are limited to localized sites, making them impractical for regional or state-level monitoring . In contrast, remote sensing provides wide spatial coverage, repeatable observations, and cost-effective means to estimate vegetation health and biomass (Othman et al., 2018) . When combined with Geographic Information Systems (GIS), remote sensing facilitates spatial mapping and analysis of carbon stock and CO_2 emissions, offering valuable insights for decision-makers (Agus et al., 2013).

This study ware applies remote sensing and GIS to compare Selangor's carbon dynamics over a ten-year period (2015–2025). By integrating land use and land cover (LULC) classification, Normalized Difference Vegetation Index (NDVI)-derived biomass estimation, and carbon stock and emission calculations, the research provides spatially explicit evidence of how urbanization has reshaped Selangor's carbon balance. The results highlight the expansion of urban emission hotspots and the contraction of forest-based carbon sinks, raising important implications for the state's Low Carbon City 2030 agenda. Specifically, this study pursues three objectives: (1) To classify land use and land cover (LULC) using supervised classification, (2) To estimate Above Ground Biomass (AGB), carbon stock, and CO_2 emissions using NDVI-derived values; and (3) To map and compare emission levels across Selangor for 2015 and 2025, providing a temporal perspective to support low-carbon planning.

Literature Review

a. Carbon Emissions and Climate Change

Carbon dioxide (CO_2) is the most dominant greenhouse gas contributing to climate change, with concentrations increasing rapidly due to human activities (International Energy Agency, 2025) (Khosravi, Raihan, Islam, Nimbarte, & Ahmed, 2025) such as fossil fuel combustion (Yaacob, Mat Yazid, Abdul Maulud, & Abdul Basri, 2023), deforestation (Panja, 2021), and urbanization (Chen et al., 2022)(Qiao, Xie, Liu, & Huang, 2025) (Ma & Ogata, 2024). Urban areas are particularly significant, accounting for more than 70% of global energy-related CO_2 emissions (Luqman, Rayner, & Gurney, 2023). The rise in emissions has disrupted natural carbon cycles, leading to global warming, sea level rise, and extreme weather events. Developing regions, including Southeast Asia, face the dual challenge of sustaining economic growth while mitigating emissions. Consequently, accurate monitoring and quantification of CO_2 emissions are essential for designing effective mitigation policies and achieving global climate goals.

b. Land Use and Land Cover (LULC) Change and Carbon Dynamics

Changes in land use and land cover directly influence carbon fluxes by altering vegetation cover and biomass density. Deforestation, agricultural expansion, and urban development are primary contributors to emissions (Houghton & Castanho, 2023) . Forests act as critical carbon sinks; however, their conversion releases large amounts of CO_2 into the atmosphere. In Southeast Asia, large-scale land conversion for plantations and urban development has significantly reduced carbon storage (Miettinen, Shi, & Liew, 2011). In Malaysia, Selangor has undergone rapid urbanization, resulting in substantial green cover loss (Hashim, Rodhan, & Abbas, 2020). Longitudinal monitoring of LULC is thus necessary for tracking carbon balance changes. Understanding LULC patterns is thus fundamental for assessing carbon dynamics and identifying emission hotspots.

c. NDVI

The Normalized Difference Vegetation Index (NDVI) is widely recognized as a reliable indicator of vegetation health and density. Calculated from the spectral difference between near-infrared (NIR) and red bands, NDVI reflects photosynthetic activity (Tucker, 1979). Higher NDVI values indicate dense, healthy vegetation, while lower values represent sparse vegetation, bare soil, or urban surfaces. NDVI has been successfully applied in tropical regions to assess vegetation conditions and estimate carbon sequestration potential (Wishnuputri et.al, 2024). According by (Sheikhi & Kanniah, 2018) (A. P. P. Hartoyo et al., 2022) , confirmed NDVI's effectiveness in capturing vegetation variability across urban–rural landscapes making it particularly valuable for monitoring urbanization impacts on vegetation cover in Selangor.

d. Above Ground Biomass (AGB)

Above Ground Biomass (AGB) represents the total dry mass of vegetation above the soil surface and serves as a direct indicator of carbon storage. AGB plays a crucial role in climate regulation, particularly in tropical forests, which contain some of the highest biomass densities globally (Saatchi et al., 2011). Traditional field-based AGB estimation is accurate but labor-intensive and limited in spatial coverage. Remote sensing provides a scalable alternative, with NDVI-based regression models commonly applied to estimate biomass across diverse landscapes (Malik, et al., 2022). Urban and agricultural areas typically register lower AGB due to vegetation removal, underscoring the importance of land cover in determining biomass distribution and carbon storage (Gibbs, et al., 2007).

e. Carbon Stock and Emission

Carbon stock refers to the amount of carbon stored in biomass, while emissions represent the release of CO_2 when biomass is lost through deforestation, land degradation, or land-use change. The Intergovernmental Panel on Climate Change (De Klein, 2006) recommends using 0.47 of AGB as the conversion factor to estimate carbon stock, which is then multiplied by 3.67 to obtain CO_2 equivalents. Numerous studies have applied this framework globally (Gibbs et al., 2007). In Malaysia, forests and peatlands are recognized as major carbon sinks (Saatchi et al., 2011) , yet they are under threat from urban expansion and plantation development. Conversely, urban landscapes tend to act as emission sources, reflecting their reduced sequestration capacity (Mustapha & Kurt, 2021) . A clear understanding of carbon stock and emissions at local scales is therefore critical for effective low-carbon planning.

f. Remote Sensing and GIS in Carbon Monitoring

Remote sensing and GIS have become indispensable for carbon monitoring due to their ability to capture large-scale, consistent, and repeatable data. Vegetation indices such as NDVI derived from Landsat, MODIS, or Sentinel imagery are widely used to estimate biomass and carbon dynamics (Tucker, 1979) . GIS enables integration and spatial analysis, facilitating the identification of emission hotspots and carbon sinks (Phong, et al., 2021). In Malaysia, most carbon mapping studies have focused on forest ecosystems and peatlands (Miettinen et al., 2011). However, localized assessments in urban and sub-urban regions such as Selangor remain limited, despite these being critical contributors to the state and national carbon footprint. By applying remote sensing and GIS techniques in such areas, researchers can generate spatially explicit evidence to guide sustainable land-use planning and low-carbon development strategies.

Methodology

a. Study Area

This study was conducted in Selangor, which is situated on the west coast of Peninsular Malaysia at approximately 3.0738° N latitude and 101.5183° E longitude. Selangor is the most urbanized and industrialized state in Malaysia and has the highest population density nationwide. It encompasses major urban centers such as Shah Alam, Petaling Jaya, Klang, and Sepang, which together form the core of the Klang Valley conurbation. These areas are the principal drivers of the state’s economic growth but also represent major sources of carbon emissions due to rapid urban expansion, industrial activity, and extensive transportation networks.

In contrast, the northern and coastal districts, including Hulu Selangor, Kuala Selangor, and Sabak Bernam, retain large tracts of secondary and mangrove forests as well as agricultural land (Najwa, et.al, 2019). These landscapes play a crucial role in regulating the state’s

carbon balance by acting as significant carbon sinks. However, forest conversion and land-use change have placed increasing pressure on these natural ecosystems.
According to Global Forest Watch (2001–2023), Selangor recorded an average annual emission of 3.13 million tonnes of CO_2e from forests, with a net emission of approximately 541,000 tonnes CO_2e per year due to land conversion. As both a hub of industrial activity and a hotspot for transportation-related emissions, Selangor contributes substantially to Malaysia's overall carbon footprint.

Given its dual role as a center of economic growth and a region of high emissions, Selangor represents an ideal case study for assessing the impacts of land-use change on carbon dynamics. Furthermore, it provides a critical context for evaluating strategies aligned with the Selangor Low Carbon City 2030 Challenge, which seeks to reduce emissions while promoting sustainable urban development.

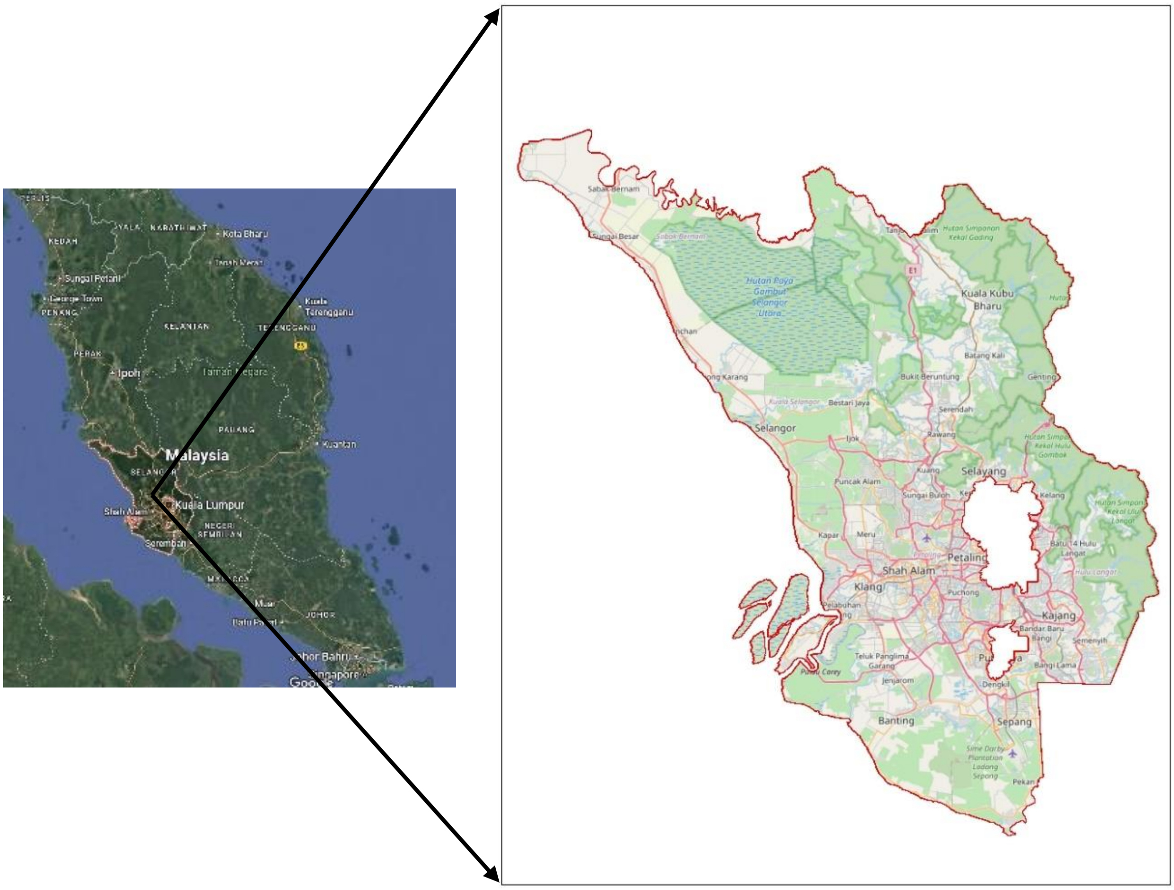

Figure 1: Location of the study area in Selangor, Malaysia.

b. Data Acquisition

This study utilized Landsat 8 Operational Land Imager (OLI) imagery as the primary dataset, which was downloaded from the United States Geological Survey (USGS) Earth Explorer portal (https://earthexplorer.usgs.gov/). Two datasets were selected, representing the years 2015 and 2025, in order to capture temporal changes in land use, vegetation cover, and carbon dynamics across Selangor. Landsat 8 provides a 30-meter spatial resolution with 11 multispectral bands and a 16-day revisit cycle, making it highly suitable for large-scale land use, vegetation monitoring, and carbon assessment (Jeppesen et al., 2019).

The datasets included key spectral bands required for vegetation analysis, particularly Band 5 (Near-Infrared, NIR) and Band 4 (Red), which were used to calculate the Normalized Difference Vegetation Index (NDVI) (H. Hartoyo, et.al, 2022) . The dataset imagery were selected with minimize cloud cover (Sheikhi & Kanniah, 2018), and atmospheric interference, ensuring consistency and reliability of spectral reflectance values (Malik et al., 2022). All geospatial datasets were standardized to the World Geodetic System 1984 (WGS 84) coordinate reference system. Preprocessing steps, including radiometric calibration and atmospheric correction, were performed using ERDAS IMAGINE 2014, ensuring consistency in spectral reflectance values. Subsequently, spatial analysis, supervised classification, and thematic mapping were conducted in ArcGIS Pro. These datasets and preprocessing procedures established the foundation for accurate land use and land cover (LULC) classification, aboveground biomass estimation, and spatial CO_2 emission mapping across Selangor.

c. Method:

i. Land Use and Land Cover (LULC) Classification

A supervised classification technique was employed to delineate the major land use and land cover (LULC) categories from Landsat 8 imagery. The classification process was performed using ERDAS IMAGINE 2014, where representative training samples were systematically selected to reflect the spectral characteristics of the landscape. Five dominant classes were identified: urban/built-up areas, vegetation, forest, bare soil, and water bodies. The classification results established a crucial baseline for subsequent analyses, particularly in quantifying vegetation cover, assessing spatial patterns of urban expansion, and estimating carbon stock. Then, classified outputs were subsequently mapped and processed using ArcGIS Pro to produce comprehensive LULC maps.

ii. Normalized Difference Vegetation Index (NDVI) Calculation

The Normalized Difference Vegetation Index (NDVI) was employed to quantify the health and density of vegetation in the study area. NDVI is a widely used spectral index that exploits the contrasting reflectance characteristics of vegetation in the red and near-infrared (NIR) regions of the electromagnetic spectrum (Alemohammad, et.al., 2018). Healthy vegetation absorbs most of the red light (for photosynthesis) while strongly reflecting NIR radiation, making NDVI an effective indicator of vegetation density and greenness (Sima & Bioresita, 2024) . NDVI was calculated using the following equation (Wishnuputri et al., 2024 ; Malik et al., 2022) :

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where NIR is the Near Infrared Band, RED is the red band. The NIR and RED represent reflectance values of Band 5 and Band 4 of Landsat 8 were utilized. The index produces values ranging from –1.0 to +1.0 (Sima & Bioresita, 2024; Wishnuputri, et.al., 2024). Negative values typically represent water bodies due to their high absorption in both spectral bands, values close to zero correspond to bare soil or non-vegetated surfaces, while higher positive values indicate dense and healthy green vegetation. (Legesse, et.al., 2024; Hartoyo et al., 2022). This differentiation allows for effective spatial assessment of vegetation cover, which is critical for estimating aboveground biomass and carbon sequestration potential.

iii. Above Ground Biomass (AGB) Estimation

Above Ground Biomass (AGB) represents the total mass of living vegetation (greenness) above the soil surface and serves as a direct indicator of carbon storage potential within an ecosystem. In this study, AGB was estimated using a remote sensing–based empirical model that relates vegetation greenness, as expressed by the Normalized Difference Vegetation Index (NDVI), to biomass density. AGB values were derived using the following regression equation :

$$ABG = a \times NDVI + b$$

To

$$ABG = 194 \times NDVI - 36.5$$

AGB values were expressed in tonnes per hectare (t/ha). where NDVI is the vegetation index calculated from Landsat 8 imagery. The generated AGB layer provides spatially explicit information on vegetation biomass across Selangor, enabling a detailed assessment of carbon stock distribution. High AGB values were typically associated with dense forested areas, whereas low values were concentrated in urban and bare land zones (Dahy, et.al., 2020) . These outputs formed the basis for subsequent conversion of biomass into carbon stock and CO_2 emission estimates.

iv. Carbon Stock Calculation

The carbon stock represents the amount of carbon stored in vegetation biomass and is a critical parameter for assessing the role of terrestrial ecosystems in mitigating climate change (Legesse et al., 2024; Raihan, et al., 2021) . Once Above Ground Biomass (AGB) was estimated, the corresponding carbon stock was derived using the default carbon fraction recommended by the Intergovernmental Panel on Climate Change (IPCC), which assumes that approximately 0.47 of dry biomass consists of carbon (Legesse et al., 2024; Sima & Bioresita, 2024). The formula used was (Legesse et al., 2024):

$$C = AGB \times 0.47$$

The resulting values represent the amount of carbon stored in vegetation per hectare. where C is the carbon stock (t C/ha) and AGB is the aboveground biomass (t/ha). This approach provides a practical and widely accepted means of estimating vegetation carbon storage, particularly when detailed field-based allometric equations are unavailable. Higher carbon stock values were generally observed in forested and densely vegetated regions (Dahy et al., 2020; Legesse et al., 2024) while urbanized and bare soil areas exhibited minimal carbon storage capacity. The carbon stock layer generated from this analysis served as an essential input for the subsequent conversion to carbon dioxide (CO_2) equivalents, allowing for spatial quantification of emission and sequestration potentials across Selangor.

v. CO_2 Emission Estimation

The final step in the analytical framework involved converting estimated carbon stock values into their equivalent carbon dioxide (CO_2) emissions. This conversion provides a direct measure of the contribution of different land use and land cover (LULC) types to greenhouse gas dynamics and climate change (Agus et al., 2013). The estimation followed the molecular weight ratio between carbon and carbon dioxide, where one unit of carbon corresponds to 3.67 units of CO_2 (De Klein, 2006). The estimation was computed as:

$$CO^2 = C \times 3.67$$

where CO_2 is the carbon dioxide equivalent (t CO_2/ha) and C is the carbon stock (t C/ha). This step enabled the quantification of spatially explicit CO_2 emissions across Selangor. Areas dominated by dense vegetation and forest showed high carbon sequestration potential (negative or low emissions), whereas urban/built-up zones and bare soils contributed to elevated emission levels due to minimal carbon storage.

vi. Spatial Categorization of Emission Zones

To facilitate spatial interpretation and policy relevance, the estimated CO_2 emission values were categorized into four distinct emission zones. This classification allowed for clear differentiation between areas of high emissions, moderate emissions, low emissions, and zones demonstrating net carbon absorption.

Table 1: Spatial categorization of CO_2 emission zones

No.	Categories Zones	Thresholds
1.	High Emission:	>100 tCO_2/ha
2.	Moderate Emission	30–100 tCO_2/ha
3.	Low Emission:	<30 tCO_2/ha
4.	Carbon Absorption:	<0 tCO_2/ha

The CO_2 emission maps provided a comprehensive overview of emission hotspots and sequestration zones, serving as a valuable tool for policymakers in prioritizing low-carbon urban development strategies and green infrastructure planning. This categorization enabled the identification of emission hotspots, transitional areas, low-emission zones, and carbon sinks, providing a comprehensive spatial overview for decision-makers.

Results and Discussion

a. Land Use and Land Cover (LULC) Map

Figures 1a and 1b illustrate the LULC distribution of Selangor for 2015 and 2025, classified into five categories: urban/built-up, forest, vegetation/agriculture, bare soil, and water bodies. The comparison reveals significant land cover transformation over the decade. In 2015, forested areas accounted for approximately 32% of Selangor's land cover, concentrated in Hulu Selangor, northern Kuala Selangor, and Sabak Bernam. By 2025, forest cover declined to around 28%, primarily due to conversion into urban and sub-urban land uses. Similarly, vegetation and agricultural lands decreased from 24% in 2015 to about 20% in 2025, reflecting the intensification of urban and infrastructure development.

Urban/built-up areas expanded markedly, rising from 38% of land area in 2015 to 42% in 2025, with growth concentrated in the Klang Valley conurbation encompassing Shah Alam, Klang, Petaling Jaya, Gombak, and Sepang. Bare soil also increased slightly (from ~5% to 6%), corresponding to construction sites and newly cleared lands. Water bodies remained relatively stable (~4%), distributed along rivers, reservoirs, and coastal regions.

These results confirm Selangor's approach as Malaysia's most urbanized and industrialized state, where land use change is driven by rapid population growth, economic development, and infrastructure expansion. (Hashim et al., 2020) similarly reported that urban expansion in Selangor has led to significant reductions in natural vegetation and agricultural lands, directly impacting ecosystem services. At the global scale, (Seto, Güneralp, & Hutyra, 2012) found that urban expansion in Asian megacities is a major driver of land conversion and greenhouse gas emissions, while (Phong et al., 2021) observed comparable patterns of vegetation loss from urban sprawl in rapidly developing Southeast Asian cities.

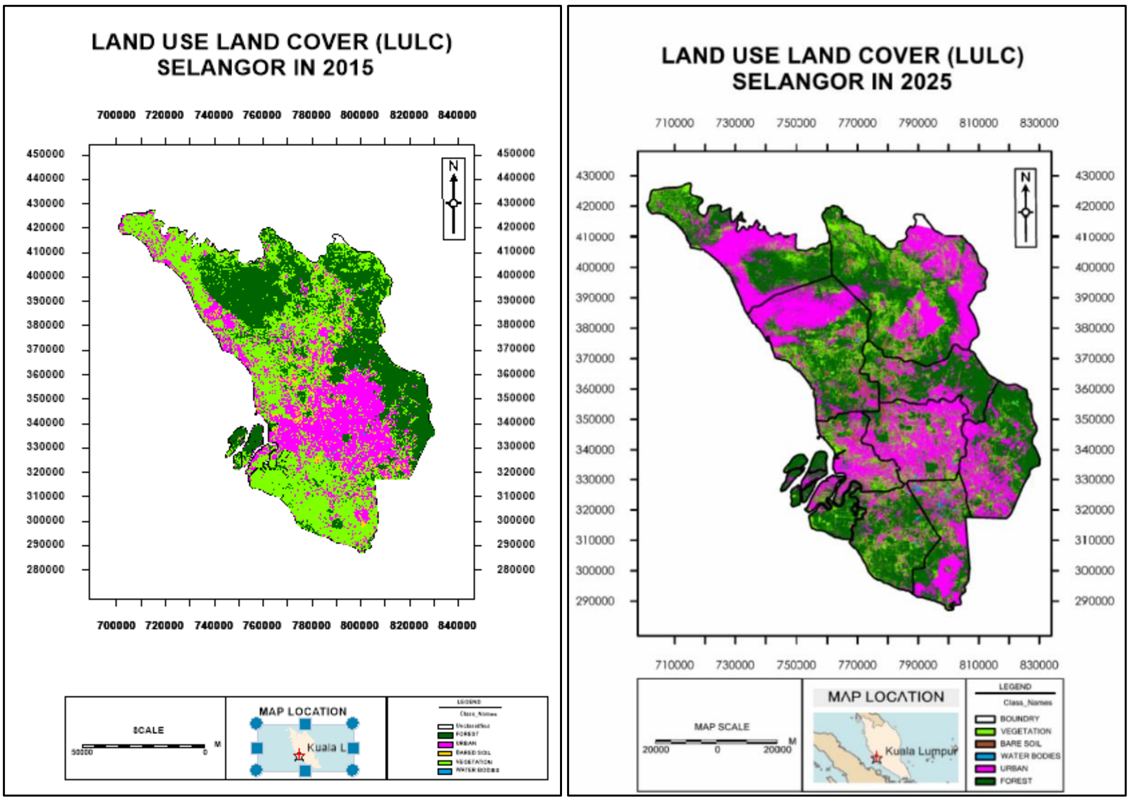

Figure 2: Land Use and Land Cover (LULC) maps of Selangor in 2015 (a) and 2025 (b).

b. Normalized Difference Vegetation Index (NDVI) Map

Figures 2a and 2b illustrate the spatial distribution of the Normalized Difference Vegetation Index (NDVI) across Selangor for the years 2015 and 2025. In 2015, the map shows that high NDVI values (>0.6), indicating dense and healthy vegetation, were concentrated in the northern and coastal districts, particularly Hulu Selangor, Sabak Bernam, and Kuala Selangor. These areas are dominated by forest reserves, mangroves, and agricultural plantations, which contribute significantly to biomass and carbon storage. Moderate NDVI values (0.4–0.6) were observed in Hulu Langat, Gombak, and Kuala Langat, reflecting a mix of vegetation, secondary forests, and semi-urban landscapes. In contrast, low NDVI values (<0.2) were widespread in Shah Alam, Klang, Petaling Jaya, and Sepang, where built-up areas, industrial zones, and infrastructure development dominate the land cover. This pattern reflects the state's urban-rural gradient, with vegetation concentrated at the peripheries and urban centers acting as hotspots of vegetation loss.

The NDVI distribution in 2025 demonstrates notable changes. High NDVI zones (>0.6) have declined, shrinking from 27% in 2015 to 23% in 2025, while low NDVI zones (<0.2) expanded from 28% to 32%. The losses are most apparent in sub-urban districts such as Hulu Langat, Gombak, and Kuala Langat, where agricultural and forested lands are increasingly replaced by residential and commercial developments. Although Hulu Selangor and Sabak Bernam continue to retain relatively high NDVI values, small areas of decline indicate pressures from land conversion and agricultural intensification. The continued dominance of low NDVI values in Shah Alam, Klang, and Sepang underscores the persistence of urban vegetation stress in the Klang Valley conurbation.

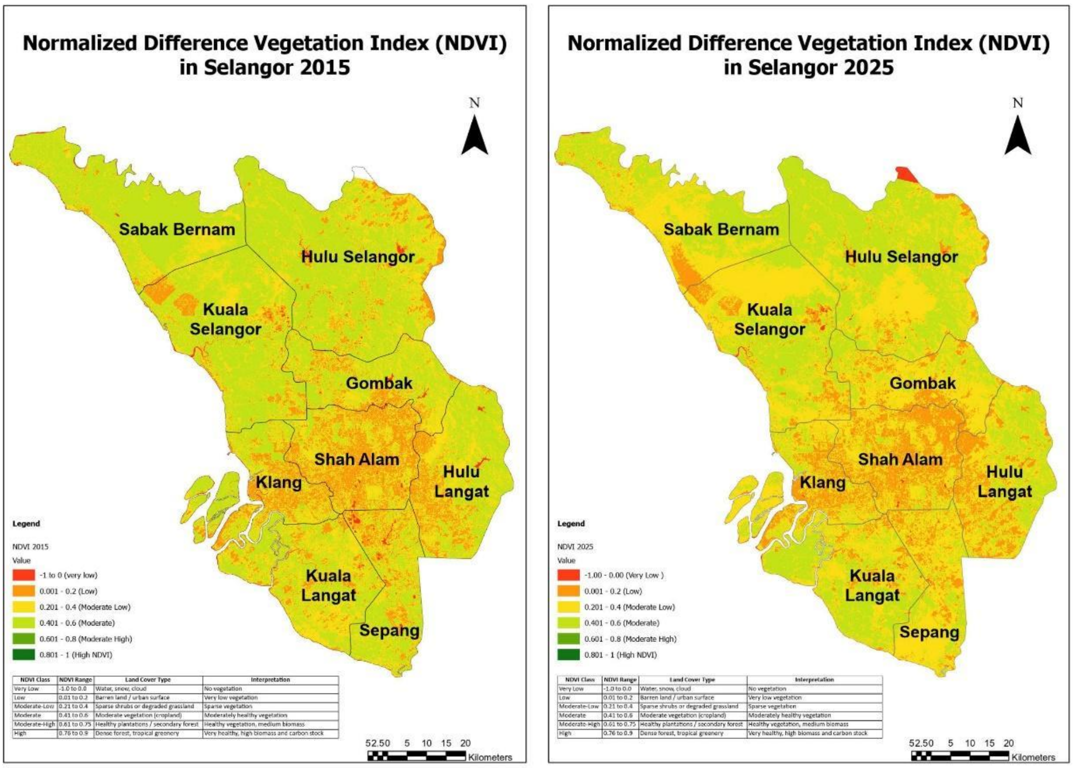

Figure 3: Normalized Difference Vegetation Index (NDVI) maps of Selangor in 2015 (a) and 2025 (b).

c. Above Ground Biomass (AGB) Map

Figures 3a and 3b show the spatial distribution of Above Ground Biomass (AGB) in Selangor for the years 2015 and 2025. In 2015, high AGB values (>100 t/ha), representing dense tropical forests and major carbon storage zones, were concentrated in the northern and coastal districts, particularly Hulu Selangor, Sabak Bernam, and Kuala Selangor. These areas are dominated by mature forests and plantations that store significant amounts of biomass. Moderate AGB zones (30–100 t/ha) were observed in Hulu Langat, Kuala Langat, and Gombak, where land cover consists mainly of secondary forests and mixed agricultural systems. In contrast, urban centers such as Shah Alam, Klang, and Sepang exhibited low AGB (<30 t/ha), consistent with built-up environments and limited vegetation cover.

By 2025, the spatial pattern of AGB reveals a noticeable reduction in high biomass areas. High AGB zones (>100 t/ha) declined from 24% in 2015 to 20% in 2025, while low biomass areas (<30 t/ha) expanded from 33% to 38%. The decline is particularly evident in sub-urban areas such as Gombak, Hulu Langat, and Kuala Langat, where agricultural and forested land has increasingly been converted into residential, commercial, and infrastructural developments. Although Hulu Selangor and Sabak Bernam remain biomass-rich, local declines highlight pressures from both urban expansion and agricultural intensification.

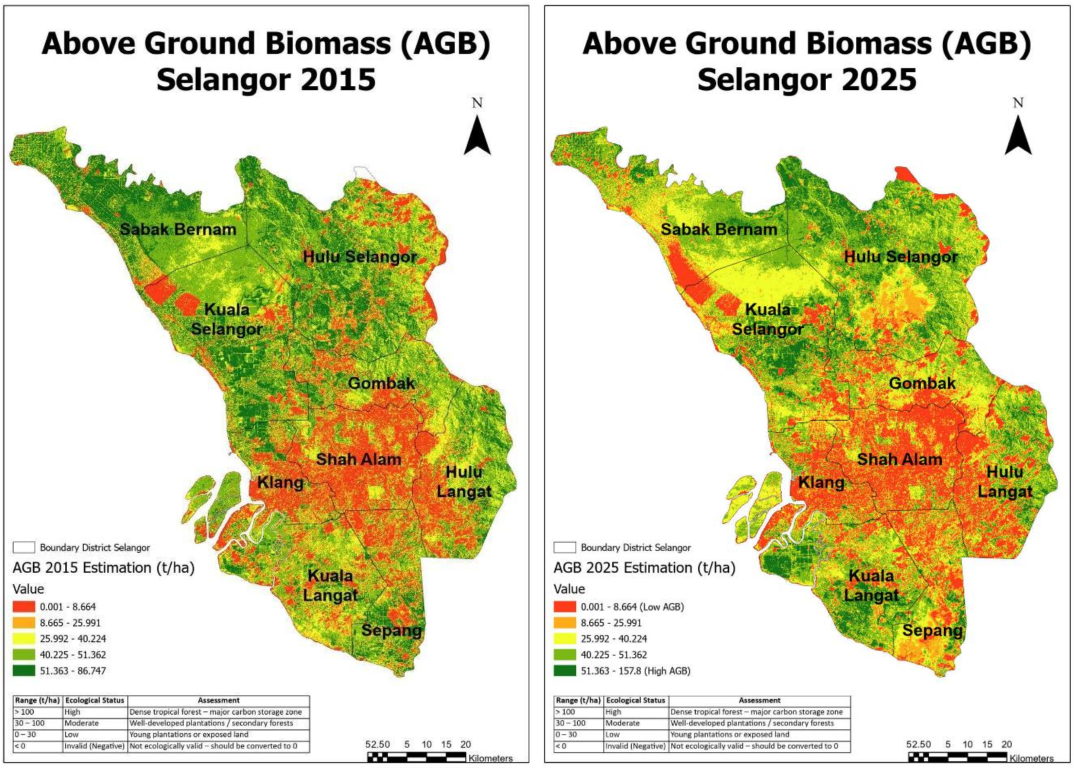

Figure 4: Above Ground Biomass (AGB) maps of Selangor in 2015 (a) and 2025 (b).

d. Carbon Stock Map

Figures 4a and 4b illustrate the spatial distribution of carbon stock in Selangor for the years 2015 and 2025. In 2015, high carbon stock values (>61 t C/ha), which represent mature tropical forests with strong sequestration capacity, were mainly concentrated in Hulu Selangor, Sabak Bernam, and parts of Kuala Selangor. These districts contained extensive forest reserves, mangroves, and agricultural landscapes that contributed significantly to the state’s carbon storage. Moderate carbon stock values (30–60 t C/ha) were more widespread in Hulu Langat, Gombak, and Kuala Langat, reflecting areas of secondary forest and mixed agriculture. In contrast, urban centers such as Shah Alam, Klang, and Sepang were dominated by low carbon stock values (<10 t C/ha), consistent with built-up areas where vegetation cover is minimal.

By 2025, the distribution shows a noticeable decline in high carbon stock areas. Regions exceeding 61 t C/ha contracted from 25% in 2015 to about 20% in 2025, while low carbon stock zones (<10 t C/ha) expanded, particularly across sub-urban districts where forests and agriculture are being converted into residential and industrial developments. While Hulu Selangor and Sabak Bernam continue to function as important carbon reservoirs, their carbon density has slightly reduced, reflecting growing land-use pressures. Meanwhile, urban areas such as Shah Alam, Klang, and Sepang remain persistently low in carbon stock, highlighting their role as emission-heavy zones with limited sequestration potential.

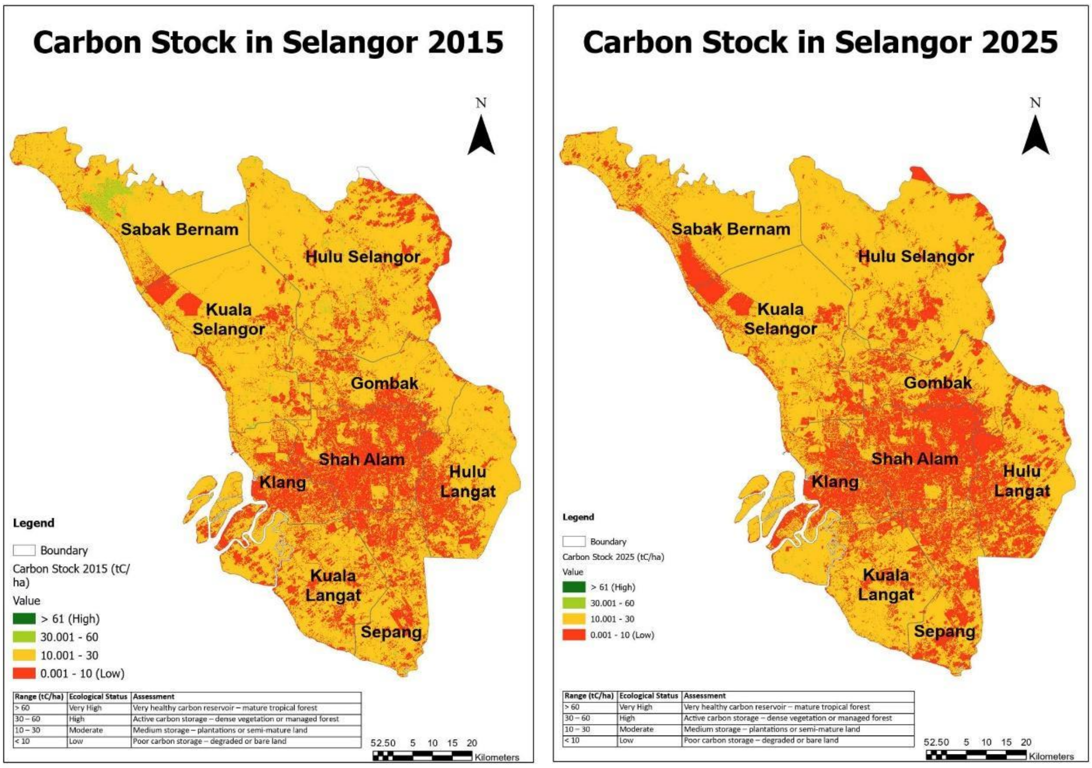

Figure 5: Carbon Stock maps of Selangor in 2015 (a) and 2025 (b).

e. Carbon emissions Map

Figures 5a and 5b present the spatial distribution of carbon dioxide (CO_2) emissions across Selangor in 2015 and 2025. In 2015, high-emission zones (>100 tCO_2e/ha) were primarily concentrated in the urban and industrial centers of Shah Alam, Klang, Petaling Jaya, and Sepang, reflecting the impact of dense built-up land cover and limited vegetation. Moderate emission areas (30–100 tCO_2e/ha) extended into sub-urban districts such as Gombak, Hulu

Langat, and Kuala Langat, where mixed land uses combine agriculture, secondary forests, and residential development. By contrast, northern and coastal districts, particularly Hulu Selangor and Sabak Bernam, contained larger tracts of low or negative emission zones (<30 tCO_2e/ha and <0 tCO_2/ha), functioning as carbon absorption areas due to extensive forest and agricultural cover.

By 2025, the emission pattern shows a clear intensification of hotspots. High-emission zones expanded from 22% of Selangor’s land area in 2015 to about 28% in 2025, with significant growth in the Klang Valley conurbation, covering Shah Alam, Klang, Gombak, and Sepang. At the same time, carbon absorption areas (<0 tCO_2/ha) declined from 15% in 2015 to 12% in 2025, particularly in Hulu Selangor and Sabak Bernam, where forest edges and agricultural zones face increasing pressure from land conversion. Moderate emission zones (30–100 tCO_2e/ha) decreased slightly, reflecting a transition toward either low-vegetation, high-emission urban cores or stable low-emission agricultural landscapes. This shift underscores the impact of urbanization on Selangor’s carbon balance, with growing built-up areas reducing the extent of carbon sinks while amplifying emission hotspots.

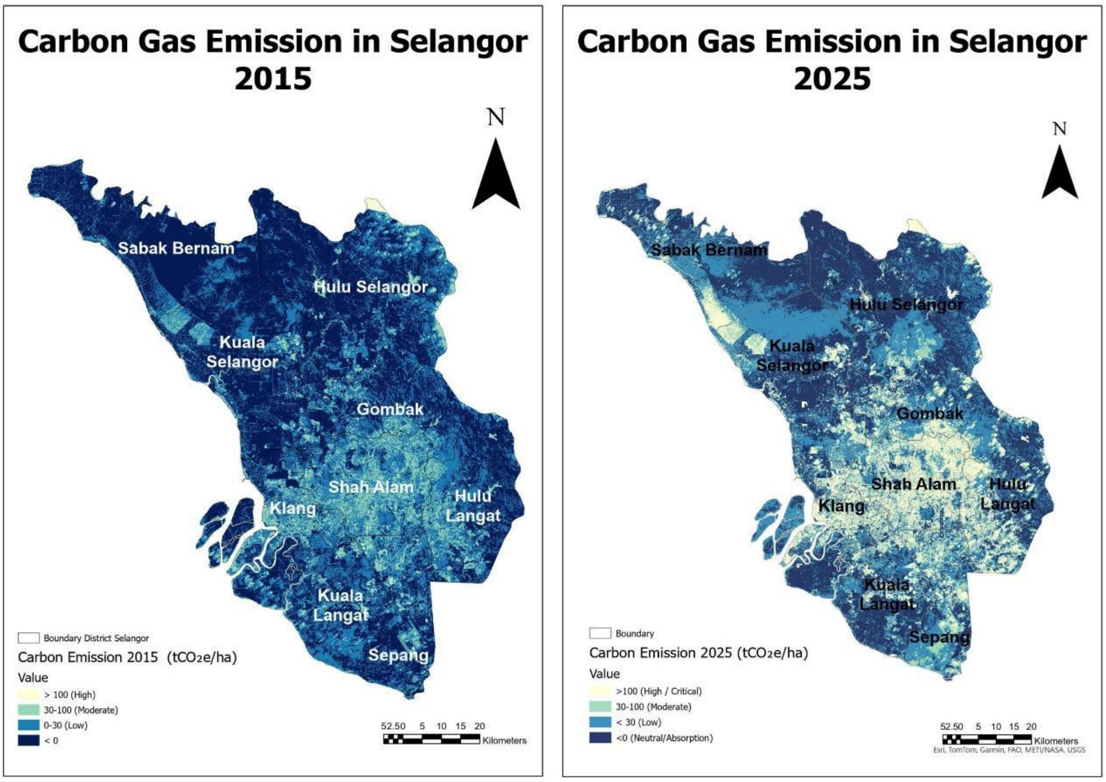

Figure 6: Carbon Gas Emission maps of Selangor in 2015 (a) and 2025 (b).

f. District-Level Carbon Indicators

The district-level percentages of NDVI, AGB, carbon stock, and CO_2 emissions for Selangor in 2015 and 2025 are presented in Table 2 and figure 7. Urbanized centers such as Shah Alam/Klang and Sepang recorded the lowest sequestration indicators, with NDVI values declining to just 21–26% of the state maximum in 2025. Their AGB and carbon stock dropped below 10%, demonstrating their negligible role in carbon storage. Despite this, their CO_2 emissions rose to 8–9% of the maximum, reflecting rapid urban expansion, energy-intensive activities, and limited vegetation cover.

Transitional districts such as Hulu Langat, Kuala Langat, and Gombak displayed moderate percentages. By 2025, their NDVI declined to 40–50% of the maximum, while AGB and carbon stock fell to 26–30%, indicating progressive loss of biomass. Their CO_2 emissions accounted for 26–29% of the maximum, down from 29–34% in 2015, suggesting that vegetated areas are increasingly replaced by built-up land. Foley et al. (2005) similarly identified sub-urban landscapes as highly vulnerable to land conversion, simultaneously contributing to emissions while losing sequestration potential.

In contrast, forested and rural districts such as Hulu Selangor, Kuala Selangor, and Sabak Bernam retained the highest percentages across all indicators. Hulu Selangor maintained NDVI at 93% of the maximum, AGB at 86%, and carbon stock at 85%, while CO_2 absorption stood at 85% in 2025. Sabak Bernam consistently registered 100% across all indicators, confirming its role as the state's strongest carbon sink due to extensive agriculture and forest cover. Overall, the table illustrates a clear imbalance: urban centers provide less than 10% of sequestration potential, transitional districts contribute a moderate 25–50%, while forested districts exceed 70% across all indicators.

Table 2: District-level averages of NDVI, Above Ground Biomass (AGB), Carbon Stock, and CO_2 emissions in Selangor for 2015 and 2025 (absolute values and % relative to maximum).

District	NDVI				AGB				C Stock				CO_2			
	NDVI		Changes Area %		Ton/ hectare (t/ha)		Changes Area %		Ton/ hectare (t C/ha)		Changes Area %		Ton/ hectare (tCO_2/ha)		Changes Area %	
	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025	2015	2025
Shah Alam/Klang	0.20	0.15	26.7	21.4	10	8	6.9	5.7	5	4	7.4	6.1	17	20	6.8	8.3
Sepang	0.22	0.18	29.3	25.7	12	9	8.3	6.4	6	4	8.8	6.1	19	22	7.6	9.1
Hulu Langat	0.35	0.30	46.7	42.9	45	38	31.0	27.1	21	18	30.9	27.3	77	67	30.9	27.7
Kuala Langat	0.40	0.35	53.3	50.0	50	42	34.5	30.0	23	19	33.8	28.8	84	70	33.7	28.9
Gombak	0.33	0.28	44.0	40.0	42	36	29.0	25.7	20	17	29.4	25.8	73	63	29.3	26.0
Hulu Selangor	0.70	0.65	93.3	92.9	130	120	89.7	85.7	61	56	89.7	84.8	224	207	90.0	85.5
Kuala Selangor	0.60	0.55	80.0	78.6	105	95	72.4	67.9	49	45	72.1	68.2	179	165	71.9	68.2
Sabak Bernam	0.75	0.70	100.0	100.0	145	140	100.0	100.0	68	66	100.0	100.0	249	242	100.0	100.0

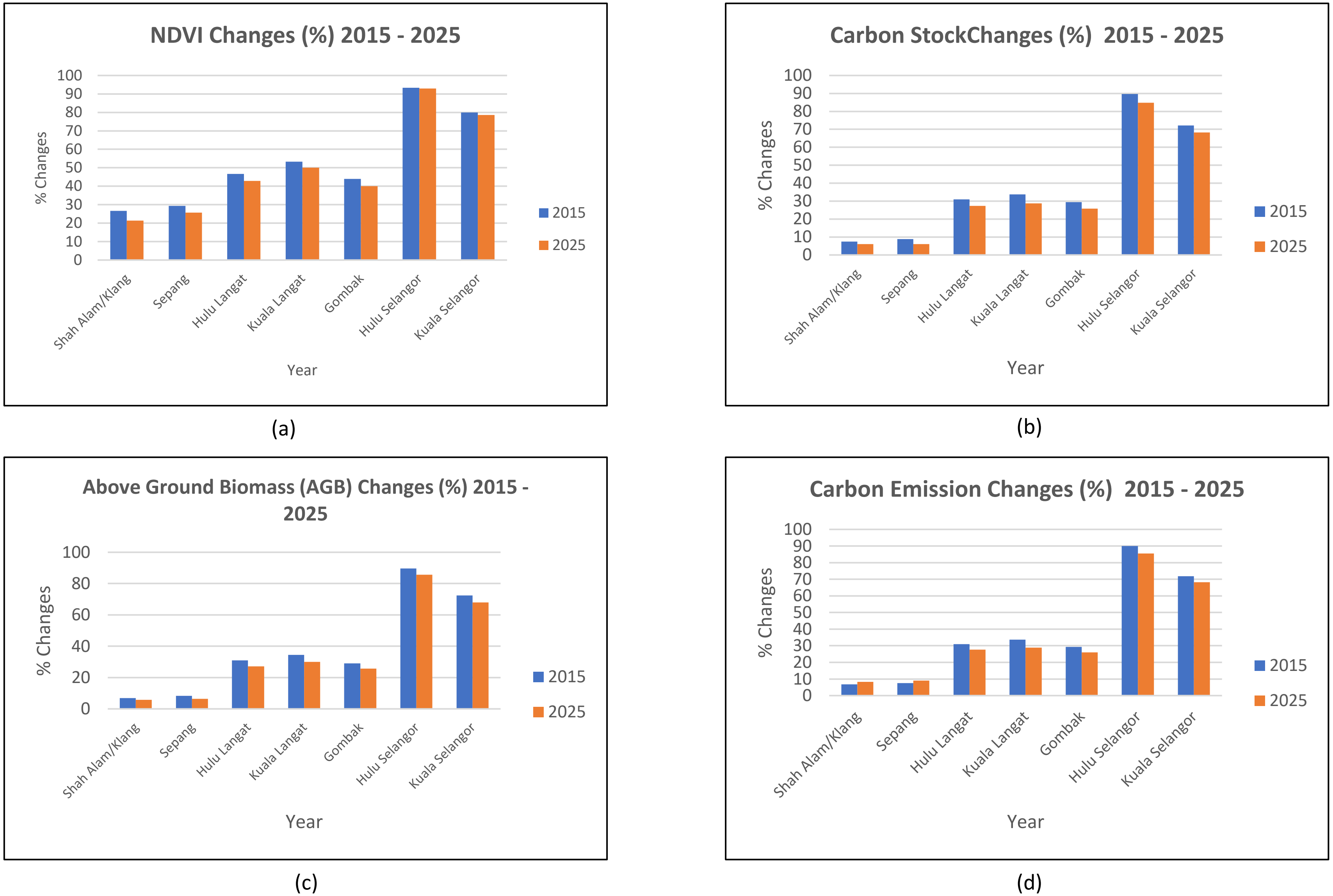

Figure 7: Percentage change of (a) NDVI , (b) AGB, (c) Carbon Stock, and (d) CO_2 across districts in Selangor between 2015 and 2025.

The district-level disparities presented in Table 1 are consistent with broader regional and global studies on land-use change and carbon dynamics. The low percentages in urbanized districts such as Shah Alam/Klang and Sepang reflect the well-documented impacts of urban expansion on vegetation cover and biomass reduction.(Kanniah et al., 2015) demonstrated that urbanization in Malaysian cities leads to a decline in NDVI and vegetation health, while (Seto et al., 2012) highlighted that urban areas worldwide are responsible for extensive land conversion and carbon emissions, accounting for more than 70% of global energy-related CO_2 emissions. These findings justify the observed weak sequestration potential (<10%) in Selangor's urban districts.

The moderate contributions from transitional districts such as Hulu Langat, Kuala Langat, and Gombak are in line with studies that identify peri-urban areas as zones of both emission generation and sequestration, but highly vulnerable to land conversion. (Gibbs et al., 2007) emphasized that suburban and agricultural frontiers are often at risk of progressive urban encroachment, leading to biomass and carbon stock loss over time. This supports the observed decline of AGB and carbon stock to 26–30% of the maximum in these districts, alongside reduced CO_2 absorption capacity.

The strong sequestration role of forested and rural districts (Hulu Selangor, Kuala Selangor, and Sabak Bernam) is consistent with tropical forest studies worldwide. (Saatchi et al., 2011) estimated that tropical forests contribute the largest share of aboveground biomass globally, storing significant carbon stocks critical for climate regulation. Similarly, (Morel et.al., 2019) confirmed that tropical landscapes act as essential carbon reservoirs despite pressures from land conversion. The high percentages (>70%) observed in these districts affirm that Selangor's rural and forested regions remain its primary carbon sinks, offsetting emissions from urban cores.

Overall, the district-level analysis demonstrates a stark imbalance between urban emission hotspots and forest carbon sinks. Urban districts contribute disproportionately to CO_2 release, while northern and coastal districts serve as the state's main sequestration reservoirs. These findings echo the global patterns identified by (Seto et al., 2012) , where urbanization is linked to intensified carbon emissions and diminished natural sinks. For Selangor, this evidence underscores the urgency of green infrastructure in cities, sustainable land management in transitional zones, and conservation of forest-rich districts to maintain ecological balance and meet sustainability targets under SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

This widening disparity emphasizes the need for differentiated strategies such as urban greening in cities, sustainable land-use in transitional zones, and conservation in forest-rich districts to meet Selangor's Low Carbon City 2030 Challenge and Malaysia's broader commitments under SDG 11 and SDG 13.

Conclusion and Recommendation

In conclusion, this study highlights the value of remote sensing and GIS as effective tools for monitoring carbon dynamics and supporting sustainable urban planning. By assessing changes in land use, vegetation, biomass, carbon stock, and CO_2 emissions over time, the research provides spatial evidence to guide strategies that balance urban development with environmental sustainability. The findings emphasize the need for integrated approaches that combine urban greening, forest conservation, and sustainable land management to strengthen carbon sequestration capacity while reducing emission hotspots. Moving forward, incorporating higher-resolution data, ground-based validation, and socio-economic indicators will further improve accuracy and policy relevance. Overall, geospatial monitoring plays a crucial role in supporting Selangor's Low Carbon City 2030 agenda and advancing Malaysia's commitments under SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

References

Agus, F., Henson, I. E., Sahardjo, B. H., Harris, N., Noordwijk, V., & Killeen, T. J. (2013). *Review of Emission Factors for Assessement of CO2 Emission from Land Use Cgange to Oil Palm in Southeast Asia*.

Alemohammad, S. H., Kolassa, J., Prigent, C., Aires, F., & Gentine, P. (2018). Global Downscaling of Remotely-Sensed Soil Moisture using Neural Networks. *Hydrology and Earth System Sciences*. https://doi.org/10.5194/hess-2017-680

Chen, F., Liu, A., Lu, X., Zhe, R., Tong, J., & Akram, R. (2022). Evaluation of the Effects of Urbanization on Carbon Emissions: The Transformative Role of Government Effectiveness. *Frontiers in Energy Research*, *10*(February), 1–12.

https://doi.org/10.3389/fenrg.2022.848800

Dahy, B., Issa, S., Ksiksi, T., & Saleous, N. (2020). Geospatial Technology Methods for Carbon Stock Assessment: A Comprehensive Review. *IOP Conference Series: Earth and Environmental Science*, *540*(1). https://doi.org/10.1088/1755-1315/540/1/012036

De Klein, C. (2006). N2O emissions from managed soils, and CO2 emissions from lime and urea application. Agriculture 54 p. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.*, *Volume 4:*(Forestry and Other Land Use.), 54. Retrieved from http://publications.lib.chalmers.se/records/fulltext/245180/245180.pdf%0Ahttps://hdl.handle.net/20.500.12380/245180%0Ahttp://dx.doi.org/10.1016/j.jsames.2011.03.003%0Ahttps://doi.org/10.1016/j.gr.2017.08.001%0Ahttp://dx.doi.org/10.1016/j.precamres.2014.12

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters*, *2*(4), 045023. https://doi.org/10.1088/1748-9326/2/4/045023

Habib, S., & Al-Ghamdi, S. G. (2021). Estimation of Above-Ground Carbon-Stocks for Urban Greeneries in Arid Areas: Case Study for Doha and FIFA World Cup Qatar 2022. *Frontiers in Environmental Science*, *9*(June 2021), 1–17. https://doi.org/10.3389/fenvs.2021.635365

Hartoyo, A. P. P., Pamoengkas, P., Mudzaky, R. H., Khairunnisa, S., Ramadhi, A., Munawir, A., … Sunkar, A. (2022). Estimation of vegetation cover changes using normalized difference vegetation index (NDVI) in Mount Halimun Salak National Park, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1109*(1). https://doi.org/10.1088/1755-1315/1109/1/012068

Hartoyo, H., Amron, A., Fitri, A. D. P., & Darmanto, Y. (2022). Sound Productivity of Spiny Lobster Panulirus homarus (Linnaeus, 1758) due to Crude Oil Contamination. *Omni-Akuatika*, *18*(S1), 72. https://doi.org/10.20884/1.oa.2022.18.1.964

Hashim, A. A., Rodhan, Z. K., & Abbas, S. J. (2020). Fresh and hardened properties of self-compacting high performance concrete containing nano-metakaolin as a partial replacement. *IOP Conference Series: Materials Science and Engineering*, *928*(2). https://doi.org/10.1088/1757-899X/928/2/022036

Houghton, R. A., & Castanho, A. (2023). Annual emissions of carbon from land use, land-use change, and forestry from 1850 to 2020. *Earth System Science Data*, *15*(5), 2025–2054. https://doi.org/10.5194/essd-15-2025-2023

International Energy Agency. (2025). *Global Energy Review 2025*. Retrieved from https://iea.blob.core.windows.net/assets/5b169aa1-bc88-4c96-b828-aaa50406ba80/GlobalEnergyReview2025.pdf

Kanniah, K. D., Sheikhi, A., Cracknell, A. P., Goh, H. C., Tan, K. P., Ho, C. S., & Rasli, F. N. (2015). Satellite Images for Monitoring Mangrove Cover Changes in a Fast Growing Economic Region in Southern Peninsular Malaysia. *Remote Sensing 2015, Vol. 7, Pages 14360-14385*, *7*(11), 14360–14385. https://doi.org/10.3390/RS71114360

Khosravi, H., Raihan, A. S., Islam, F., Nimbarte, A., & Ahmed, I. (2025). A Comprehensive Approach to CO 2 Emissions Analysis in High-Human-Development-Index Countries Using Statistical and Time Series Approaches. *Sustainability*, *17*(603), 1–35.

Legesse, F., Degefa, S., & Soromessa, T. (2024). Estimating Carbon Stock using Vegetation Indices and Empirical Data in the Upper Awash River Basin. *Discover Environment*, *2*. https://doi.org/10.1007/s44274-024-00165-8

Li, Y., Li, M., & Wang, Y. (2022). Forest Aboveground Biomass Estimation and Response to Climate Change Based on Remote Sensing Data. *Sustainability (Switzerland)*, *14*(21). https://doi.org/10.3390/su142114222

Luqman, M., Rayner, P. J., & Gurney, K. R. (2023). On the Impact of Urbanisation on CO2 Emissions. *Npj Urban Sustainability*, *3*(1), 1–8. https://doi.org/10.1038/s42949-023-00084-2

Ma, B., & Ogata, S. (2024). Impact of Urbanization on Carbon Dioxide Emissions—Evidence from 136 Countries and Regions. *Sustainability (Switzerland)*, *16*(18). https://doi.org/10.3390/su16187878

Malik, A., Nasrudin, A., Parikesit, & Withaningsih, S. (2022). Vegetation Stands Biomass and Carbon Stock Estimation using NDVI - Landsat 8 Imagery in Mixed Garden of Rancakalong, Sumedang, Indonesia. *IOP Conf. Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/1211/1/012015

Miettinen, J., Shi, C., & Liew, S. C. (2011). Deforestation rates in insular Southeast Asia between 2000 and 2010. *Global Change Biology*, *17*(7), 2261–2270.

https://doi.org/10.1111/J.1365-2486.2011.02398.X

Mohd Zaini, R., Mohd Noor, N., & Hashim, M. (2020). Extracting carbon emission for industrial area by using Landsat 8: Case study of Klang, Malaysia. *ACRS 2020 - 41st Asian Conference on Remote Sensing*, (1), 1–7.

Morel, R. P., & , Cynthia Coburn1, Amy Koehler Catterson2, and J. H. (2019). (PDF) The Multiple Meanings of Scale: Implications for Researchers and Practitioners. *Educational Researcher*, *48*(6), 369–377. Retrieved from https://www.researchgate.net/publication/334071022_The_Multiple_Meanings_of_Scale_Implications_for_Researchers_and_Practitioners

Mustapha, A. T., & Kurt, M. (2021). The Growth and Challenges of Virtual Learning of English Language in Nigeria in Times of COVID-19 Pandemic. *International Online Journal of Education and Teaching*, *8*(3), 1312–1323.

Najwa Shahrin, N., Asmat, A., Atiqah Hazali, N., & Sahak, N. (2019). Land use and land cover (LULC) modification on the climate and air quality variations. *IOP Conference Series: Earth and Environmental Science*, *373*(1). https://doi.org/10.1088/1755-1315/373/1/012009

Olivier, J. G. J. and P. J. A. H. . (2020). Trends in Global Co2 and Total Greenhouse Gas Emissions. In *PBL Netherlands Environmental Assessment Agency*.

Othman, M., Idris, N., Juneng, L., Makmom, A., Portia, W., Khan, F., … Sulaiman, N. (2018). Impact of regional haze towards air quality in Malaysia : A review. *Atmospheric Environment*, *177*(June 2017), 28–44. https://doi.org/10.1016/j.atmosenv.2018.01.002

Panja, P. (2021). Deforestation, Carbon dioxide increase in the atmosphere and global warming: A modelling study. *International Journal of Modelling and Simulation*, *41*(3), 209–219. https://doi.org/10.1080/02286203.2019.1707501

Phong, T. N., Thang, V. T., & Hoai, N. T. (2021). What motivates farmers to accept good aquaculture practices in development policy? Results from choice experiment surveys with small-scale shrimp farmers in Vietnam. *Economic Analysis and Policy*, *72*, 454–469. https://doi.org/10.1016/J.EAP.2021.09.015

Qiao, W., Xie, Y., Liu, J., & Huang, X. (2025). The Impacts of Urbanization on Carbon Emission Performance: New Evidence from the Yangtze River Delta Urban Agglomeration, China. *Land*, *14*(1), 1–18. https://doi.org/10.3390/land14010012

Raihan, A., Begum, R. A., Nizam, M., Said, M., & Pereira, J. J. (2021). Assessment of Carbon Stock in Forest Biomass and Emission Reduction Potential in Malaysia. *Forests*, *12*(1294).

Ribeiro, F. N. D., Salinas, D. T. P., Soares, J., De Oliveira, A. P., De Miranda, R. M., & Souza, L. A. T. (2016). The Evolution of Temporal and Spatial Patterns of Carbon Monoxide Concentrations in the Metropolitan Area of Sao Paulo, Brazil. *Advances in Meteorology*, *2016*, 1–13. https://doi.org/10.1155/2016/8570581

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., … Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(24), 9899–9904. https://doi.org/10.1073/pnas.1019576108

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083–16088. https://doi.org/10.1073/PNAS.1211658109

Sheikhi, A., & Kanniah, K. D. (2018). Impact of Land Cover Change on Urban Surface Temperature in Iskandar Malaysia. *Chemical Engineering Transactions*, *63*. https://doi.org/10.3303/CET1863005

Sima, P., & Bioresita, F. (2024). Estimation of Biomass and Carbon Stock Using NDVI from Multispectral Camera in the Revegetation Area of PT Berau Coal. *International Journal of Marine Engineering Innovation and Research*, *9*(2), 245–251. https://doi.org/10.12962/j25481479.v9i2.20416

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, *8*(2), 127–150. https://doi.org/10.1016/0034-4257(79)90013-0

Unit Perancang Ekonomi Negeri (UPEN) Selangor. (2022). *Rancangan Selangor Pertama*.

Wishnuputri, S., Withaningsih, S., & Parikesit, P. (2024a). Estimation of carbon stock in mixed garden tree stands in Jatigede Subdistrict, Sumedang Regency using NDVI (Normalized Difference Vegetation Index). *E3S Web of Conferences*, *495*, 02005. https://doi.org/10.1051/E3SCONF/202449502005

Wishnuputri, S., Withaningsih, S., & Parikesit, P. (2024b). Estimation of Carbon Stock in Mixed Garden Tree Stands in Jatigede Subdistrict , Sumedang Regency using NDVI

(Normalized Difference Vegetation Index). *ICYES 2023*, *495*.

Yaacob, N. F. F., Mat Yazid, M. R., Abdul Maulud, K. N., & Abdul Basri, N. E. (2023). Spatial temporal pattern of carbon dioxide emission from vehicle. *IOP Conference Series: Earth and Environmental Science*, *1167*(1). https://doi.org/10.1088/1755-1315/1167/1/012009