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Ecological dynamics and carbon sequestration in the 150 kV Tentena–Kolonedale transmission corridor

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ABSTRACT

The construction of the 150 kV Tentena–Kolonedale high voltage overhead transmission line (SUTT) requires clearing a right of way (RoW) corridor to ensure the safety and reliability of the power transmission system, an activity that can alter land cover and reduce biomass, carbon stock, and CO_2 sequestration capacity. This study evaluated land cover change in the RoW corridor of the 150 kV Tentena–Kolonedale line and its effect on biomass, carbon stock, CO_2 sequestration, and the economic value of carbon, focusing on the segment between Tower TIP 92 and TIP 99 in Poso and North Morowali Regencies, Central Sulawesi. Land cover change was analyzed using multitemporal Sentinel-2 NDVI imagery for 2019–2024, while biomass, carbon stock, CO_2 sequestration, and carbon economic value were estimated using IPCC (2019) conversion factors. Results show the corridor remained dominated by high-density vegetation throughout the observation period, ranging from 85.52 to 91.04 ha. High-density vegetation decreased only marginally, from 90.89 ha in 2019 to 90.88 ha in 2024 (−0.01 ha, 0.01%), so more than 99% of the corridor retained dense vegetation cover. Biomass ranged from 12,828 to 13,656 tons, carbon stock from 6,029.16 to 6,418.32 tons C, and potential CO_2 sequestration from 22,126.02 to 23,555.23 tons CO_2e, with the estimated economic value of carbon ranging from IDR 3.32 to 3.53 billion, peaking at IDR 3,533,284,500 in 2023. Comparing 2019 and 2024 conditions reveals a loss of 1.50 tons of biomass, 0.76 tons C of carbon stock, 2.79 tons CO_2e of sequestration potential, and about IDR 418,500 (±0.01%) in carbon economic value. These findings indicate that construction and management of the corridor caused only very limited land cover change and carbon loss. The observed vegetation changes were relatively small, indicating limited ecological disturbance during the observation period; because formal statistical significance testing was not performed, these findings are interpreted descriptively rather than inferentially, though dominant high-density vegetation continued to sustain the corridor's function as both a carbon sink and stock. The integration of Sentinel-2 NDVI analysis with biomass and carbon estimation proved effective for evaluating the ecological impact of transmission-line infrastructure, supporting sustainable vegetation management and carbon mitigation strategies.

Keywords: land cover change, right of way, 150 kV transmission line, NDVI, biomass, carbon stock, CO_2 sequestration, carbon economic value.

INTRODUCTION

The 150 kV Tentena–Kolonedale high voltage overhead transmission line (SUTT) plays a strategic role in strengthening the electricity system of Poso and North Morowali Regencies, Central Sulawesi Province. With a network length of approximately 126 circuit-kilometers and 362 towers, the line is expected to improve electricity quality, reduce PT PLN (Persero)'s operating costs, and support the dedieselization program that reduces reliance on diesel power plants and associated carbon emissions. The route passes through production forest, limited production forest, and other land use areas, with span distances ranging from about 142 m to 599 m and a standard tower height of approximately 32 m. Under Ministry of Energy and Mineral Resources Regulation No. 13 of 2021 (ESDM RI No 13 Tahun 2021, 2021) and Indonesian National Standard SNI 04-6918-2002 (SNI, 2002), a minimum horizontal free-space distance of 10 m on each side of the transmission axis must be kept clear of vegetation, which requires clearing a right of way (RoW) corridor along the transmission route.

RoW clearing is essential to prevent flashover, short-circuiting, and other operational disturbances, but it requires felling a substantial number of trees along the corridor, which reduces the carbon sequestration potential of the affected vegetation and, in many cases, can only be offset through compensatory planting elsewhere over a long recovery period. Deforestation, forest fires, and the conversion of forest to plantations, cropland, mining, and settlements remain major sources of carbon emissions; tree cover loss in Indonesia reached approximately 13.56 million ha between 2013 and 2022 (Goldman et al., 2023). Because vegetation absorbs and stores atmospheric CO_2 as biomass, increasing vegetation-based carbon sequestration is an important strategy for climate change mitigation, and Indonesia has formalized this principle through its national carbon economic value framework (Perpres, 2021), making the monitoring of vegetation change along linear infrastructure corridors both ecologically and economically relevant.

Vegetation management along power-line corridors has long been recognized as a major operational challenge. Ahmad et al., (2013) reviewed vegetation-encroachment monitoring techniques for transmission-line rights-of-way and highlighted the need for more systematic remote sensing approaches, while Mahdi et al., (2012) similarly reviewed optical satellite-based methods for detecting vegetation encroachment in power transmission corridors, and Matikainen et al., (2016) provided a broad review of remote sensing methods including synthetic aperture radar, LiDAR, and optical imagery for power-line corridor surveys, concluding that most previous work has focused on network components rather than surrounding vegetation. Li and Lin, (2019) found that clearing transmission corridors in southeastern China degrades forest landscape cover and reduces carbon stocks. More recently, (Tempa et al., 2024) demonstrated that Sentinel-2-based NDVI effectively captures land use/land cover and vegetation change dynamics, Nasir et al., (2025) showed that Sentinel-2 NDVI can reveal carbon patterns across vegetation density gradients in mangrove ecosystems, and Carlos et al., (2025) used regression kriging simulation to map the spatial distribution of aboveground biomass in tropical forests. Wang et al., (2026) further reported that vegetation around power transmission facilities undergoes gradual post-construction recovery. However, these studies either evaluate transmission corridors outside Indonesia, focus on general forest or mangrove biomass without reference to RoW management, or stop at NDVI or biomass estimation without extending the analysis to carbon stock, CO_2 sequestration, and economic valuation. The novelty of the present study lies in integrating Sentinel-2 multitemporal NDVI-based land cover change analysis with biomass, carbon stock, CO_2 sequestration, and carbon economic value estimation specifically for the RoW corridor of the 150 kV Tentena–Kolonedale transmission line an evaluation that remains limited within the Indonesian transmission-infrastructure context. This study aims to (1) analyze land cover change within the RoW corridor of the 150 kV Tentena–Kolonedale transmission line for the period 2019–2024, (2) analyze the resulting change in biomass, carbon stock, CO_2 sequestration, and carbon economic value associated with vegetation loss, and (3) formulate recommendations for sustainable RoW corridor management.

Unlike previous studies that primarily focus on vegetation mapping or biomass estimation independently, this study integrates multitemporal Sentinel-2 NDVI analysis with IPCC Tier-1 carbon accounting to evaluate ecological dynamics within an construction 150 kV transmission corridor. In addition to assessing vegetation cover changes, this research quantifies above-ground biomass, carbon stock, CO_2 sequestration, and carbon economic value simultaneously, thereby providing an integrated ecological assessment framework for power transmission infrastructure in Indonesia. To the authors' knowledge, similar studies focusing on transmission line RoW ecosystems in Indonesia remain very limited, making this study an important contribution to ecological monitoring and sustainable infrastructure management.

MATERIALS AND METHODS

Study area and research period

The study was conducted in the RoW corridor of the 150 kV Tentena–Kolonedale transmission line, covering the segment between Tower TIP 92 and Tower TIP 99 in North Morowali Regencies, Central Sulawesi Province. Land cover conditions were compared across six observation years (2019, 2020, 2021, 2022, 2023, and 2024). Field verification and spatial data analysis were carried out at the Graduate School of Hasanuddin University between October and December 2025.

Data and materials

The software used for spatial analysis included ArcGIS/QGIS, Google Earth, and Microsoft Excel. Primary data consisted of Sentinel-2 MSI Level-2A multispectral satellite imagery with 10 m spatial resolution for the period 2019–2024. Secondary data included the RoW corridor boundary, tower coordinates, forest function status, spatial planning documents (Kesesuaian Kegiatan Pemanfaatan Ruang and Rencana Detail Tata Ruang), environmental management and monitoring records for the 150 kV Tentena–Kolonedale–Bungku transmission line (Witjaksono, 2019), and the biomass and carbon conversion factors from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Calvo Buendia et al., 2019).

Satellite data

Sentinel-2 Level-2A multispectral imagery with a spatial resolution of 10 m was utilized to analyze vegetation dynamics along the 150 kV Tentena–Kolonedale transmission corridor. Image processing, clipping, NDVI calculation, raster classification, and spatial analysis were performed using ArcGIS version 8.0. Multitemporal Sentinel-2 Level-2A Surface Reflectance imagery was obtained from the European Space Agency (ESA) archive through the Google Earth Engine platform using the COPERNICUS/S2_SR_HARMONIZED image collection. The imagery was acquired by the MultiSpectral Instrument (MSI) with a spatial resolution of 10 m. Vegetation analysis was performed using Band 4 (Red) and Band 8 (Near Infrared) to derive the normalized difference vegetation index (NDVI) (Table 1).

Image preprocessing

Image preprocessing included selecting cloud-free Sentinel-2 scenes, clipping imagery according to the official transmission RoW, calculating NDVI values, raster classification, and polygon area calculation. All datasets were projected into the same coordinate system before analysis to ensure spatial consistency across all observation years.

Annual vegetation conditions were represented using Sentinel-2 imagery acquired during the period 1 January–31 December of each observation year (2019–2024). Instead of relying on a single acquisition date, annual median composite images were generated to minimize cloud contamination and temporal variability. A total of 47 Sentinel-2 Level-2A scenes covering two MGRS tiles (51MTT and 51MTU, from both Sentinel-2A and Sentinel-2B platforms) met the selection criteria across the six observation years, with an overall mean cloud cover of 13.25% (range 0.95–19.38%). The number of scenes and cloud cover statistics for each observation year are summarized in Table 2.

Image selection criteria

Sentinel-2 imagery was selected according to the following criteria:

1) covering the study area (MGRS tiles 51MTT and 51MTU);
2) acquired within the observation period from 2019 to 2024;
3) having cloud coverage below 20% (Cloudy Pixel Percentage <20%);
4) cloud masking performed using the QA60 quality assurance band;
5) annual median composite generation to reduce cloud effects and seasonal variation.

Table 1. Sentinel-2 imagery metadata used in this study

Parameter	Description
Satellite	Sentinel-2
Product	Level-2A Surface Reflectance
Collection	Copernicus/S2_SR_Harmonized
Sensor	MultiSpectral Instrument (MSI)
Spatial resolution	10 m
Spectral bands	Band 4 (Red), Band 8 (NIR)
Platform	Google Earth Engine

Table 2. Sentinel-2 acquisition periods, scene counts, and cloud cover statistics used for annual median composites, 2019–2024

Observation year	Acquisition period	Number of scenes	Cloud cover, % (Mean / Range)
2019	1 Jan–31 Dec 2019	13	13.81 (3.34–19.34)
2020	1 Jan–31 Dec 2020	3	16.24 (14.27–18.91)
2021	1 Jan–31 Dec 2021	6	11.46 (2.35–17.30)
2022	1 Jan–31 Dec 2022	3	14.59 (7.81–18.08)
2023	1 Jan–31 Dec 2023	14	11.66 (0.95–19.38)
2024	1 Jan–31 Dec 2024	8	14.82 (4.44–17.76)

Right of way

The corridor boundary used in this study followed the official land acquisition and transmission corridor mapping developed by PT PLN (Persero) in collaboration with the Center of Technology Universitas Hasanuddin. The supporting inventory includes parcel boundaries, transmission tower identification (TIP), vegetation inventory, ownership information, and field observations collected during corridor surveys. These datasets served as reference layers during image interpretation and spatial analysis.

Spatial datasets

The spatial analysis utilized several GIS datasets, including (1) transmission corridor boundaries derived from tower buffer polygons, (2) transmission tower locations, (3) annual NDVI raster layers (2019–2024), (4) reclassified vegetation raster layers, (5) vegetation polygons converted from raster, and (6) overlay datasets generated using Union/Intersect operations. These datasets were used sequentially to estimate vegetation cover, biomass, carbon stock, and carbon sequestration (Table 3).

Table 3. GIS datasets used in this study

Dataset	Format	Purpose
Transmission corridor	Shapefile	Study area clipping
Tower locations	Shapefile	Tower reference
NDVI raster	GeoTIFF	Vegetation analysis
Reclassified raster	GeoTIFF	Vegetation classes
Raster to polygon	Shapefile	Area calculation
Overlay	Shapefile	Vegetation change analysis

Land cover change analysis

Vegetation density was quantified using the NDVI, calculated from the Near Infrared (Band 8) and Red (Band 4) bands of Sentinel-2 imagery (Europeenne, 2015):

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

Higher NDVI values indicate higher photosynthetic activity and denser vegetation canopy cover (Europeenne, 2015). The continuous NDVI surface for each observation year was reclassified in GIS software into three vegetation classes (Table 4), with NDVI threshold values adapted from commonly used tropical vegetation classification standards and further refined through visual interpretation supported by official corridor vegetation inventory. This interpretation was intended to improve consistency between satellite-derived vegetation classes and observed vegetation conditions along the transmission corridor.

Each vegetation class was converted into polygon data, and the area of each class was calculated in hectares for every observation year using the Calculate Geometry function. The same reclassification parameters were applied consistently across all years to ensure that identified changes reflect actual vegetation dynamics rather than differences in processing method. The resulting classification maps were then overlaid to identify areas of stable, increasing, decreasing, or fluctuating vegetation condition (change detection) (Figure 1).

Biomass, carbon stock, CO_2 sequestration, and economic value estimation

Above-ground biomass (AGB) was estimated from the area of the high-vegetation class using a tropical woody-biomass conversion factor of 150 tons ha^{-1}, following the IPCC (2019) approach

Table 4. NDVI-based vegetation classification used in this study

Vegetation class	NDVI range	Land cover characteristics
Low	0.20 – <0.40	Sparse shrub, grass, open land, low vegetation density
Medium	0.40 – <0.60	Secondary vegetation, mixed gardens, medium vegetation density
High	≥ 0.60	Dense vegetation, tree stands, secondary forest, high-biomass woody vegetation

Note: Adjusted through the authors' interpretation based on commonly used NDVI thresholds for tropical vegetation.

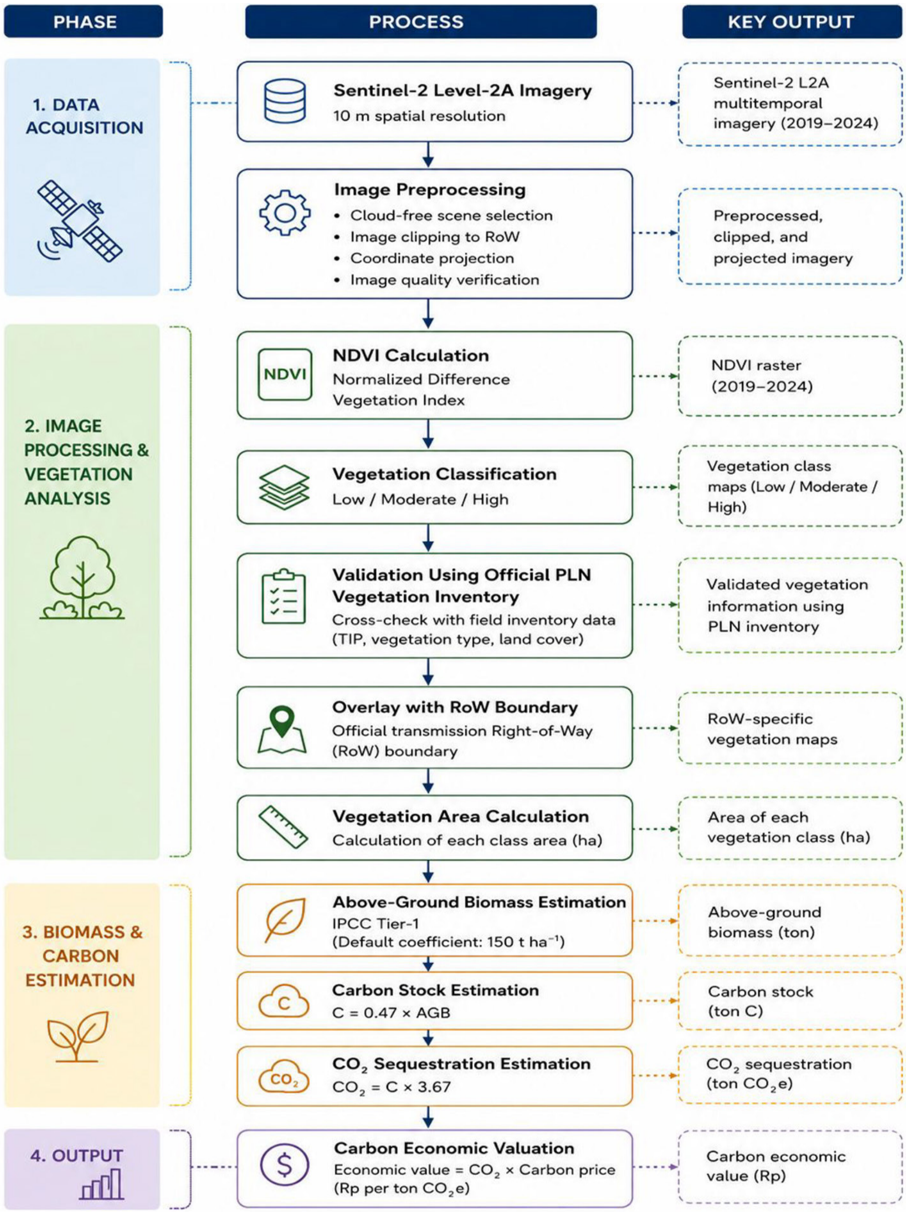

Figure 1. Analytical workflow of the study, from Sentinel-2 image acquisition to carbon economic valuation

(Calvo Buendia et al., 2019), consistent with the Sentinel-2-based biomass estimation approach demonstrated for private forests in Indonesia (Askar et al., 2018). As alternatives, field-based allometric biomass models have also been developed for various Indonesian forest ecosystem types (Krisnawati et al., 2012) and for tropical lowland dipterocarp forest (Ain et al., 2018); a vegetation-area-based conversion factor was adopted in this study because field-measured diameter and height data were not available across the entire corridor:

$$AGB = High\text{-}vegetation\ area \times 150\ ton\ ha^{-1} \quad (2)$$

Biomass estimation

Above-ground biomass was estimated using the IPCC Tier-1 approach, employing a generalized biomass coefficient of 150 t ha^{-1} for areas classified as high-density vegetation. This coefficient represents a regional default value recommended for large-scale ecological assessment when field-based biomass measurements are unavailable. Consequently, biomass estimates in this study should be interpreted as indicative regional estimates suitable for temporal comparison rather than precise stand-level biomass measurements.

Carbon stock was derived from biomass using the IPCC carbon fraction of 0.47 (Calvo Buendia et al., 2019):

$$C = 0.47 \times AGB \quad (3)$$

Potential CO_2 sequestration was estimated by converting carbon stock into CO_2-equivalent mass using the molecular-weight ratio of CO_2 to C (44/12 = 3.67):

$$CO_2\ (ton\ CO_2e) = C \times 3.67 \quad (4)$$

Finally, the economic value of sequestered carbon was estimated by multiplying total CO_2 sequestration by an assumed carbon price of IDR 150,000 per ton CO_2e, adopted by the authors as an indicative reference within Indonesia's national carbon economic value (Nilai Ekonomi Karbon) framework (Perpres, 2021):

$$Carbon\ economic\ value\ (IDR) = \\ = \Sigma C\ (ton\ CO_2e) \times Carbon\ price \quad (5)$$

The resulting biomass, carbon stock, CO_2 sequestration, and carbon economic value estimates for each observation year were compared descriptively, and the 2019 and 2024 conditions were contrasted to quantify the overall effect of land cover change during the study period.

Validation

Although direct biomass field measurements were not available, spatial interpretation was supported using the official PT PLN vegetation inventory prepared during the transmission corridor land acquisition survey. The inventory documents include vegetation types, parcel mapping, ownership information, and tower identification numbers (TIP), providing an independent reference for verifying vegetation distribution interpreted from Sentinel-2 imagery. As an illustration, Table 5 compares two towers marking the boundary of the studied corridor segment (TIP 92 and TIP 99) against the vegetation type recorded in the PLN/CoT field inventory.

Uncertainty analysis

The primary sources of uncertainty include (1) the 10 m spatial resolution of Sentinel-2 imagery, (2) mixed pixels along vegetation boundaries, (3) seasonal vegetation variability, (4) generalized IPCC biomass coefficients, and (5) absence of direct biomass measurements. These uncertainties may affect absolute biomass estimates but are expected to have limited influence on comparative temporal analysis because identical procedures were consistently applied across all observation years.

RESULTS AND DISCUSSION

Land cover change in the RoW corridor, 2019–2024

Change detection analysis shows that most of the RoW corridor falls into the "stable high" category, indicating that high-density vegetation continued to dominate the corridor throughout

Table 5. Comparison between the NDVI-based vegetation class and the PLN/CoT field inventory for two boundary towers of the studied corridor segment

Tower ID (TIP)	Land status (field survey)	Recorded vegetation (PLN/CoT inventory)	NDVI-based vegetation class	Consistency
TIP 92	Protected forest area	Mixed forest stand: Beringin, Bayur, Sentok, Pulai, Binuang, Kenanga, Tepis (15 trees / 400 m²)	High	Consistent
TIP 99	Protected forest area	Mixed forest stand: Bayur, Jongi, Dao, Sentok, Jambu burung, Siuri, Uru tandu, Bebangun (9 trees / 400 m²)	High	Consistent

Note: Both towers lie within the RoW corridor segment used in this study; the field inventory data confirm dense forest cover consistent with the NDVI-derived high-density vegetation classification.

the observation period (Figure 2). Areas experiencing a decrease in vegetation density are relatively limited and concentrated around several tower footings and construction/maintenance access corridors, consistent with clearing, land acquisition, and right-of-way maintenance activities. Conversely, some segments show an increase in vegetation density, indicating secondary regrowth and natural regeneration after disturbance. This pattern agrees with Wang et al., (2026), who reported that vegetation change around power transmission facilities is generally localized to zones directly used for construction and maintenance, while vegetation outside those zones tends to retain its natural condition.

Table 6 compares vegetation class areas between 2019 and 2024. High-vegetation cover decreased only marginally, from 90.89 ha to 90.88 ha (−0.01 ha, or −0.01%), while low vegetation increased by 0.03 ha and medium vegetation remained essentially unchanged. In 2024, high-density vegetation still accounted for 90.88 ha, or about 99.75% of the 91.10 ha total observation area, confirming that the RoW corridor retained the great majority of its dense vegetation cover despite six years of construction and operational activity.

Vegetation change identified between 2023 and 2024 was concentrated around Tower TW.093–TW.098, where medium- and low-vegetation classes emerged, most likely reflecting localized corridor-maintenance activity rather than a permanent land use conversion. This finding is consistent with Tempa et al., (2024), who noted that Sentinel-2 NDVI effectively captures short-term vegetation fluctuations that do not necessarily indicate a permanent change in land cover.

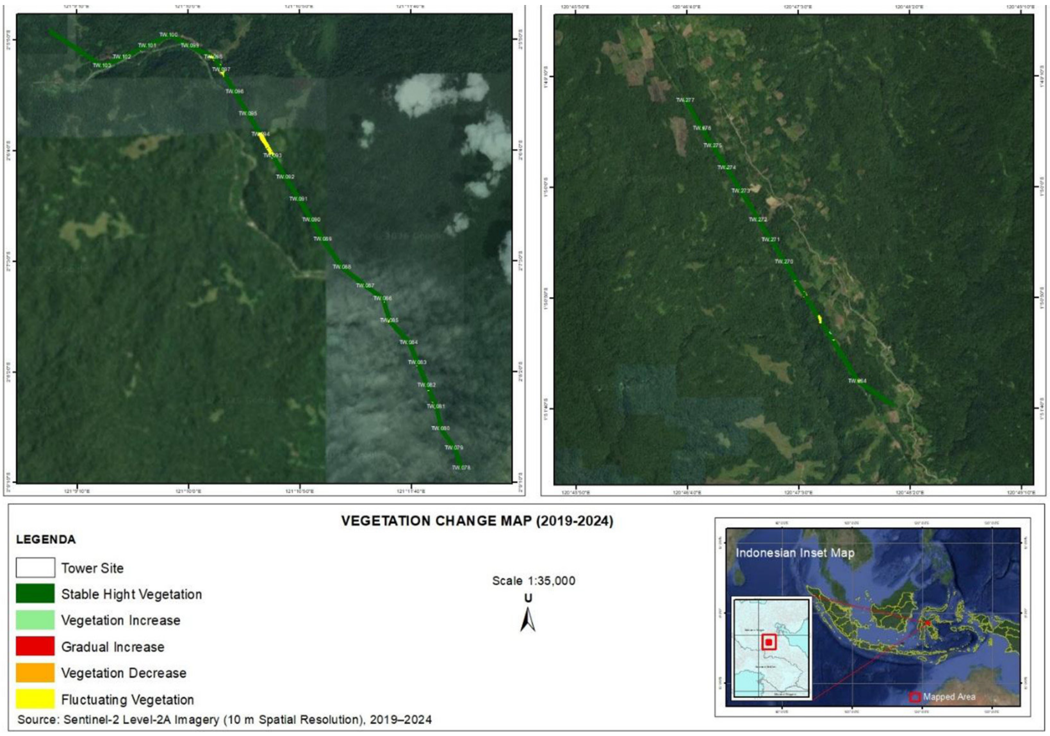

Figure 2. Vegetation change map of the RoW corridor, 2019–2024, derived from multitemporal NDVI classification of Sentinel-2 imagery

Table 6. Land cover change in the RoW corridor of the 150 kV Tentena–Kolonedale transmission line, 2019–2024

Vegetation class	2019 (ha)	2024 (ha)	Change (ha)	Change (%)
Low	0.03	0.06	+0.03	+100.00
Medium	0.16	0.16	0.00	0.00
High	90.89	90.88	−0.01	−0.01
Total	91.08	91.10	+0.02	+0.02

Note: Source authors' analysis of Sentinel-2 NDVI classification, 2019 and 2024.

Biomass, carbon stock, and CO_2 sequestration, 2019–2024

Biomass, carbon stock, and CO_2 sequestration were estimated annually from the high-vegetation area using Equations 2–4; the corresponding economic value of carbon was estimated using Equation 5 (Table 7). Biomass ranged from 12,828 tons (2020) to 13,656 tons (2023), following the same pattern as the high-vegetation area declining when the corridor was actively cleared and recovering once construction activity subsided. The lowest biomass, carbon stock, and CO_2 sequestration values all occurred in 2020, coinciding with the smallest high-vegetation extent (85.52 ha) during the observation period, after which all three parameters recovered progressively through 2023 before showing a slight decline in 2024.

The temporary decline in 2020 (a loss of about 805.5 tons of biomass, 378.6 tons C of carbon stock, and roughly 1.390 tons CO_2e of sequestration potential relative to 2019) reflects reduced high-vegetation cover during that period. The subsequent recovery through 2021–2023 indicates that the corridor's vegetation has meaningful regenerative capacity once clearing and access-road construction activities decrease, consistent with (Wang et al., 2026), who observed that secondary vegetation around transmission facilities can recover biomass and carbon stock within a relatively short period after localized disturbance. A comparable link between vegetation density and carbon storage has also been reported in other vegetated ecosystems, for example across mangrove density gradients using Sentinel-2 NDVI (Nasir et al., 2025).

Although field biomass measurements were unavailable, the use of the IPCC Tier-1 default biomass coefficient provides a standardized approach that is widely adopted for regional ecological assessments. Accordingly, the primary objective of this study was to evaluate temporal changes in vegetation cover and carbon storage consistently across observation years rather than to quantify absolute biomass at the stand level. Therefore, the biomass values reported should be interpreted as indicative regional estimates rather than precise field-derived measurements. Despite this limitation, the standardized methodology enables consistent comparison of vegetation dynamics over time within the transmission corridor. Future studies are recommended to incorporate field biomass inventories, species-specific allometric equations, or LiDAR-based observations to improve biomass estimation accuracy and reduce uncertainty.

Economic value of carbon in the RoW corridor

The economic value of carbon followed the same trajectory as biomass and carbon stock (Table 7), ranging from IDR 3.32 billion in 2020 to IDR 3.53 billion in 2023. Comparing the two endpoints of the study period, the carbon economic value decreased only slightly, from IDR 3,527,466,000 in 2019 to IDR 3,527,047,500 in 2024 a reduction of about IDR 418,500, or roughly 0.01% of the 2019 value. Framed within Indonesia's national carbon economic value (Nilai Ekonomi Karbon) mechanism (Perpres, 2021), this outcome reinforces the conclusion that, despite six years of construction, operation, and maintenance activity, the corridor's carbon-related ecosystem service value has remained essentially stable, because more than 99% of the corridor retained high-density vegetation throughout the period.

Table 7. Biomass, carbon stock, CO_2 sequestration, and economic value of carbon in the RoW corridor, 2019–2024

Year	High vegetation (ha)	Biomass (ton)	Carbon stock (ton C)	CO_2 sequestration (ton CO_2e)	Carbon economic value (IDR)
2019	90.89	13,633.50	6,407.75	23,516.44	3,527,466,000
2020	85.52	12,828.00	6,029.16	22,126.02	3,318,903,000
2021	88.38	13,257.00	6,230.79	22,877.00	3,431,550,000
2022	90.38	13,557.00	6,371.79	23,384.47	3,507,670,500
2023	91.04	13,656.00	6,418.32	23,555.23	3,533,284,500
2024	90.88	13,632.00	6,406.99	23,513.65	3,527,047,500

Note: Source authors' calculation based on Sentinel-2 NDVI-derived high-vegetation area, IPCC (2019) biomass and carbon conversion factors (150 ton ha^{-1} biomass, 0.47 carbon fraction, 3.67 CO_2 conversion factor), and an assumed carbon price of IDR 150,000 per ton CO_2e.

Relationship between land cover change and carbon sequestration

Comparing 2019 and 2024 conditions directly (Table 8) shows a consistent, near-proportional relationship between vegetation area, biomass, carbon stock, and CO_2 sequestration: a 0.01 ha (0.01%) reduction in high-vegetation area corresponded to a 1.50-ton loss in biomass, a 0.76-ton C loss in carbon stock, and a 2.79-ton CO_2e loss in sequestration potential each equivalent to roughly a 0.01% change relative to the 2019 baseline. This close correspondence supports the well-established positive relationship between vegetation density, above-ground biomass, and carbon storage reported for tropical forest biomass mapping (Ain et al., 2018; Carlos et al., 2025).

Because the observed land cover change was concentrated in a few localized segments (mainly around Tower TW.093–TW.098) rather than distributed across the entire corridor, the aggregate loss in biomass and carbon remained very small relative to the corridor's total carbon stock. This localized-disturbance pattern is consistent with Ahmad et al. (2013) and Mahdi et al. (2012), who noted that vegetation encroachment and clearing activity in transmission corridors are typically confined to well-defined maintenance zones rather than distributed across the entire right-of-way.

Implications for RoW corridor management

Although the overall carbon loss identified in this study is small, RoW clearing remains an unavoidable operational requirement, and its cumulative impact across an entire transmission network can still be substantial. Based on the study findings and PT PLN (Persero) UIP Sulawesi's planning practice, four complementary management strategies are recommended (Table 9): (1) planning transmission routes away from forest areas during the pre-tender route-planning stage, which is generally the least costly option on Sulawesi Island this approach has previously avoided about 5 km of Protected Forest, equivalent to protecting around 1,000 trees from felling, and re-routing a limited number of spans away from forest during the pre-construction stage can avoid the loss of roughly 215 kg C per year at a cost of about IDR 10 million; (2) re-routing the transmission line during the land-acquisition or construction stage, which is markedly more costly than pre-tender route planning because towers and land acquisition are already partly committed; (3) using taller and slimmer transmission towers (e.g., type Aa+18 and above) in forested or plantation areas where re-routing is no longer feasible, since taller towers can span over standing trees and avoid felling, whereas shorter towers up to type Aa+15 require full clearing beneath

Table 8. Comparison of biomass, carbon stock, and CO_2 sequestration between 2019 and 2024

Parameter	Unit	2019	2024	Absolute change	Change (%)
High-vegetation area	ha	90.89	90.88	−0.01	−0.01
Above-ground biomass (AGB)	ton	13,633.50	13,632.00	−1.50	−0.01
Carbon stock	ton C	6,407.75	6,406.99	−0.76	−0.01
CO_2 sequestration potential	ton CO_2e	23,516.44	23,513.65	−2.79	−0.01

Note: Source authors' analysis of Sentinel-2 NDVI classification and IPCC (2019) conversion factors, 2019 and 2024.

Table 9. Overview of RoW corridor management strategies for minimizing vegetation and carbon loss

Strategy	Implementation stage	Relative cost	Carbon-related benefit
Route planning away from forest	Pre-tender / route planning	Lowest	Avoids felling entirely on re-routed spans (e.g., ~215 kg C/year avoided for ~IDR 10 million on a 20–30-span re-route)
Re-routing during land acquisition/construction	Land acquisition / construction	About 300× higher than pre-tender re-routing	Same carbon benefit as pre-tender re-routing, at substantially higher cost
Taller, slimmer towers (e.g., Aa+18 and above)	Construction (forest/ plantation segments)	Moderate, increases with tower height	Avoids felling beneath the span; towers below Aa+18 require full clearing
Replacement planting	Post-construction / operation	Highest per unit of carbon offset	Compensates felled vegetation over 10–15 years of growth and monitoring

Note: Source compiled by the authors from PT PLN (Persero) UIP Sulawesi route-planning and cost data.

the line an approach consistent with recent technical-economic analysis of compact lattice tower design for 500 kV SUTET in Indonesia, which found that redesigning tower configuration can reduce the corridor footprint while remaining economically viable (Fauzi and Ahsin, 2026); and (4) replacement planting of vegetation in affected locations in coordination with local forestry and environmental agencies, recognizing that this option requires 10–15 years of monitoring and is generally the most expensive strategy per unit of carbon compensated.

Taken together, these strategies indicate that avoiding forest areas during route planning offers by far the most cost-effective protection of carbon stock, while re-routing, taller towers, and replacement planting provide progressively costlier fallback options for segments where forest avoidance is no longer feasible once construction has begun.

Limitations

This study has several limitations. First, above-ground biomass was estimated using the IPCC Tier-1 default coefficient instead of field-derived allometric equations. Second, below-ground biomass was not included. Third, seasonal variability and mixed pixels inherent in medium-resolution satellite imagery may introduce uncertainty in vegetation classification. Therefore, biomass and carbon estimates should be interpreted as regional-scale ecological indicators.

CONCLUSIONS

Land cover in the RoW corridor of the 150 kV Tentena–Kolonedale transmission line remained dominated by high-density vegetation throughout 2019–2024, with an area ranging from 85.52 to 91.04 ha, or more than 99% of the total observation area. The overall change between 2019 and 2024 was very small (a 0.01 ha, or 0.01%, reduction in high-vegetation area) and was concentrated in a few localized segments around tower footings and construction/maintenance access roads rather than distributed across the corridor, indicating a localized rather than landscape-scale disturbance pattern.

Biomass, carbon stock, and CO_2 sequestration followed the same pattern, ranging from 12,828 to 13,656 tons, 6,029.16 to 6,418.32 tons C, and 22,126.02 to 23,555.23 tons CO_2e, respectively, with the corresponding economic value of carbon estimated at IDR 3.32–3.53 billion. Comparison between 2019 and 2024 shows a loss of only 1.50 tons of biomass, 0.76 tons C of carbon stock, 2.79 tons CO_2e of sequestration potential, and about IDR 418,500 (≈0.01%) in carbon economic value, confirming that the near-proportional relationship between vegetation area, biomass, and carbon translates into only a minor net carbon loss at the corridor scale.

Overall, construction and operation of the 150 kV Tentena–Kolonedale RoW corridor resulted in only relatively small vegetation changes, indicating limited ecological disturbance rather than significant degradation; because formal statistical testing was not conducted, this finding is interpreted descriptively rather than inferentially. The corridor continues to function as an effective carbon sink and carbon stock. Four complementary management strategies are recommended to sustain this function: planning transmission routes away from forest areas at the pre-tender stage, re-routing during land acquisition or construction when necessary, using taller and slimmer towers in forested segments, and replacement planting in affected locations, with route planning at the earliest possible stage offering the most cost-effective protection of corridor carbon stock. This study estimated only above-ground biomass and carbon stock. Future research should extend the analysis to below-ground biomass and soil organic carbon dynamics, drawing on modeling frameworks developed for other ecosystem types, to provide a more complete carbon budget for transmission-line RoW corridors.

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