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RESEARCH ARTICLE

Land Cover Changes and Distribution of Carbon Stocks in the Tembawang Agroforestry Area, Bengkayang Regency, West Kalimantan, Indonesia

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ABSTRACT

Tembawang agroforestry represents a traditional forest management system practiced by Dayak communities in Kalimantan and is recognized for its ecological and livelihood functions. This study examines land cover changes and carbon stock distribution in Tembawang agroforestry in Cipta Karya Village, West Kalimantan. The research applied a combination of field surveys and remote sensing using Sentinel satellite imagery from 2019 and 2023. Vegetation data were collected through observation plots to assess species composition, density, and biomass for carbon estimation using allometric equations. A total of 17 tree species were identified across Tembawang and rubber forest areas. Four species showed the highest density values: *Durio zibethinus*, *Hevea brasiliensis*, *Elateriospermum tapos*, and *Ochanostachys sumatrana*, with densities ranging from 25 to 268.75 ind ha^{-1} and an overall mean of 260.42 $\pm$ 110.00 ind ha^{-1}. Estimated aboveground carbon stocks varied widely between 5.13 and 632.11 Mg C ha^{-1}, with an average of 269.71 $\pm$ 181.79 Mg C ha^{-1}. Land cover analysis indicated no significant change in secondary dryland forest over the past five years. However, mixed dryland agricultural areas, including parts of Tembawang, gardens, and cultivated fields, decreased by approximately 100 ha. The spatial distribution of carbon stocks across secondary dryland forest and mixed agricultural land ranged from 0 to 453.96 Mg C ha^{-1}, reflecting substantial variability in carbon storage across the landscape. These findings highlight the role of Tembawang agroforestry in maintaining carbon stocks while undergoing moderate land use changes.

Keywords: Aboveground carbon stock, Allometric, Cipta Karya village, Mixed dry agricultural land, Sentinel imagery

Introduction

Global schemes aimed at reducing carbon emissions through the REDD (Reducing Emissions from Deforestation and Forest Degradation) program have entered their second decade since being established at the United Nations Climate Change Conference (COP 11) in 2005.[1] The REDD program, which has evolved into REDD+, focuses on preventing deforestation and forest degradation, promoting forest conservation, enhancing carbon stocks, and providing financial incentives for developing countries.[2] In recent years, Indonesia, as a developing country, has also implemented a carbon trading scheme in the form of emission allowances and carbon offsets, with international transactions officially commencing on the Indonesian Carbon Exchange (IDXCarbon) in January 2025.

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Carbon stocks within a landscape can be assessed using a spatial approach supported by remote sensing data, including multispectral satellite imagery, radar, and drone-based technologies. Estimates of landscape carbon storage are commonly derived by integrating direct field measurements with spectral information extracted from remotely sensed images, as demonstrated in studies by Csillik et al.[3] and Bordoloi et al.[4] in tropical rainforest ecosystems and across various land-use types in Northeast India. Furthermore, changes in carbon stock dynamics can be quantified through land cover change analysis, particularly in estimating carbon losses resulting from deforestation and forest degradation. Previous studies by Malik et al.[5] and Li et al.[6] have shown that such approaches can quantify carbon losses from past periods and project potential future losses over the coming decades in the absence of significant land-use change mitigation.

Changes in land cover, particularly forest ecosystems, have reached approximately 561 million km^2 globally, including areas affected by forest degradation and deforestation.[7] Land conversion from forested areas to other land-use types results in increased carbon dioxide emissions and has significant environmental, social, and socio-economic impacts.[8] Efforts to reduce deforestation rates in Indonesia have been continuously implemented by the government through the Ministry of Environment and Forestry; however, Indonesia remains among the ten countries with the highest primary forest deforestation rates during 2022–2023.[9] Various strategies have been adopted to address deforestation in Indonesia, including the implementation of the FOLU Net Sink 2030 program, community involvement through social forestry schemes, and sustainable landscape management approaches. In addition, community-managed agroforestry systems have the potential to reduce deforestation pressure while enhancing carbon sequestration capacity within the landscape.[10,11]

Agroforestry is defined as a land-use system that integrates agricultural practices and forest components within the same landscape; rather than merely utilizing trees for agricultural purposes.[12] Agroforestry systems provide a wide range of products, including timber, fruits, rubber, latex, and other non-timber forest products, which can enhance food security and improve local livelihoods and community economies.[13] In addition, the agroforestry concept plays a significant role in carbon sequestration by increasing tree cover on agricultural land; approximately 1.83 Pg of carbon can be sequestered in above- and below-ground biomass through a 1% increase in tree cover across global agricultural landscapes.[14]

Tembawang agroforestry has been practiced for generations by the Dayak communities in Indonesia, particularly in Kalimantan. Local communities utilize both timber and non-timber forest products, such as fruits, rubber, and various plant-based resources used for medicinal purposes and daily household needs.[15] Tembawang agroforestry also plays an important role in the carbon cycle; according to Rafdinal et al.,[16] Tembawang systems contribute annual litterfall ranging from 10.95 to 11.40 tons ha^{-1} yr^{-1}, with an estimated litter decomposition rate of 0.75–0.81 g day^{-1}. Further research by Rafdinal et al.[17] indicates that Tembawang agroforestry systems can store up to 90.26 t C ha^{-1} in aboveground biomass, with more than 60% of total carbon storage contributed by tree species with diameters exceeding 50 cm.

In line with Indonesia's commitment to REDD+, carbon trading mechanisms, and the FOLU Net Sink 2030 policy, community-managed agroforestry systems are increasingly recognized for their dual role in sustaining carbon stocks and supporting rural livelihoods. Despite this growing policy relevance, empirical evidence on land cover dynamics and spatial patterns of carbon stocks in traditional agroforestry systems remains limited, particularly in locally managed landscapes such as Tembawang. Tembawang agroforestry, practiced by Dayak communities in Kalimantan, represents a unique land-use system that integrates ecological sustainability, food security, and economic resilience through long-term customary management. However, comprehensive assessments that combine vegetation structure, aboveground carbon stock estimation, and spatial analysis of land cover change in Tembawang landscapes are still scarce. Therefore, this study aims to (i) analyze vegetation characteristics in Tembawang agroforestry, (ii) estimate aboveground carbon stocks, and (iii) assess land cover changes and the spatial distribution of carbon stocks in Cipta Karya Village, Bengkayang Regency, West Kalimantan. The findings are expected to provide scientific evidence to support REDD+ implementation and inform evidence-based land-use planning in community-managed agroforestry landscapes.

Materials and methods

Study area

This research was conducted in the Tembawang forest area of Cipta Karya Village, which is administratively located within Bengkayang Regency, West Kalimantan Province, Indonesia Fig. 1. The study area corresponds to the Cipta Karya Village Traditional Forest, characterized by a tropical montane forest

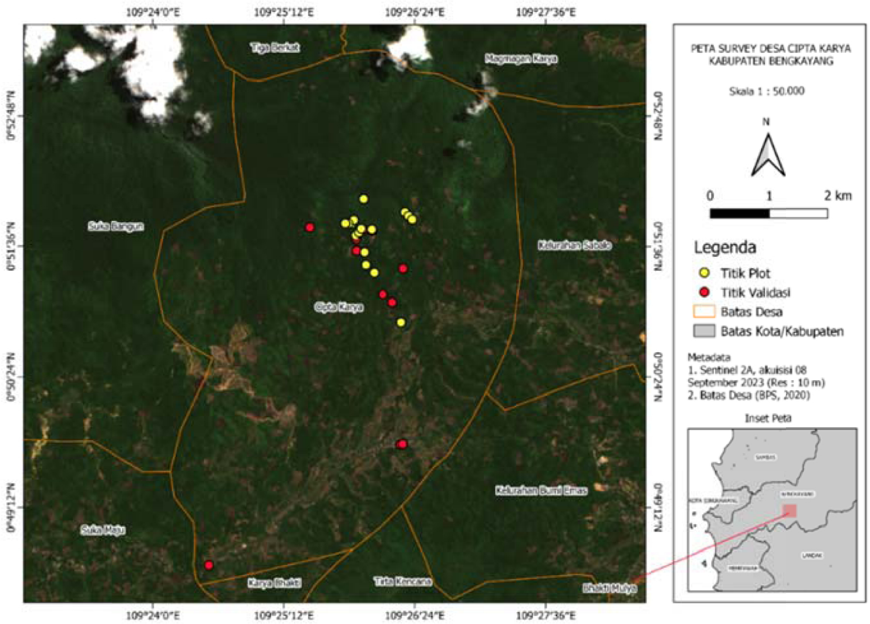

Fig. 1. Map of research location, Bengkayang Regency, Indonesia.

ecosystem. The Cipta Karya Village Traditional Forest is situated at an elevation ranging from 200 to 350 m above sea level. The region experiences a humid tropical climate with an annual mean rainfall ranging from approximately 3,000 to 3,500 mm and a mean annual air temperature of 26–27 °C. The dry season typically occurs between June and August, although rainfall is still present throughout the year. This ecosystem is surrounded by local plantation and agricultural lands, predominantly dominated by rubber (*Hevea brasiliensis*) vegetation. The forest floor at the study site is generally composed of podzolic soils interspersed with rocky substrates. The terrain is characterized by slopes ranging from 30° to 50°. The total area of Cipta Karya Village is approximately 43.09 km^2.[18]

Site selection was conducted using a purposive sampling approach, based on the presence and distribution of Tembawang forest systems. A total of 16 sampling plots and 26 land-cover validation points were established to verify the occurrence and spatial extent of Tembawang forests, and these were grouped into four sampling stations: Tembawang Kalung Bawah, Tembawang Sigurang, Tembawang Bekui, and rubber-based agroforestry. The study was conducted over a period of approximately one year to generate baseline data for assessing the ecological status and existing conditions of the ecosystem within the Tembawang forest area of Bengkayang Regency, West Kalimantan.

Procedures

Vegetation sampling was conducted using a systematic sampling design. Ten parallel line transects, each spaced 100 m apart, were established across the forest area. A randomly selected 20 m × 20 m sample plot (main plot) was used for tree and shrub assessments.[19] All plant species recorded within each plot were identified to the species level using standard botanical identification references, including *Flora Malesiana*,[20] and online taxonomic databases such as Plants of the World Online (POWO).[21] Within each plot, the diameter at breast height (DBH) and total height (H) of all individuals with DBH ≥ 2 cm were measured. DBH was measured using a diameter tape, while tree height up to 5 m was measured using a graduated pole, and trees exceeding 5 m were measured using a clinometer.[19]

Land cover data were derived from an integration of field observations and multi-temporal Sentinel-2 imagery acquired in 2019 and 2023. Image preprocessing included radiometric, geometric, and atmospheric corrections to ensure data quality.[22] Land cover mapping was conducted using false-color RGB composites, and a guided classification was carried out to separate the vegetation from other land covers.[23] Map validation and accuracy assessment were conducted using the 2021 acquisition, supported by field surveys and ground-truthing activities. Field data included georeferenced points of Tembawang vegetation presence, information on vegetation structure and species composition, canopy cover, and carbon stock estimates. Finally, spatial analysis was applied to quantify area changes, enabling the estimation of losses and gains in the Tembawang forest area across the study periods.

Accuracy assessment metrics were not recalculated for the baseline land cover map used in this study. The 2019 land cover map was obtained from the official Ministry of Environment and Forestry (MoEF) of Indonesia, which serves as a nationally standardized geospatial database. This official dataset has been produced through rigorous technical procedures and is required to meet a minimum overall accuracy standard of ≥70%, as mandated by national land cover mapping guidelines. In this study, the MoEF land cover map was used as a reference database to ensure consistency and comparability in temporal land cover analysis. Field validation points mentioned in the methodology were not intended to reassess the accuracy of the MoEF map, but were instead used to support the development of the existing land cover map (2023) derived from Sentinel-2 imagery. The field data were applied for on-screen digitization, visual interpretation, and class verification of the current land cover, as well as for comparison with the MoEF land cover classification scheme. This approach follows common practices in studies that integrate official land cover datasets with recent satellite imagery for change detection analysis.

Land cover change analysis utilized the official Ministry of Environment and Forestry (MoEF) land cover map for 2019 as a standardized baseline and Sentinel-2 imagery for 2023 classification. While using different data sources may introduce potential bias, consistent land cover classification schemes and field validation were applied to minimize discrepancies. This approach allows for a reliable assessment of general land cover trends while acknowledging potential uncertainty associated with multi-source data comparison.

Estimation of aboveground biomass and carbon stocks was conducted using non-destructive sampling methods, based on field observation plots and allometric equations developed by Ketterings et al.[24] or other available species-specific allometric models. Spatial modeling of carbon stocks was performed using simple linear regression, which related vegetation index values derived from satellite imagery to carbon stock estimates obtained from the field observation plots.

Data analysis

Tree density was calculated using the equation proposed by Mueller-Dombois and Ellenberg,[25] as presented below:

$$Density = \frac{number\ of\ individuals\ of\ a\ species}{sample\ plot\ area\ (ha)}$$

Basal area is calculated based on the Mueller-Dombois & Ellenberg[25] equation as follows:

$$Basal\ area = \frac{\pi\ x\ D^2}{4}$$

Carbon stocks are estimated allometrically from aboveground biomass (AGB) based on the following equation:[24]

$$AGB = 0.11\ \rho\ D^{2.62}$$

Where:
ρ = wood density
D = diameter at breast height

Species-specific allometric equations were applied when available, while generalized equations proposed by Ketterings et al.[24] were used for species without specific models. Wood density (ρ) values for dominant species were obtained from the Global Wood Density Database, including *Durio zibethinus* ($\rho = 0.55$ g cm^{-3}), *Hevea brasiliensis* ($\rho = 0.49$ g cm^{-3}), *Elateriospermum tapos* ($\rho = 0.65$ g cm^{-3}), and *Octomeles sumatrana* ($\rho = 0.32$ g cm^{-3}). Carbon stock values were calculated assuming that the carbon content is 50 % of total aboveground biomass.[26]

The data analysis in this study was primarily descriptive and exploratory. Basic descriptive statistics, including mean, range, and standard deviation, were calculated for tree density, basal area, aboveground biomass, and carbon stock across the four sampling stations. No inferential statistical tests (e.g., correlation analysis or analysis of variance) were applied, as the objective of the study was to characterize vegetation structure and carbon stock distribution rather than to test statistical differences or causal relationships among variables or stations. Comparisons among stations were therefore interpreted based on observed patterns and magnitude differences.

Results and discussion

Characteristics of tree stands in Tembawang Agroforestry

Survey results indicated that a total of 17 tree species were recorded in the Tembawang and rubber agroforestry forest areas at the study site. Species composition, stand density, and basal area were classified according to the locally recognized Tembawang forest types, based on data from 16 observation plots

Table 1. Characteristics of tree stands at the research station.

Variabel	Station (Tembawang/Agroforestry)			
	Kalung Bawah	Sigurang	Bekui	Rubber
Number of species	6	8	6	5
Density (ind ha^{-1})	400	200	291.67	150
Dominant species density (ind ha^{-1})				
D. zibethinus Murr	106.25	93.75	133.33	37.5
H. brasiliensis Muell. Arg	268.75	0	100	150
E. tapos Blume	0	25	50	0
O. sumatrana Miq	0	112.5	0	0
Basal Area (m^2 ha^{-1})	75.15	66.84	63.08	27.12

Table 1. Across the four Tembawang forest groups, the number of species ranged from 5 to 8, with individual tree densities ranging from 200 to 219.67 ind ha^{-1}. Four species consistently exhibited the highest density values across all sites, namely durian (*Durio zibethinus* Murr.), rubber (*Hevea brasiliensis* Muell. Arg.), kelempai (*Elateriospermum tapos* Blume), and benuang (*Octomeles sumatrana* Miq.), with densities ranging from 25 to 268.75 ind ha^{-1}. The basal area across the Tembawang forest types ranged from 27.12 to 75.15 m^2 ha^{-1}.

Tembawang agroforestry represents a traditional forest management system practiced by the Dayak people, primarily characterized by fruit tree species, such as durian (*Durio zibethinus* Murr.), langsat (*Lansium domesticum* Corr.), cempedak (*Artocarpus integra* Merr.), and others. In addition to fruit-producing species, Tembawang systems also include tree species utilized for non-fruit purposes, such as rubber (*Hevea brasiliensis* Muell. Arg.) and benuang (*Octomeles sumatrana* Miq.). The species composition of Tembawang agroforestry at the study site is relatively similar to that reported in other regions, comprising tree species used for fruit production, non-fruit products, and timber, as documented in Tembawang forests of Sintang Regency [27] and the Tembawang Nanga Pemubuh Forest in Sekadau Regency. [17]

Species found in this study were smaller than in research by Vernie et al. [28] in the Tembawang Agroforestry, Landak Regency and Rafdinal & Pitopang [29] in the Tembawang Agroforestry, Sekadau Regency, the number of tree species found was 21 species and 43 species. The number of tree species recorded in this study (17 species) was lower than those reported in other Tembawang studies conducted in nearby regions. However, this difference reflects local land-use preferences rather than ecosystem degradation. The Tembawang agroforestry system in Cipta Karya Village is strongly dominated by economically valuable species, particularly *Durio zibethinus* and *Hevea brasiliensis*, which are intentionally maintained by the community. Species richness in Tembawang systems is therefore highly context-dependent and influenced by cultural practices, livelihood strategies, and market-oriented production rather than solely ecological factors.

The basal area recorded across the four sampling stations ranged from 27.12 to 75.15 m^2 ha^{-1}. The basal area values observed at the study site were relatively lower than those reported for other Tembawang agroforestry systems in Sekadau Regency, which ranged from 8.16 to 323.55 m^2 ha^{-1}. [29] Basal area is a key structural parameter that reflects tree density and the degree of competition within forest stands and serves as an important indicator for forest management planning. [30,31] In tropical forests, basal area values generally range between 16 and 42 m^2 ha^{-1}; [32,33] however, the basal area at the present study site exceeded this range, likely due to the dominance of two planted species, durian (*Durio zibethinus*) and rubber (*Hevea brasiliensis*), established by local communities. Despite this, higher basal area values may positively contribute to aboveground carbon storage within forest ecosystems. [34]

The highest individual tree density across all observation plots was recorded in the smallest diameter class (20–40 cm), with an average density of 120 ind ha^{-1}, while the lowest density occurred in the largest diameter class (>80 cm), with an average density of 20 ind ha^{-1} Fig. 2. In contrast, the highest basal area was observed in the 60–80 cm diameter class, with an average value of 28.24 m^2 ha^{-1}, whereas the lowest basal area was recorded in the 40–60 cm diameter class, averaging 7.91 m^2 ha^{-1}.

The stand structure at the study site exhibited a diameter distribution pattern resembling an inverted J-shaped curve. Based on the findings of Pamoengkas et al. [35] in logged-over dipterocarp forests, a stand structure characterized by this distribution pattern indicates healthy regeneration dynamics and supports the long-term sustainability of forest structure. Such inverted J-shaped distributions are commonly observed in natural forests and play a crucial role in forest regeneration and recruitment processes. [36]

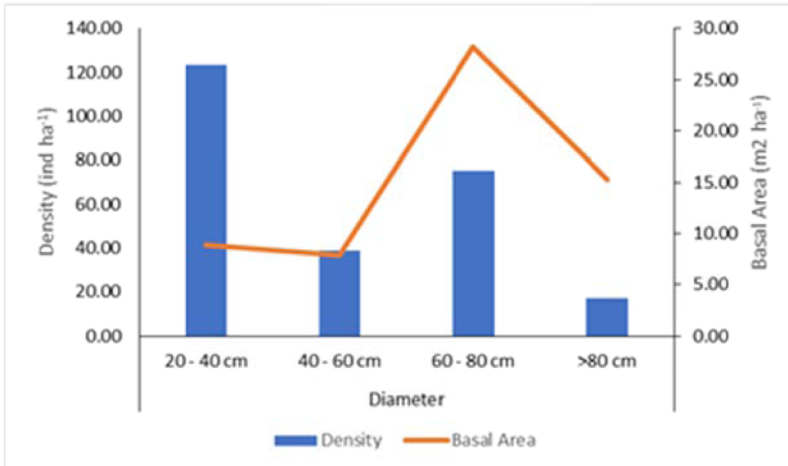

Fig. 2. Relationship of diameter class (20–40, 40–60, 60–80, 80 and above) with density and basal area of all locations.

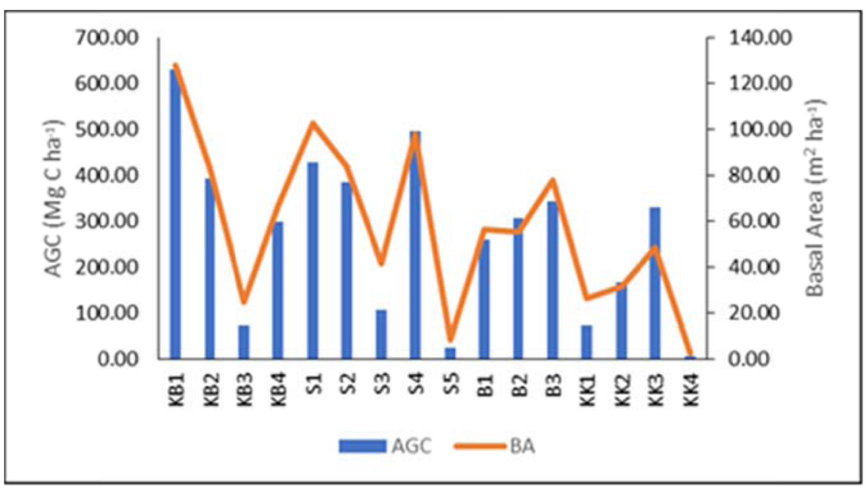

Fig. 3. AGC values at each station/plot, a) Kalung Bawah (KB), b) Sigurang (S), Bekui (B) and Rubber Plantation (KK).

Carbon stocks in Tembawang Agroforestry

Estimates of aboveground carbon stock (AGC) at the study site, derived from available allometric equations, ranged from 5.13 to 632.11 Mg C ha^{-1}. The highest AGC value was recorded in Tembawang Kalung Bawah (KB), while the lowest was observed in the rubber plantation (KK) Fig. 3. Vegetation carbon stock values are strongly influenced by tree density, diameter, and basal area, as reported by previous studies.[24] The mean carbon stock at the study site was 269.71 ± 181.79 Mg C ha^{-1}, which is considerably higher than values reported for other Tembawang agroforestry systems, such as Tembawang Alak in Sintang Regency (59.83–144.07 Mg C ha^{-1})[27] and Tembawang Nanga Pemubuh in Sekadau Regency (42.01–90.26 Mg C ha^{-1}).[17]

Uncertainty in carbon stock estimation arises from several sources, including the use of generalized allometric equations, variability in wood density values, and the assumption that carbon content constitutes 50% of biomass. These uncertainties may result in over- or underestimation of carbon stocks. However, the applied methods follow widely accepted FAO and IPCC[26] and are appropriate for landscape-scale assessments in data-limited tropical agroforestry systems.

Improved agricultural practices, such as agroforestry, have been widely reported at the global scale to store higher amounts of aboveground biomass carbon and soil organic carbon than conventional agricultural systems. Long-term global assessments (6–20 years) indicate that agroforestry systems can accumulate carbon stocks approximately 28–68% higher than those of traditional agriculture.[37,38] However, carbon storage capacity varies substantially depending on regional ecological conditions, management history, and species composition.

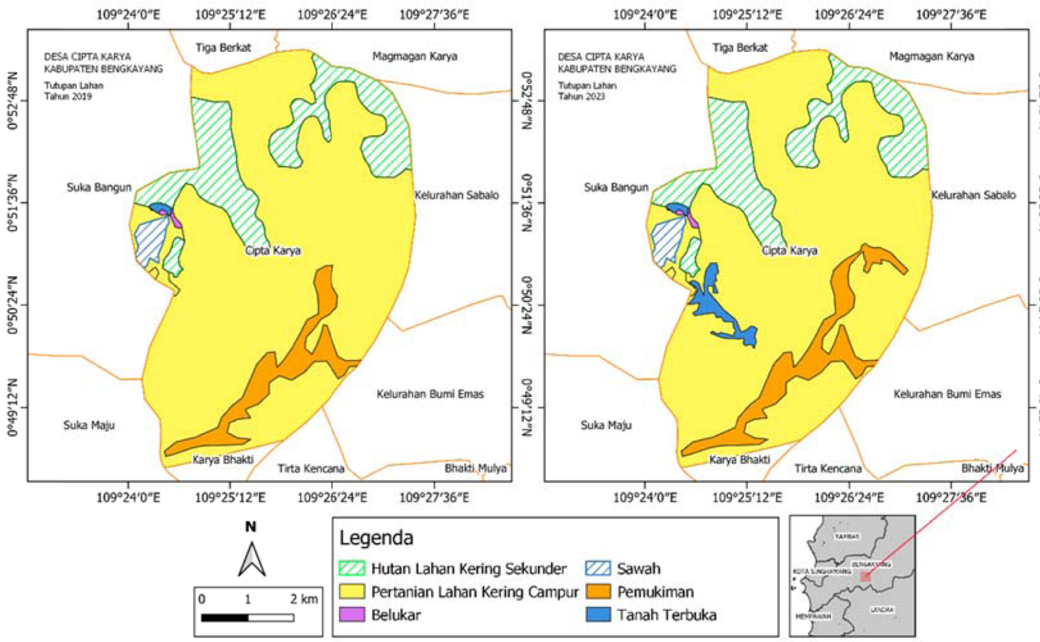

Fig. 4. Land cover map in 2019 (left) and 2023 (right) of Tembawang Agroforestry area.

In the local and regional context, the results of the present study demonstrate that Tembawang agroforestry not only exceeds the carbon stock levels typically reported for conventional agricultural systems but, at several observation stations, also approaches or surpasses those of secondary forests. Comparable local studies conducted in Indonesia reported aboveground carbon stock values ranging from 58.51 to 90.79 Mg C ha^{-1} in Tembawang and secondary forest systems,[27] while secondary forest carbon stocks of approximately 88.5 Mg C ha^{-1} have been documented in similar tropical environments.[39] These findings indicate that, under sustained community-based management, Tembawang agroforestry can function as a carbon-dense land-use system comparable to secondary forests, highlighting its significance for locally grounded climate mitigation strategies.

Land cover changes and carbon stock in Tembawang Agroforestry

Spatial analysis of land cover in Cipta Karya Village was conducted by comparing datasets from 2019, derived from the Indonesian Ministry of Environment and Forestry Land Cover Map, and 2023, based on recently digitized land-cover data. The analysis revealed an increase in residential areas and open land over the study period Fig. 4. In recent years, the expansion of road infrastructure and residential development has become increasingly evident, as indicated by satellite imagery interpretation and field-based validation results.

No significant change was detected in the area of secondary dryland forest over the past five years; however, mixed dryland agriculture—comprising portions of Tembawang agroforestry, gardens, and cultivated fields—experienced a reduction of approximately 100 ha Table 2. This decline corresponds to a decrease from 3,068.86 ha (75.86%) in 2019 to 2,969.74 ha (73.41%) in 2023, indicating a gradual contraction of mixed agroforestry-dominated landscapes. The reduction is primarily associated with continuous land-use pressure, including land-clearing activities and the conversion of agroforestry areas into settlements and open land, as evidenced by the concurrent increase in settlement areas and a substantial expansion of open land during the same period. Mixed dryland agriculture constitutes the dominant land-cover type in Cipta Karya Village, accounting for approximately 75% of the total area, followed by secondary dryland forest, which represents around 16% of land cover.

The absence of a formal accuracy reassessment for the MoEF land cover map represents a methodological choice rather than a limitation of data quality. The use of nationally standardized land cover products is widely accepted in land cover change studies, particularly when the objective is to ensure temporal consistency and policy relevance. By using the MoEF land cover map as a baseline and applying field-validated interpretation for the current land cover, this study prioritizes comparability and alignment with national forest monitoring frameworks.

Table 2. Area and proportion of land cover at the location in 2019 and 2023.

	Distribution/Year			
	2019		2023	
Land Cover	Area (ha)	%	Area (ha)	%
Secondary dry land forest	659.32	16.30	659.32	16.30
Mixed dry agricultural land	3,068.86	75.86	2,969.74	73.41
Shrub	5.71	0.14	5.71	0.14
Paddy field	52.14	1.29	52.14	1.29
Settlement	251.74	6.22	287.10	7.10
Open land	7.52	0.19	71.28	1.76

Deforestation and land degradation significantly affect the ecosystem's carbon stock potential. Based on the findings of Ferraz et al.,[40] intact forests in Kalimantan, Indonesia, have an estimated carbon stock of 185.52 Mg C ha^{-1}, calculated using a carbon fraction of 0.48. Carbon stocks in degraded forests were reported to decline by approximately 20–64%, ranging from lightly degraded to severely degraded forest conditions, relative to intact forests. In the present study, assuming an average aboveground carbon stock value of 269.71 Mg C ha^{-1} within mixed dryland agroforestry systems, the conversion of approximately 100 ha over the past five years is estimated to have resulted in a potential carbon release of about 2,697.1 Mg C. This estimate highlights the cumulative impact of gradual land-use change and underscores the importance of maintaining mixed agroforestry systems such as Tembawang to sustain landscape-level carbon storage.

Results of the linear regression analysis between the vegetation index (NDVI) derived from satellite imagery and field-based carbon stock estimates revealed a positive relationship, with a coefficient of determination (R^2) of 0.38. The relationship between the two variables was expressed by the equation $y = 3058.1x - 2489.7$. This equation was applied to visualize the spatial distribution of carbon stocks across secondary dryland forest and mixed dryland agricultural land-cover types in Cipta Karya Village Fig. 5. The regression model was developed exclusively for these two land-cover types due to limited data availability for shrubland and rice field categories, which require different analytical approaches.

The linear regression between NDVI values and field-based aboveground carbon stock estimates yielded a coefficient of determination (R^2) of 0.38, indicating a moderate relationship. Although higher R^2 values are generally desirable, several studies have shown that NDVI–biomass relationships in structurally complex vegetation often yield moderate correlations due to variability in species composition, canopy structure, and environmental conditions. In high-density vegetation, the NDVI signal frequently

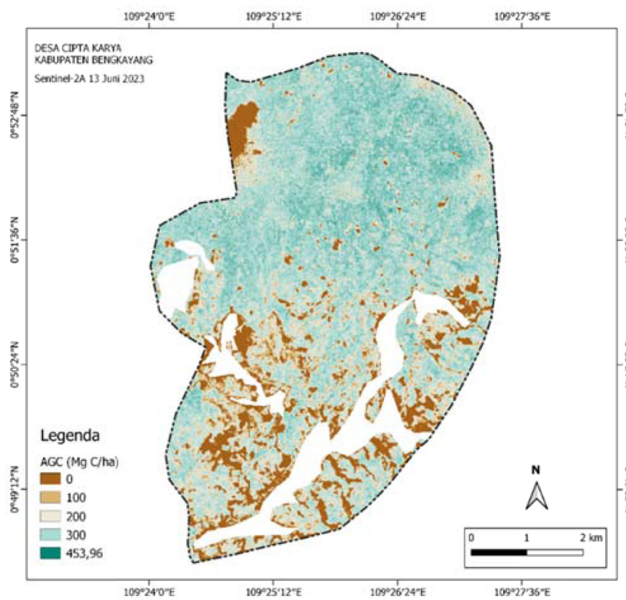

Fig. 5. AGC distribution map in secondary dry land forests and mixed dry land agriculture.

saturates, limiting its ability to differentiate between high biomass levels and producing only moderate explanatory power in regression models.[41] In this study, the regression model was intended as a spatial extrapolation tool to visualize general patterns of carbon stock distribution rather than as a high-precision predictive model. Therefore, the resulting carbon distribution map should be interpreted as representing relative spatial variation across the landscape. The limitations of NDVI-based modeling, including saturation effects in dense canopy areas and sensitivity to canopy structural variation, are acknowledged and discussed.

The spatial distribution of aboveground carbon stocks across secondary dryland forest and mixed dryland agricultural land-cover types in Cipta Karya Village ranged from 0 to 453.96 Mg C ha^{-1}. Carbon stock values of zero at several locations were attributed to the presence of open land and areas obscured by cloud cover, particularly in the northern part of the village. Overall, the dominant carbon stock values observed at the site were approximately 300 Mg C ha^{-1}. Several comparable studies related to carbon stock spatial mapping in forest and agroforestry systems include Gesta et al.,[42] who reported carbon stock values ranging from 0 to 18 Mg C ha^{-1} on plantation land in Butuan City, Philippines, with a coefficient of determination (R^2) of 0.68. Similarly, Solomon et al.[43] documented carbon stock values ranging from 93.47 to 187.13 Mg C ha^{-1} in dryland forests of Northern Ethiopia. The role of Tembawang agroforestry in maintaining carbon stocks is consistent with previous findings that emphasize the importance of forest biomass and reforestation strategies in stabilizing carbon emissions and enhancing ecosystem resilience.[44]

This study concludes that seventeen tree species were recorded in the Tembawang agroforestry and rubber forest systems, with individual tree densities ranging from 200 to 219.67 ind ha^{-1}. Four dominant species consistently exhibited the highest density values across all observation sites, namely Durian (*Durio zibethinus* Murr), Rubber (*Hevea brasiliensis* Muell. Arg), Kelempai (*Elateriospermum tapos* Blume), and Benuang (*Octomeles sumatrana* Miq), with density values ranging from 25 to 268.75 ind ha^{-1}. Spatial land-cover analysis revealed a reduction of approximately ±100 ha in mixed dryland agricultural areas, which partially represent Tembawang agroforestry systems, over the last five years. Aboveground carbon stock values within the Tembawang agroforestry landscape ranged from 0 to 453.96 Mg C ha^{-1}, and were spatially distributed across secondary dryland forest and mixed dryland agricultural land-cover types.

Conclusion

Our study reveals that seventeen tree species were recorded in the Tembawang agroforestry and rubber forest areas, with individual densities ranging from 200 to 219.67 ind ha^{-1}. Four species consistently exhibited the highest density values across all locations, namely Durian (*Durio zibethinus* Murr), Rubber (*Hevea brasiliensis* Muell. Arg), Kelempai (*Elateriospermum tapos* Blume), and Benuang (*Octomeles sumatrana* Miq), with density values ranging from 25 to 268.75 ind ha^{-1}. Aboveground carbon stock values in the Tembawang agroforestry area ranged from 0 to 453.96 Mg C ha^{-1}, and were spatially distributed across secondary dryland forest and mixed dryland agricultural land-cover types. This study demonstrates that Tembawang agroforestry in Cipta Karya Village plays a significant role in maintaining aboveground carbon stocks while supporting community livelihoods. Despite moderate species richness, the dominance of economically valuable tree species contributes substantially to carbon storage. The observed reduction of approximately 100 ha of mixed dry agricultural land over five years highlights the importance of land-use planning to prevent further carbon loss. These findings underscore the potential contribution of community-managed agroforestry systems to REDD+ implementation, sustainable land-use planning, and Indonesia's FOLU Net Sink 2030 targets. Strengthening the integration of traditional agroforestry systems into climate mitigation policies can enhance both ecological and socio-economic resilience in tropical landscapes.

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Authors' declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images that are not ours have been included with the necessary permission for re-publication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of West Kalimantan, Indonesia.

Authors' contributions statement

R., and R.L. conceptualized and designed the study. R., and A.R. conducted the field sampling. A.R. and E.S. performed the data analysis and interpretation. R., and R.L. assisted with the ecological analysis. R and R.L. wrote the paper with input from all authors.

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تغيرات الغطاء الأرضي وتوزيع مخزونات الكربون في منطقة تيمباوانغ الزراعية الحرجية، مقاطعة بنغكايانغ، كاليمانتان الغربية، إندونيسيا

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الخلاصة

تُمثل الزراعة الحرجية بنظام تيمباوانغ نظامًا تقليديًا لإدارة الغابات تمارسه مجتمعات الداياك في كاليمانتان، وهي معروفة بوظائفها البيئية ودورها في سبل العيش. تهدف هذه الدراسة إلى تحليل تغيرات الغطاء الأرضي وتوزيع مخزونات الكربون في نظام تيمباوانغ الزراعي الحرجي في قرية سيتا كارجا، كاليمانتان الغربية. اعتمد البحث على مزيج من المسوحات الميدانية والاستشعار عن بعد باستخدام صور الأقمار الصناعية Sentinel لعامي 2019 و2023. تم جمع بيانات الغطاء النباتي من خلال قطع تجريبية لتقييم تركيب الأنواع، والكثافة، والكتلة الحيوية من أجل تقدير الكربون باستخدام المعادلات التلومية (allometric equations). تم تحديد 17 نوعًا من الأشجار في مناطق تيمباوانغ والغابات المطاطية. أظهرت أربعة أنواع أعلى قيم للكثافة، وهي: Durio zibethinus، وHevea brasiliensis، وElateriospermum tapos، وOchanostachys sumatrana، حيث تراوحت الكثافات بين 25 و268.75 فرد/هكتار، بمتوسط عام قدره 260.42 ± 110.00 فرد/هكتار. تراوحت تقديرات مخزون الكربون فوق سطح الأرض بين 5.13 و632.11 ميغاغرام كربون/هكتار، بمتوسط 269.71 ± 181.79 ميغاغرام كربون/هكتار. أشارت نتائج تحليل الغطاء الأرضي إلى عدم وجود تغير كبير في الغابات الجافة الثانوية خلال السنوات الخمس الماضية. ومع ذلك، انخفضت المناطق الزراعية المختلطة الجافة، بما في ذلك أجزاء من تيمباوانغ والحدائق والأراضي المزروعة، بمقدار يقارب 100 هكتار. تراوح التوزيع المكاني لمخزونات الكربون عبر الغابات الجافة الثانوية والأراضي الزراعية المختلطة بين 0 و453.96 ميغاغرام كربون/هكتار، مما يعكس تباينًا كبيرًا في تخزين الكربون عبر المنظر الطبيعي. تؤكد هذه النتائج دور نظام تيمباوانغ الزراعي الحرجي في الحفاظ على مخزون الكربون رغم التغيرات المعتدلة في استخدام الأراضي.

الكلمات المفتاحية: مخزون الكربون فوق سطح الأرض، المعادلات التلومية، قرية سيتا كارجا، الأراضي الزراعية الجافة المختلطة، صور الأقمار الصناعية Sentinel.