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ORIGINAL RESEARCH PAPER

Carbon stock dynamics of forest to oil palm plantation conversion for ecosystem rehabilitation planning

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ABSTRACT

BACKGROUND AND OBJECTIVES: Efforts to enhance carbon stocks and boost carbon absorption potential are essential for climate change mitigation. Peatland ecosystems, known for their high organic content, are particularly vulnerable to environmental management. The study aimed to examine the alterations in land use and land cover that occurred between 1998 and 2022, spanning a 24-year duration. Additionally, it sought to assess the associated variations in carbon stocks within the designated Kepau Jaya specific purpose forest area. The area under investigation encompasses a peatland ecosystem that has experienced substantial changes in land cover and land use. This study investigated the fluctuations in carbon stock caused by these alterations and provides valuable perspectives on the potential of agroforestry systems to promote a wider range of land uses. Additionally, it highlights their role in ecosystem restoration initiatives and the better management of forest peatland regions.

METHODS: A spatial analysis was conducted on Landsat 5 and 8 satellite images by using shapefile data stored within the Google Earth Engine platform. Data analysis was carried out using Classification and Regression Tree, a decision tree algorithm used in machine learning for guided classification. Furthermore, purposive sampling was utilized to gather socioeconomic data, followed by the implementation of a benefit-cost analysis.

FINDINGS: The results revealed significant changes in the land cover within the Kepau Jaya specific purpose forest area over a 24-year period, with forested areas and open areas decreasing by 23.15 hectares per year and 16.94 hectares per year respectively, and oil palm plantation areas expanding by 40.10 hectares per year. From 1998 to 2022, there has been a consistent annual decline in carbon stocks, resulting in a reduction of 1,933.11 tons of carbon per year. The changes in land use and cover are closely linked to this decline. In an effort to increase plant species diversity in the area and support the gradual transition away from monoculture, a participatory agroforestry scheme was implemented by intercropping *Coffea liberica* and *Shorea balangeran* between oil palm rows in a 2-hectare oil palm plantation block within the agroforestry demonstration plot. According to measurements taken at breast height, the aboveground biomass of these species was measured, leading to projected estimates of carbon stocks in Kepau Jaya specific purpose forest area reaching 19,455 tonnes of carbon by the year 2030, with *Coffea liberica* contributing 4,148 tonnes carbon and *Shorea balangeran* contributing 15,307 tonnes carbon.

CONCLUSION: The study area experienced a substantial reduction in forest cover, whereas the extent of oil palm areas expanded significantly. The findings underscore the need for proactive measures to strengthen the governance of specific-purpose forest areas through community empowerment and the establishment of demonstration plots to promote agroforestry development. The results of this study provide insights for long-term forest rehabilitation strategies aimed at fostering sustainable forest management that yields environmental and socio-economic benefits in the long run.

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INTRODUCTION

Indonesia has made remarkable advancements in curbing deforestation while maintaining national development and economic stability. In pursuit of reaching net-zero emissions by 2060, the administration released Presidential Regulation Number 98/2021 concerning Carbon Pricing. This regulation lays out the necessary steps, instructions, and initiatives for the enforcement of carbon pricing in Indonesia, aiming to bolster the nation's efforts in reducing greenhouse gas emissions as specified in its Nationally Determined Contributions (NDCs). Indonesia's commitment to preventing climate change is also articulated in its enhanced NDC document with unconditional efforts amounting to 31.89 percent (%) and conditional efforts through international support totaling 43.2% (UNFCCC, 2022). Recognizing the importance of peatlands as essential ecosystems due to their abundant biodiversity and critical function in addressing climate change, Indonesia has established a goal to restore 2 million hectares (ha) of peatlands by 2030 in its updated NDC (UNFCCC, 2022). Peatlands are recognized for their substantial terrestrial carbon deposits and their integral role in the global carbon cycle. Globally, peatlands store around 329-525 gigatonnes per carbon (GtC), or 15-35% of total terrestrial carbon (Murdiyarso *et al.*, 2004). Although accounting for merely 3% of the earth's land area, these areas store approximately 100 gigatonnes (Gt) of carbon, representing 30-40% of the total carbon found in soil worldwide (Loisel and Galego-Sala, 2022). Peat swamp forests are important ecosystems that play a vital role in the global carbon cycle and climate change mitigation (Jonathan *et al*., 2023). Despite their ecological importance, the peat swamp forests of Indonesia are currently experiencing extensive deforestation, drainage, and conversion. Alterations in land use and cover within these forests have the potential to harm the ecosystem and diminish its capacity for carbon sequestration (Basuki *et al*., 2021). The conversion of peat swamp forests into other uses removes vegetation and alters the structure of the peat ecosystem, disrupting its function as a natural carbon sink. The analysis of land-use changes in peatlands is crucial for estimating the potential contribution of global peatlands to greenhouse gas emissions in the future (Leifeld *et al*., 2019). Numerous investigations have delved into the relationship between alterations in land use and cover and the capacity to sequester carbon in peat swamp forests. Hergoualc'h and Verchot (2011) found that converting peat swamp forests into agricultural land can reduce the potential for carbon storage by up to 90%. Additionally, Murdiyarso *et al*. (2015) and Novita *et al*. (2021) found that burning peatlands in Indonesia can lead to significant carbon emissions into the atmosphere by releasing carbon stored in peat soil. It is evident that the transformation of peat swamp forests into alternative land uses diminishes their capacity for carbon storage and obstructs endeavors to mitigate climate change. Changes within the forest are unavoidable as a result of social interactions in the neighboring region, driven by the uncontrolled exploitation of forest resources and the necessity to satisfy the demand for land. To ensure the preservation of forests, economic considerations should be factored into land use planning (Larson, 2013). It is essential to comprehend the changes in land use and cover dynamics concerning the capacity for carbon capture in peat forests. Acknowledging the importance of peatlands in the carbon cycle on a global scale and their susceptibility to deterioration allows us to emphasize the need for their preservation, rehabilitation, and sustainable supervision. Fiantis *et al*., 2023). Indonesia harbors about half the known tropical peatlands worldwide, with the majority, 84%, situated in Southeast Asia (Page *et al*., 2011). The significant occurrence of tropical peatlands in Indonesia highlights the necessity for effective peatland management practices that are sustainable, particularly due to their vulnerability to climate change, quick transformation into alternative land uses, and subsequent depletion of carbon, biodiversity, and ecosystem services. This has positioned peatland management as a central focus of Indonesia's climate mitigation endeavors. Indonesia is home to 13.4 million ha of peatland that store about 14% of the global peat carbon pool, with Riau Province alone containing 3.8 million ha of peatlands (Nugrahani, 2022). According to Rosalina *et al*. (2013), the peatlands in Riau account for 56.42% of the total peatland area in Sumatra Island, thus underlining the importance of peatland protection and restoration in the province in both national and global climate efforts. Substantial alterations in land use and carbon storage have transpired in Riau Province during recent decades. Between 1990 and 2020, the Blega watershed experienced a reduction of 25.98% in carbon stock as a result of modifications in land cover (Rahman *et al*., 2023). The predominant changes in land cover in Riau stem from the expansion of oil palm plantations, with the area increasing from 6.4% in 1990 to 74% in 2020 (Numata *et al*., 2023). On the contrary, the forest area in Riau witnessed a significant decline from 70.8% in 1990 to merely 18% in 2020, thereby exerting a profound influence on the carbon stocks within the region (Numata *et al*., 2023). These land cover changes can affect carbon stocks, carbon flux, and overall carbon sequestration potential (Raj and Jhariya, 2021). It is imperative to undertake endeavors aimed at averting substantial alterations in land cover and enhancing or preserving the current carbon reservoir in Riau. These efforts are regulated through the Regulation of the Ministry of Environment and Forestry (MoEF) Number 168/2022, which signifies Indonesia's commitment to help the forestry and other land use (FOLU) sector transform into a net sink by 2030 to address the impacts of climate change. The FOLU net sink 2030 operational plan includes increasing forest carbon reserves, reducing deforestation and forest degradation in peatlands, restoration of peatlands, and implementing sustainable forest management practices. The comprehension of the patterns and consequences of alterations in land use on the capacity of peatlands to store carbon is crucial for devising sustainable approaches to landscape management. The study aimed to analyze the dynamics of land use and land cover change over a 24-year period from 1998 to 2022 and estimate the corresponding changes in carbon stocks in Kepau Jaya specific purpose forest area (SPFA). Furthermore, the study provides valuable information on the potential benefits of incorporating agroforestry systems into monoculture oil palm plantations. This integration can not only increase land use diversity but also support long-term ecosystem rehabilitation efforts and promote better governance of forest peatland areas.

MATERIALS AND METHODS

Study area

The study area is the Kepau Jaya SPFA, a 1,027-ha research forest located administratively in the village of Kepau Jaya, Siak Hulu District, Kampar Regency, Riau Province, Indonesia. Kepau Jaya SPFA has been designated an integrated forest ecosystem primarily for government-led forest assessments, experiments, and research activities. As a result of the copious presence of Acacia mangium trees that are rich in nectar, the local community has purportedly utilized the area for beekeeping activities. Since its establishment in 2000, the forests within the SPFA have experienced both primary and secondary succession processes (Kurniasih and Sudarmalik, 2013). Geographically, the area is located between 101° 26' 41" – 101° 29' 27" east (E) and 00° 18' 53" – 00° 17' 44" north (N). This forest area was designated as a special purpose forest under Decree Number 74/2005 of the MoEF. Fig. 1 shows the geographic location of the study area in Kepau Jaya, Siak Hulu District, Kampar Regency, Riau Province, Indonesia. The Kepau Jaya forest area has an average temperature of 298.15 Kelvin (K), a maximum temperature of 302.85K, a minimum temperature of 295.25K, a wind speed of 1,128 meters per second (m/s), a solar radiation of 14,422 kilo joule per square meter per day (kJ/m^2/d), and an annual rainfall of 216 millimeters (mm). The Schmidt-Ferguson classification designates Kepau Jaya SPFA as possessing a type A climate. A preliminary investigation revealed that the depth of peat at Kepau Jaya SPFA ranges from 0.4 m to 5.0 m, averaging at 147 cm. Furthermore, the groundwater level varies between 48 cm and 132.5 cm, averaging at 85.7 cm. Organic matter within the study site encompasses all plant-derived biomass on the forest floor or below ground. If biomass is present on the forest floor, it is categorized as new biomass, but when found below ground, it is deemed as biomass undergoing decomposition, akin to peat, which is an organic substance undergoing decomposition. The availability of peat organic sources is influenced by factors such as their chemical composition, decomposition rate, and interaction with soil properties (Bibi *et al.*, 2018). These organic sources in nature contain carbon compounds and have been abundant throughout history. The ongoing decomposition or presence of organic material serves as a potential source of organic matter in the present, as analyzed through the carbon element content within the soil, operating within the natural carbon cycle (Rahman *et al.,* 2020).

Data collection

Spatial data was collected and analyzed using the Google Earth Engine (GEE) platform. This research

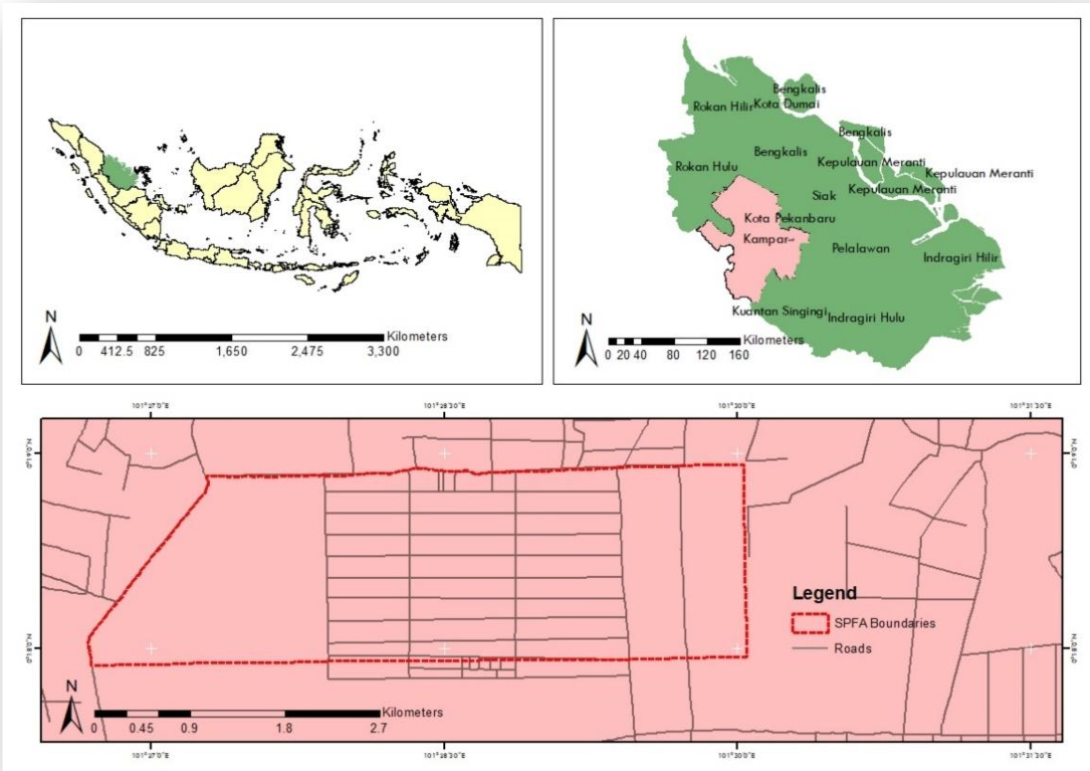

Fig. 1: Geographic location of the study area in the Kepau Jaya, Siak Hulu District, Kampar Regency, Riau Province, Indonesia

utilized Landsat 5 satellite images captured in 1998, 2001, 2004, 2007, and 2010; and Landsat 8 satellite images captured in 2013, 2016, 2019, and 2022. The geospatial data of Kepau Jaya SPFA was incorporated into the GEE system in order to access data for analysis. Furthermore, the actual coordinates from the field were utilized as the main data points in ground truthing to validate the different land cover categories present at the study site. Throughout the project, surveys and field observations were conducted to assess the current conditions of Kepau Jaya SPFA. Primary data collection was carried out using the participatory rural appraisal (PRA) method, involving the community in all stages from needs recognition to evaluation. Structured questionnaires were utilized to conduct in-depth interviews with respondents who were affiliated with forest farmer groups (FFGs). These interviews were further enhanced by incorporating open-ended one-on-one inquiries to gather additional valuable insights. Considering the specific objectives and scope of activities, purposive sampling was employed to select 26 respondents (all members of FFGs). To enhance the validity of the study, supplementary data was acquired via a thorough examination of existing records. This dataset encompasses details pertaining to the limits of the Kepau Jaya SPFA, the socio-economic status of the neighboring community, and the pertinent legislation and guidelines governing the management of forested regions.

Data analysis

Land use and land cover change of the Kepau Jaya SPFA

The satellite images utilized in this research were sourced from United States Geological Survey (USGS) Landsat 5 Surface Reflectance Tier 1, USGS Landsat 8 Collection 1 Tier 1 Top of Atmosphere (TOA) Reflectance, and USGS Landsat 8 Collection 2 Tier 1 TOA Reflectance datasets. The storage

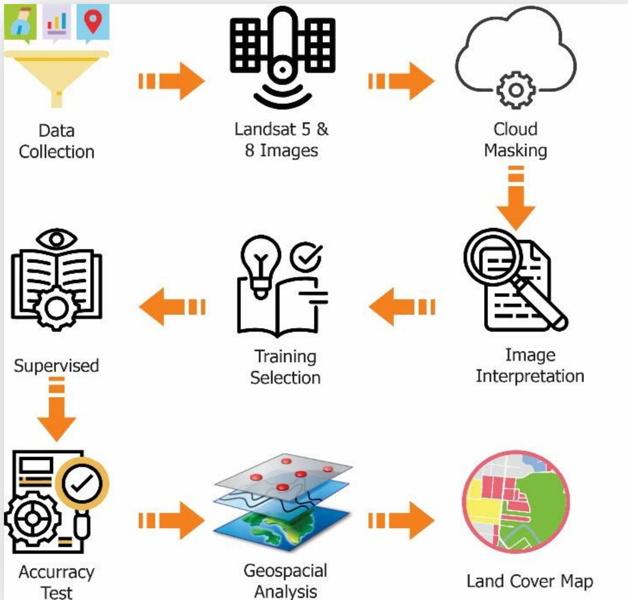

Fig. 2: The flow chart of the analysis

durations for these images were chosen based on specific intervals, taking into account the availability of cloud removal and median algorithms offered by GEE. These algorithms guarantee that the satellite images used are free from clouds and provide an accurate representation of the conditions during a specific time period. A cloud-based satellite image analysis method was used to carry out data analysis. GEE was used to process and analyze the satellite images. The stages of satellite image analysis are shown in Fig. 2. Upon dissection of the plane and implementation of tessellation, the image was subjected to interpretation. Image interpretation is a methodical process used to categorize an object within an image by analyzing its color pattern and visual attributes. The land use features were identified through the interpretation of images and clustering techniques. GEE was subsequently employed to conduct supervised classification for the purpose of categorizing land uses, thereby providing a comprehensive depiction of each land use type. This classification of land use served as a valuable tool or point of reference in the analysis and interpretation of remote sensing imagery for land use mapping. At this classification stage, the digitalization process can also highlight objects in the study area, such as forest vegetation, oil palm, and open areas. Data analysis was carried out using a guided classification method using machine learning, namely Classification and Regression Tree (CART), which has a consistent 80% accuracy for time-series mapping. The classification approach used was pixel-based or multispectral classification (Sellami and Rhinane, 2022).

The accuracy of the classification data was evaluated through an accuracy assessment technique. This evaluation involved the comparison of the classification results from the sample training area with the test sample, presented in the form of an error matrix (confusion matrix). To ensure more accurate results, the sample used as a training area and the sample used for accuracy testing must be taken from different places (Montes *et al.*, 2023). The process of examining changes in land and forest cover involved comparing land cover classes at the initial Observation Time (T0) with those at the Subsequent Time (T1) and identifying objects that have remained unchanged as well as those that have undergone transformations (i.e., objects at T0 and T1 were not the same). The calculation of the area for each object, distinguishing between those that underwent changes and those that remained unchanged, was performed for every 3-year interval based on Eq. 1

Table 1: Constant value of carbon stocks based on land cover

No.	Land Cover	Carbon Stock (tC/ha)	Source
1	Secondary peat forest	84.39	FRL, 2022
2	Oil palm plantation:		
	> 1-year-old plantation	0.70	MoEF, 2017
	> 2-year-old plantation	1.00	
	> 9-year-old plantation	11.88	
	> 11-year-old plantation	13.07	
	> 13-year-old plantation	12.49	
	> 17-year-old plantation	16.43	
3	Open area	0	FRL, 2022

(BSN, 2014):

$$PTH = \frac{(A1 - A0)}{(T1 - T0)} \quad (1)$$

Where; PTH = the change in forest or land cover per year in a certain period (ha/year), A0 = the area at the time of initial observation (ha), A1 = the area at the subsequent observation (ha), T0 = year of initial observation, T1 = year of subsequent observation.

The study utilized an online tool for creating Sankey diagrams to visually display the progression of land use throughout different time periods. Each type of land use was represented as a node, and the connections between nodes demonstrated the movement between categories. This visual representation proves to be a valuable method for showcasing the changes in land use patterns over time.

Changes in carbon stocks and carbon sequestration in the Kepau Jaya SPFA

A GIS-based spatial analysis was carried out to assess the carbon potential of different land cover classes using activity data and carbon stock data for each class (Tosiani *et al*., 2020). The land cover classification system used in this study was the Indonesian National Standard (SIN): 8033 (BSN, 2014). The total carbon stock was determined by multiplying the land cover class with the respective carbon stock data for each land cover type, as illustrated in Table 1. Eq. 2 was used to calculate the total carbon stock (Tosiani, 2015):

$$The\ annual\ total\ carbon\ stock = A(tC/ha)\,x\,B(ha/years) \quad (2)$$

Where; A = carbon stocks per land cover (tC/ha), B = annual activity data/land cover area (ha/year).

The process of calculating carbon reserves involved determining the area of each land cover class in Kepau Jaya SPFA over a period of 24 years, from 1998 to 2022 (at three-year intervals), which was then referred to as annual activity data. The above-ground biomass was associated with the carbon stock data of each land cover class. The calculation method employed in this study was based on the stock difference method, as described using Eq. 3 (Tosiani, 2015):

$$\Delta C = \frac{(Ct_2 - Ct_1)}{t_2 - t_1} \quad (3)$$

Where; ΔC = annual change in carbon stock in each pool (tC/year), Ct_1 = carbon stock in each pool at the beginning (tC), Ct_2 = carbon stock in each pool at the end (tC)

The amount of carbon deposits obtained was then converted into a Carbon Dioxide (CO_2) absorption value using the formula for the ratio of the molecular weight of carbon dioxide to carbon using Eq. 4 (Stripple *et al*., 2018):

$$CO_2 = \left(\frac{44}{12}\right) X\,C \quad (4)$$

Where; (CO_2) = amount of gas (CO_2) absorbed (tCO_2/ha), C = amount of carbon stored (tC/ha)

Scenario interventions are used to forecast the potential for increased carbon sequestration. encompass the development of hypothetical scenarios that replicate the consequences of specific interventions or alterations in land use practices on the process of carbon sequestration.

Fig. 3: Examples of the appearance of earth's surface object: a) Open land, b) Forest, c) Oil Palm plantations

Potential carbon stock increases from agroforestry approaches

National efforts to combat the widespread conversion of forests to oil palm plantations include the Long-Term Rehabilitation Strategy (also known as the Restoration Period Strategy or Strategi Jangka Benah in Indonesia). As mandated by Government Regulation Number 23/2021 and MoEF Regulation Number 24/2021, the strategy focuses on restoring forests while allowing smallholder oil palm farmers to continue harvesting their palms through agroforestry approaches. In the case of Kepau Jaya SPFA, liberica coffee (*Coffea liberica*) and meranti (*Shorea balangeran*) are recommended as agroforestry plants due to their economic value and capacity to contribute to the restoration of forest cover. In the context of the Long-Term Rehabilitation Strategy, the calculation of aboveground biomass (AGB) for the suggested species was conducted by utilizing measurements of their diameter at breast height (DBH). Although the Indonesian government possesses information on species-specific allometric equations, the study refers to values from existing literature to quantify the carbon stock values in this study. The biomass of *Coffee liberica* was calculated using the allometric model where AGB = 0.281 $DBH^{2.0635}$ (Najih, 2021), while that for *Shorea balangeran* was based on the mixed allometric model for peatlands where AGB = 0.206284 $DBH^{2.4511}$ (Krisnawati *et al.*, 2012). The diameter growth approach was applied in the computation of the biomass for *Shorea balangeran*. According to Budiman *et al.* (2020), the diameter growth rate of a 9 year-old *Shorea balangeran* planted in an agroforestry system is 2.25 centimeters per year (cm/year). Meanwhile, Najih *et al.* (2021) noted that 5 year-old *Coffea liberica* plants exhibited a diameter growth of 8.7 millimeters per year (mm/y). The aboveground carbon stock is computed by multiplying the total biomass of dead wood with the carbon fraction default value of 0.47, as shown in Eq. 5 (BSN, 2019):

$$Cv = B_{OV}\, x\, C\, organic \tag{5}$$

Where: Cv = Carbon content of biomass in kilograms (kg), B_{OV} = Total biomass (kg), *C organic* = Default carbon fraction, using a carbon content of 0.47 kgC per kg of dead matter (based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines).

RESULTS AND DISCUSSION

Interpretation of Landsat 5 and 8 imageries

Landsat 5 and 8 images were interpreted by choosing the most suitable band combination to ensure precise land cover classification. Upon conducting a visual assessment of land cover elements in Kepau Jaya SPFA, three principal categories were identified: open spaces, forests, and oil palm plantations. The intensity of colors was taken into account to determine the quantity of individual elements per unit area, resulting in different shades representing specific land cover types in the visual representations. Specifically, during the study period, open land was depicted as light brown, forests as dark green, and oil palm plantations as light green. The brightness of the green color also indicated vegetation density, with high-density forests appearing darker compared to low-density forests or oil palm plantations. Built-up and open lands were depicted in light brown. For instance, Fig. 3 illustrates the reflectance appearance of surface objects using a combination of Landsat 5 bands 543 and Landsat 8 bands 654.

It is crucial to assess the benefits and constraints of various methods for calculating carbon using remote sensing data. The utilization of remote sensing technology enables researchers to overcome the limitations in space and time that are frequently encountered when employing traditional statistical methods for data collection (Zhang *et al*., 2024). Carbon emissions estimation is made possible through the analysis of various factors such as land use, biomass, and carbon sequestration values (Adelisardou *et al*., 2022). indicates that utilizing remote sensing technologies, such as Google Earth Engine, is a precise and economical approach to quantifying carbon sequestration. The accuracy of carbon estimation is enhanced by effectively classifying various land cover types through the utilization of satellite imagery and geographic information systems. This is accomplished by employing the support vector machine algorithm in conjunction with GEE for land use and land cover analysis (Adelisardou *et al*., 2022). Remote sensing techniques offer benefits in terms of spatial coverage and precision. Nevertheless, there are obstacles associated with accurately measuring carbon storage and sequestration. This is a result of uncertainties in directly sampling carbon pools and the requirement for higher resolution in land use and land cover classifications (Adelisardou *et al*., 2022).

Land cover classification in Kepau Jaya SPFA

One of the key benefits of processing and analyzing the collected dataset using GEE is its scalability and computational efficiency, which allows for the analysis of large-scale datasets with ease (Gorelick *et al*., 2017). Through the utilization of GEE, comprehensive spatial and temporal assessments can be conducted, valuable information can be derived from the data, and precise land use trends can be produced over a period of time.

Land cover changes in Kepau Jaya SPFA were observed and analyzed over a span of 24 years from 1998 to 2022. Landsat 5 satellite imagery was utilized for interpretation in 1998, 2001, 2004, 2007, and 2010, while Landsat 8 satellite imagery was utilized for the years 2013, 2016, 2019, and 2022. The analysis of the two sets of Landsat satellite images revealed land typologies in Kepau Jaya SPFA to be open land, forest, and oil palm plantations. Changes in land use and cover for each category are depicted in Fig. 4. Notably, the pattern of land conversion in SPFA occurred prior to its classification as a special-purpose forest area in 2005, coinciding with the period of social upheaval and political developments in Indonesia. The resulting instability at the national level had cascading effects on social dynamics within village communities, driven in part by efforts to meet land resource needs and achieve household economic stability. Furthermore, the utilization of the CART machine learning technique in the supervised classification method yielded data analysis outcomes that effectively categorized the land use typology into open areas, forests, and oil palm plantations. The objective of simplifying land use classes was to streamline the process of identifying a shared pattern in the fluctuations of land cover and utilization (Farda, 2017). The illustration in Fig. 5 depicts the trend of land use changes in the Kepau Jaya SPFA area from 1988 up to 2022, revealing a shift from forested areas to open areas, and subsequently to the extensive establishment of oil palm plantations. Generally, there was a deficit in forested areas, but a surplus in oil palm plantation areas within the Kepau Jaya SPFA area. Oil palm plantation areas saw the most significant changes over the 24-year period, showing a consistent annual growth rate of 40.1 hectares per year, whereas forest areas witnessed a decline of 23.15 hectares per year. This decline was linked to the rise in land utilization for residential purposes and the extension of land for oil palm plantations. In developing nations, the transformation of land into agricultural land to satisfy escalating food needs is a frequent phenomenon (Campos, *et al*., 2005). Ismed *et al*. (2013) further noted that the limited availability of land to meet human needs has resulted in changes or conversion of land use functions, such as the transformation of forests into various types of land use such as for agriculture, plantations, forest plantations, settlements, and the increase in illegal logging.

The assessment conducted on the land cover area in Kepau Jaya SPFA revealed an impressive degree of precision, ranging from 88.05% to 97.49%. These findings comply with the prescribed guidelines for land cover mapping tests, which stipulate a minimum accuracy threshold of 85% (Malik *et al*., 2024). Over the 24-year period, significant changes occurred in the land cover of Kepau Jaya SPFA. Before 2004, there was a noticeable shift from forests and open

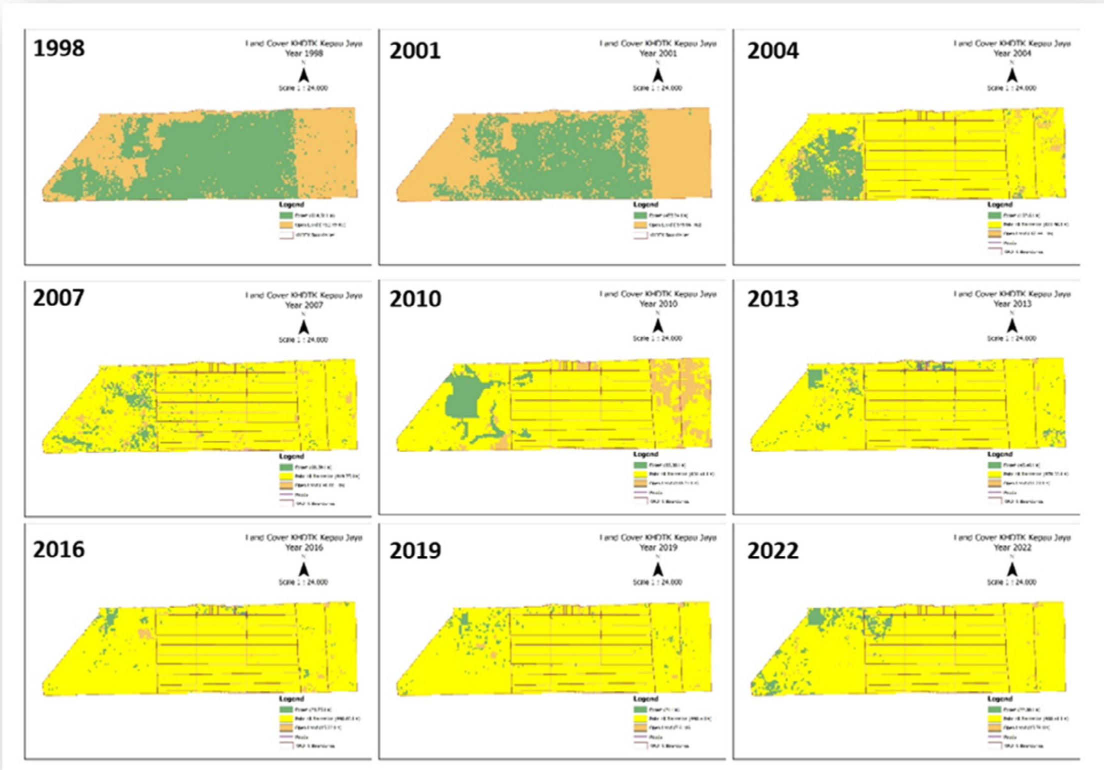

Fig. 4: Changes in the land cover of Kepau Jaya SPFA in the years studied
(Green-colored area represent forest areas; orange-colored areas indicated open areas; yellow-colored areas indicate palm oil plantation areas; purple lines indicate roads)

areas to oil palm, and following that year, oil palm land cover tended to be steady (Fig. 5). According to another study conducted in Sumatra (Gatto *et al*., 2015), along with other land uses like shrubs, mixed dryland agriculture, and fallow land, existing secondary dryland forests (on mineral soils) and secondary swamp forests have been converted to oil palm plantations. The peat ecosystem in Riau province has been selected as a research location due to its abundance of palm oil plantations. To ensure the sustainability of peat ecosystems, it is crucial to implement appropriate management practices due to their fragile nature. These ecosystems possess the remarkable capacity to sequester carbon and contain approximately 30% organic matter. However, if human activities in the surrounding areas are not properly regulated, they can pose a substantial threat to the long-term sustainability of these ecosystems (Hidayat *et al.,* 2020). Driven primarily by intense anthropogenic activities, notably the expansion of oil palm plantations to meet the needs of the growing population. Land use transformation within the SPFA region reached its highest point in 2004 as a result of land clearance activities conducted by local communities. This escalation in land clearing activities not only increased the susceptibility to forest fires but also facilitated the transition of forested areas into monoculture plantations. This phenomenon is believed to be closely associated with the enactment of Law Number 32/2004, which grants regional governments autonomy in managing regional economic development and natural resources, thus conferring authority and decision-making power for natural resource management in the area. Differences in the designated status and function of the areas are the underlying factors influencing the

Fig. 5:

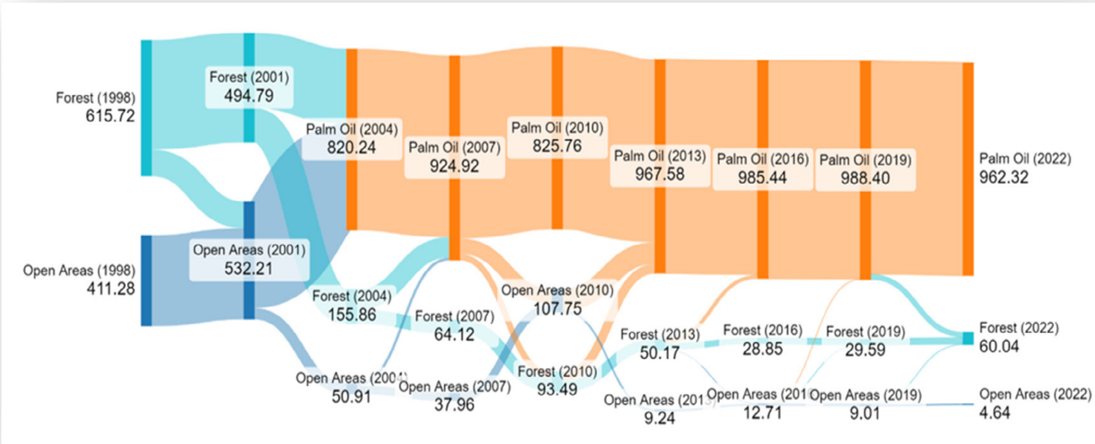

Fig. 5: Dynamics of land cover change of Kepau Jaya SPFA

impact of regulations on illegal land clearing and area conversion in Kepau Jaya SPFA. Consequently, differences in the status and function of areas can be observed, as outlined in the Regional Spatial Plans (RSP) of Riau Province (Regional Regulation Number 10/1994) and Kampar Regency (Regional Regulation Number 11/2011). The Riau Province RSP designated the SPFA administrative region as a forestry area, while the Kampar Regency RSP designated it as a plantation area. The process of reconciling the differing land use designations outlined in the two regional regulations has been finalized, and efforts to harmonize the regulations are currently ongoing.

Potential carbon stocks and emission absorption profile based on land cover type

The calculations provided in this section specifically focus on the carbon stock above ground level. The estimation of carbon stocks was carried out by considering the different land cover classes within the Kepau Jaya SPFA, with the assistance of Tosiani (2015) as a reference. The original forest ecosystems within the research area consist of peat forests. These forests located on Sumatra Island exhibit an average carbon stock in the above-ground biomass (AGB) pool ranging from 110.29 to 182.76 tC/ha (95% CI). Conversely, the disturbed or secondary peat forests that result from disturbances show an average carbon stock in the AGB pool ranging from 77.61 to 91.17 tC/ha (95% CI) (FRL, 2022). Forests converted to oil palm are secondary peat forests. This oil palm has a lower carbon stock of 0.70 - 16.43 tC/ha which varies according to the age of the plant (MOEF, 2017). Over the past ten years, the conversion of forests to oil palm plantations has increased globally, going from 14.1 to 34.5% between 2009 and 2019 (Zhao *et al*., 2024). The conversion of rainforest to oil palm plantations can lead to carbon losses in which experts estimate a loss of 174 tC/ha (Guillaume, *et al.*2023). Various management strategies implemented in oil palm plantations can result in diverse impacts on the dynamics of carbon stocks. The assessment of carbon stock levels is crucial in determining the ability of land cover to sequester carbon. The quantification of CO_2 emissions can be conducted through the utilization of a carbon stock-focused method following the acquisition of a land use change matrix (Setiawan *et al*., 2016). Carbon sequestration and removal in agriculture are crucial strategies for mitigating climate change and reducing greenhouse gas (GHG) emissions. Carbon sequestration in agriculture can be achieved through different approaches, including soil carbon sequestration, afforestation, and reforestation (Kamyab, *et al.*, 2023). The analysis of land cover in Kepau Jaya SPFA over 24 years (1998 – 2022) showed annual variations in carbon stocks, ranging from 7,536.19 to 51,406.46 (Table 2). Additionally, Fig. 6 illustrates the trend of changes in carbon potential in the Kepau Jaya SPFA.

Climate variability has exerted a notable influence

Table 2: Estimates of carbon stock in Kepau Jaya SPFA based on land cover type

Type	Forest tC/y	Oil palm plantation tC/y	Open lands tC/y	Total tC/y	Change in carbon stock/year (ΔC) tC/y
1998	51,406.46	-	-	51,406.46	1,1933.11
2001	41,310.02	-	-	41,310.02	
2004	13,012.75	820.24	-	13,832.99	
2007	5,353.38	2,182.81	-	7,536.19	
2010	7,805.48	1,948.79	-	9,754.27	
2013	4,188.69	12,646.27	-	16,834.96	
2016	2,408.69	12,879.70	-	15,288.39	
2019	2,470.47	16,239.41	-	18,709.88	
2022	5,011.90	15,810.92	-	20,822.82	
SD	18,364.82	7,196.66	-		
Mean	14,774.20	6,947.57	-		
SE	6,121.61	2,398.89	-		

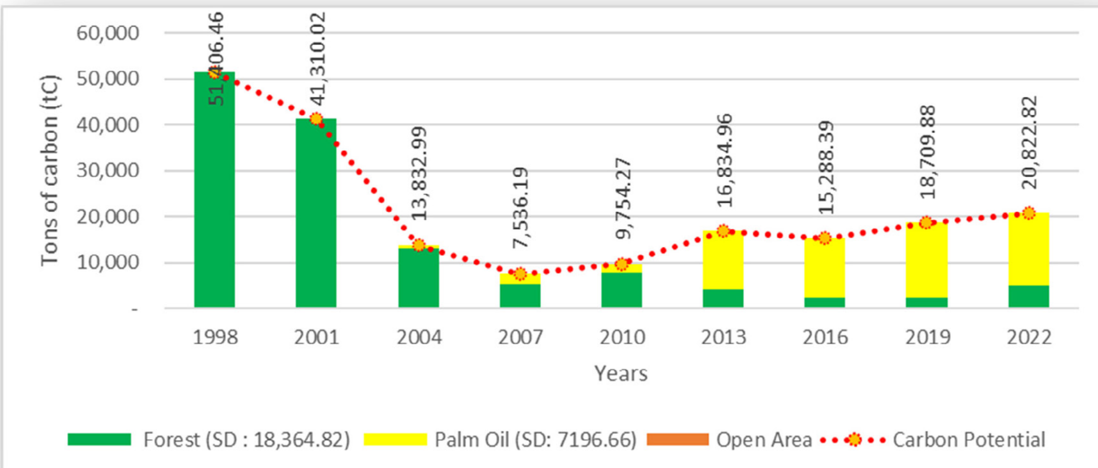

Fig. 6: Changes in ABG carbon potential in Kepau Jaya SPFA

on the quantity of organic carbon sequestered in soil, particularly in the guise of soil organic carbon (SOC). This phenomenon arises from the acceleration of organic matter decomposition due to rising temperatures, leading to a decline in the soil's carbon content (Beillouin, *et al.*, 2023). Climate change can have a significant impact on the decomposition, stabilization, and input of SOC, which ultimately affects the overall carbon balance in terrestrial ecosystems. Elevated temperatures have the potential to accelerate the breakdown of organic material, leading to the release of carbon from the soil. However, the overall global equilibrium of carbon movement in and out of the soil remains ambiguous at present (Guo, *et al.*, 2023). This contributes to increased greenhouse gas emissions, further exacerbating climate change (Harris *et al.*, 2021). Overall, carbon stock in the Kepau Jaya SPFA was estimated to have decreased by 1,933.11 tC/y from 1998 to 2022, mainly due to extensive land conversion from forests to oil palm plantations. The consequence of this event was twofold: a decline in biodiversity and a notable impact on carbon stocks and the absorption of CO_2 from diverse land uses. The process of converting forests into oil palm plantations entails the elimination of dense vegetation and the depletion of soil organic matter, resulting in the release of CO_2-equivalent emissions (Wan Mohd

Jaafar *et al*., 2020). The conversion of forests to oil palm plantations leads to a significant reduction in carbon sequestration capacity, as described by a previous study which found that the carbon stock of oil palm plantations was only 45% of that in primary forests (Cooper *et al*., 2020). The efficiency of forest ecosystems in capturing and storing carbon dioxide is attributed to their diverse vegetation and significant soil carbon reservoirs. On the other hand, oil palm plantations, especially those with monoculture plantings, have lower biomass and a diminished capacity for carbon sequestration (Novita *et al*., 2021). Land use changes such as conversion from forest land to agricultural land can lead to a loss in soil carbon, with a decrease of 20-50% in SOC when forest land is converted into cultivated land. Previous literature has shown that soil carbon stocks reduce when land is converted from grassland to cropland (-59%), forest land to cropland (-42%), forest to plantation (-13%), and grassland to plantation (-10%), whereas soil carbon stocks increase after land use changes from cropland to forest (+53%), cropland to grassland (+19%), cropland to plantation (+18%), and forest to grassland (+8%). (Sharma, *et al*., 2019).

According to Fig. 6, the year 2007 marked the lowest carbon stocks for the 1998–2022 period, at 7,593.80 tC. This result is attributed to the conversion of open space and forested areas into oil palm plantations over an estimated area of 924.92 ha. As a consequence of this conversion, the carbon reserves in Kepau Jaya SPFA underwent alterations. The carbon reserves in each specific location are predominantly influenced by the distinct land cover and vegetation characteristics present in that particular area. When there is a shift in land use from vegetation with a high biomass content to those with a low biomass content, it leads to a decrease in carbon production (Tedese *et al*., 2023). Peat forests store the most carbon of all the types of forests in the world (Murdiyarso *et al*., 2004), serving as carbon sinks for thousands of years (Beaulne *et al*., 2021). The peat forests in Indonesia are reported to store 30% more carbon than the total above- and belowground biomass of all forests in the country (Warren *et al*., 2017). The carbon found in peat swamp forests is derived from tree biomass, peat mass, understory vegetation, litter, dead wood, and soil organic matter (Gibbs *et al*., 2007). Changes in land cover in Kepau Jaya SPFA affect the potential CO_2 sequestration as seen in Fig. 7. It is evident that the year 2007 witnessed the lowest level of potential CO_2 sequestration, as the lowest estimates of carbon stock at Kepau Jaya SPFA was observed in the same year. The optimal condition of the forest, characterized by dense land cover and diverse vegetation types, will

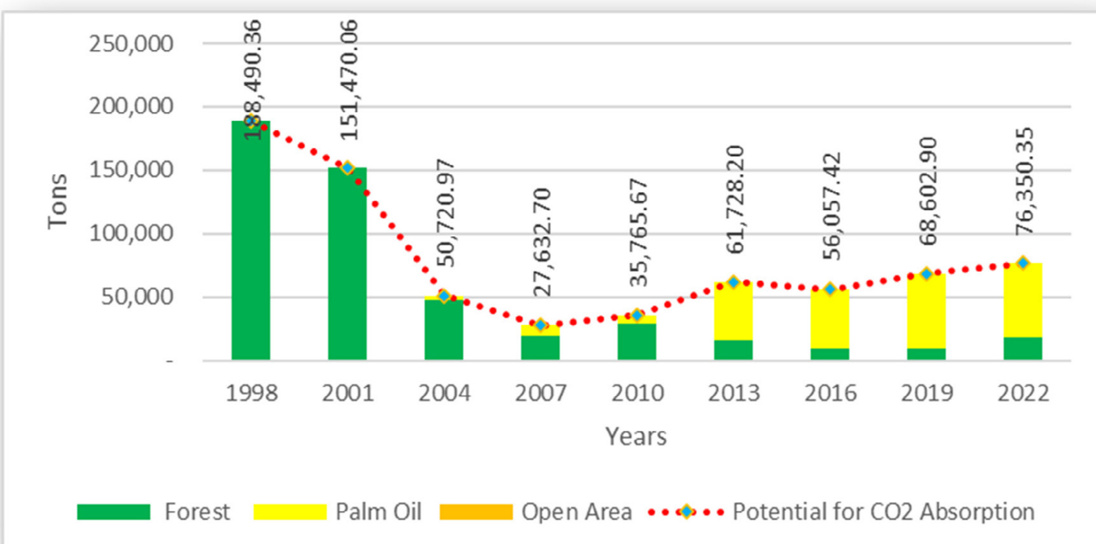

Fig. 7: Potential for CO_2 absorption at Kepau Jaya SPFA

result in the highest possible CO_2 absorption capacity.

Potential for increasing carbon stocks through agroforestry approaches under a long-term rehabilitation strategy

The enhancement of carbon reserves in Kepau Jaya SPFA can be accomplished by implementing the strategies outlined in Indonesia's Long-Term Rehabilitation Strategy (referred to as *Strategi Jangka Benah*), which aims to restore damaged forests, especially those converted to monoculture plantations, by transitioning them into mixed plantations or agroforestry systems that mimic the ecological functions of natural forests. Regulations governing the Long-Term Rehabilitation Strategy in Law Number 6/2023 serve as a legal framework to resolve current land tenure issues and conflicts. These regulations provide a range of choices for resolving issues, considering the classification of the forest area, whether it is designated for conservation, production, or specific purposes. Proposed schemes include land ownership transfer, reforestation, and social forestry partnership programs, such as agroforestry. The implementation of the Strategy includes integrating forest trees, agricultural crops, and plantation plants into the existing oil palm monoculture through agroforestry systems. These activities aim to improve forest composition, increase biodiversity, promote carbon sequestration, and enhance ecosystem functionality (Kusumaningrum and Izdihar, 2022). A previous study determined that the carbon stock in agroforestry varied significantly based on basal area and total species, with strong and weak correlations, respectively (Hartoyo *et al.*, 2022). Furthermore, it has the capability to enhance soil organic matter content, either by recovering plant organic matter post-harvest or through the process of composting (Yuniawati and Tampubolon, 2021). The Strategy defines a time period of 15-25 years to rehabilitate damaged state forests into mixed plantations or agroforestry, wherein management rights are granted to cultivate oil palm while transitioning to forest product utilization through social forestry (Peteru and Komarudin, 2022). This project, from a technical standpoint, aims to increase the diversity of plant species in the region, thereby bolstering carbon sequestration efforts. The process began with a PRA to gather preferences of FFG members for the plant species to be planted among the existing oil palm (Fig. 8). Implementing an agroforestry scheme presents a practical solution for the reforestation efforts in the Kepau Jaya SPFA region (Yunianto and Sutrisno, 2019). The primary goal of the agroforestry approach is to strategically replenish forestry resources. Therefore,

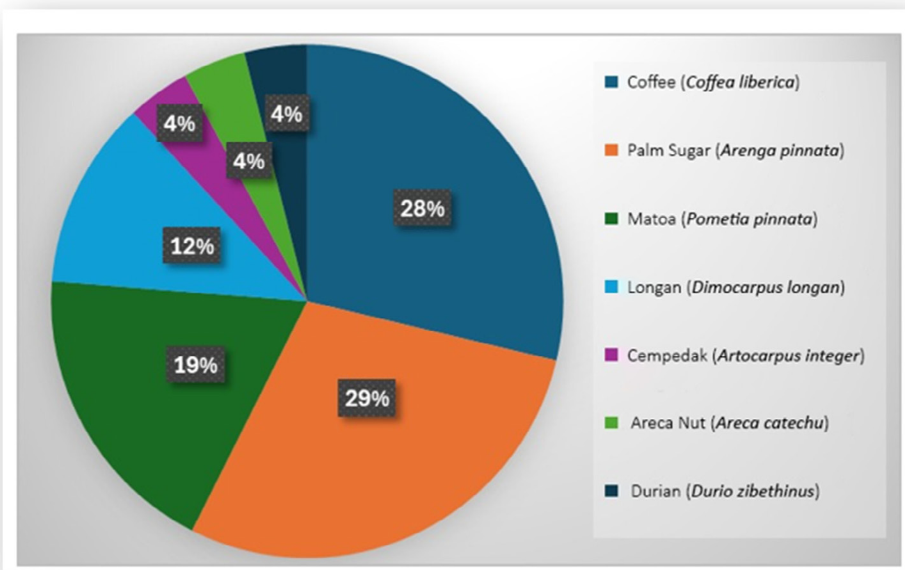

Fig. 8: The PRA results indicating the preferences for agroforestry plant species of FFG members for communities around Kepau Jaya SPFA

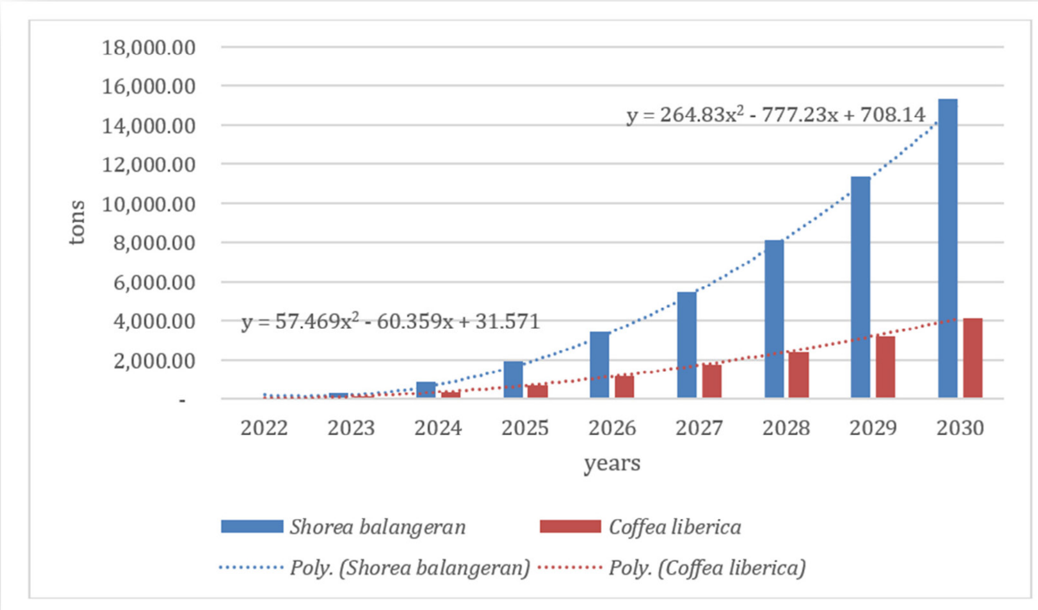

Fig. 9: Increasing carbon stock projection with the long-term rehabilitation program

the plant species chosen for intercropping among oil palm rows must exhibit the ability to thrive in shaded conditions, or at least partially shaded conditions, in order to promote successful growth and facilitate ecological succession.

In order to investigate the potential enhancement of carbon stocks within the Kepau Jaya SPFA area through agroforestry, the study established a 10-ha agroforestry demonstration plot composed of multipurpose forest tree species as primary crops and agricultural crop species as intercrops. The monoculture oil palm plantation block located within the demonstration plot area is ten years old and currently in its productive phase. Upon persuading and convincing private land owners at Kepau Jaya SPFA to restore the peat swamp forest ecosystem, Liberica coffee (*Coffea liberica*) was planted as an intercrop among the oil palm plants, while meranti (*Shorea balangeran*), a native timber species classified as a vulnerable in the International Union of Conservation of Nature's Red List of Threatened Species, was placed at the borders of the plantation. Based on diameter at breast height measurements, the aboveground biomass of these species was quantified accordingly in order to obtain a projected estimation of carbon stocks in the oil palm plantation block of the agroforestry plot to reach 19,455 tonnes of carbon by 2030, with *Coffea liberica* accounting for 4,148 tonnes of carbon and *Shorea balangeran* contributing 15,307 tonnes of carbon (Fig. 9). The survival rate of the two species after three months of planting was considerably low (Table 3) due to a lack of proper maintenance by the landowner, attacks by monkeys and pests, and extremely hot air temperatures in several open areas. According to Table 3 and in line with MoEF Regulation Number 23/2021 regarding the Implementation of Forest and Land Rehabilitation, replanting and periodic maintenance is a necessary activity to ensure survival rates in demonstration plots.

The conversion of forest areas to oil palm plantations influences carbon stocks and results in increased carbon emissions. Between 1990 and 2005, approximately 50-60% of oil palm plantations contributed to carbon emissions (Besar, *et al.*, 2020). The conversion of forests to oil palm plantations resulted in a significant 93% reduction in vegetation carbon (Novita, *et al.* 2021). Oil palm plantations are recognized for their reduced carbon stocks in comparison to forests, given that the conversion

Table 3: Growth conditions in the 3-ha monoculture oil palm plantation block designated for long term rehabilitation (2021-2024)

Species	Number of plants planted (2021/2022)	Number of plants replanted (2023)	Number of living plants	Survival rate (%) (2024)	Mean of height (cm)	Mean of diameter (mm)
Liberica coffee (*Coffea liberica*)	500	200	279	39.86%	69	8.64
Meranti (*Shorea balangeran*)	110	75	101	54.59%	241	25.22
Average				47.23%		

process causes soil carbon loss, leading to a decrease in SOC ranging from 20-50%. This loss in soil carbon negatively affects soil quality and plant productivity. Moreover, the reduction in soil carbon stocks also has implications for global carbon dynamics, as soil is a major carbon reservoir with high carbon sequestration potential. (Sharma, *et al*., 2019). The carbon storage capacity of oil palm plantations is much lower than that of forests. Young oil palm plantations (1-5 years old) have lower aboveground carbon storage capacity, with a range of 1.3 to 16.2 Mg C/ha (Novita *et al*., 2021), in contrast to forests which can have carbon stocks ranging from 3.5 to 5.5 Mg C/ha per year (Besar *et al*., 2020). The conversion of forest land to oil palm plantations usually results in a loss of soil carbon, with estimates indicating a reduction of 20-50% in soil organic carbon (SOC). A decline in soil carbon content has the potential to negatively impact soil quality and plant productivity. Furthermore, the depletion of soil carbon reserves holds considerable importance for the global carbon cycle, as soil plays a critical role as a primary carbon sink capable of storing carbon. (Besar, *et al*., 2020).

Initiatives aimed at improving carbon storage by introducing a variety of plant species have been implemented in partnership with FFGs. This initiative aims to enhance the forest ecosystem in Kepau Jaya SPFA by engaging and empowering the local community. Kurniawan *et al*. (2023) identified red chili as a potential plant for development within the agroforestry system at Kepau Jaya SPFA. Household income for FFGs has exhibited a correlation with this agricultural commodity, highlighting a noteworthy association. Notably, this commodity offers a relatively swift turnover, resulting in a nominal revenue of up to US$ 2,898.60 per person during each harvest period, which occurs six months after the initial planting. It is anticipated that through permanent cultivation, there will no longer be a need for the expansion of agricultural areas, thereby reducing the depletion of forest stands and alterations to land cover in Kepau Jaya SPFA.

CONCLUSION

Kepau Jaya SPFA has undergone land use and cover changes in its forested areas, oil palm plantations, and open areas. Analysis of Landsat 5 and 8 images at a 95.99% accuracy reveals a 23.15 ha/year decrease in forested land cover, a 16.94 ha/year decrease in open areas, and a 40.10 ha/year expansion of oil palm plantations. The alteration in the makeup of current vegetation is associated with the decrease in potential carbon stocks and carbon absorption. Consequently, the potential carbon stocks in Kepau Jaya SPFA decreased by 4,157.26 tC/year over the 24-year period due to this extensive forest conversion. These transformations were ascribed to a multitude of factors, encompassing societal turmoil, political intricacies, and regulatory structures. The lowest potential carbon stocks occurred in 2007, coinciding with the conversion of open space and forests into oil palm plantations. This transformation not only resulted in a decline in biodiversity but also had an influence on carbon stocks and the absorption of CO_2. The potential for CO_2 absorption was directly correlated with the trend of carbon potential, highlighting the importance of maintaining forest cover for carbon sequestration. To address this, a Long-Term Rehabilitation Strategy is underway to enhance potential carbon uptake in the peat swamp forests while providing support and incentives for smallholder farmers to transition from oil palm cultivation to agroforestry practices will be essential for the long-term sustainability of restoration approaches. Measurements form the monoculture palm oil block within the agroforestry demonstration plot in Kepau Jaya SPFA yielded measurements indicating that the coffee and meranti intercrops exhibited a meager survival rate of 47.23% within a span of three months. This can be attributed to inadequate maintenance practices by the landowner, the presence of monkey pests, and the occurrence of excessively high air temperatures in certain exposed regions. Furthermore, it is imperative to provide assistance and rewards to small-scale farmers in order to facilitate and incentivize their shift from oil palm farming to agroforestry methods. This is of utmost importance for ensuring the enduring viability of restoration endeavors. Such ecosystem rehabilitation approaches possess the capacity to be adjusted and implemented in diverse peatland ecosystems, thereby aiding national endeavors to promote smallholder farmers in diminishing their dependence on oil palm cultivation. The comprehensive analysis of land cover changes and carbon stocks in Kepau Jaya SPFA highlights the complex interplay between human activities, regulatory frameworks, and environmental sustainability. Sustainable land management practices, play a crucial role in addressing the challenges posed by escalating land use pressure, as they contribute to the reduction of carbon emissions and the conservation of forest ecosystems. The involvement of local communities and the provision of regulatory support further enhance the effectiveness of these practices. Overall, the results underscore the importance of integrating agroforestry applications within oil palm plantations to provide significant benefits for income as well as enhanced carbon storage through healthy crop growth. While the study concentrated on obtaining precise estimates of ABG in order to offer thorough insights into variations in carbon stock levels over an extended period, along with supplementary agroforestry measures. However, a drawback of this approach was the exclusion of belowground biomass from the assessment. Further studies quantifying the belowground biomass of the study area can help to improve the understanding of the carbon dynamics of this biome and refine our strategies for sustainable land management practices. The findings of the study also indicate necessity for further inquiries to pinpoint the most effective tree-crop pairings that can enhance both carbon sequestration and financial advantages. It is crucial to identify appropriate combinations in regions where local communities rely significantly on nearby forests, taking into account factors like land suitability, shade tolerance, and economic value.

AUTHOR CONTRIBUTIONS

D. Frianto was responsible for collecting field data surveys, conducting formal analysis of Landsat satellite imageries, conceptualization of the manuscript, consolidation of the required data, drafting, and revising the manuscript. E. Sutrisno collected field data surveys, involved in the conceptualization of the manuscript, consolidation of the required data, drafting, and revision of the manuscript. A. Wahyudi collected field data surveys, involved in the conceptualization of the manuscript, consolidation of the required data, and revision of the manuscript. E. Novriyanti field data surveys, involved in the conceptualization of the manuscript, consolidation of the required data, drafting, and revision of the manuscript. H. Kurniawan collected field data surveys, involved in the conceptualization of the manuscript, consolidation of the required data, drafting, and revision of the manuscript. A.S. Yunianto was involved in the collection of field data surveys, conceptualization of the manuscript, consolidation of the required data, and drafting of the manuscript. H. Khotimah was coordinating the Project activities and data collection, conceptualization of the manuscript, consolidation of the required data, and drafting of the manuscript. A. Windyoningrum was the coordinator of the Project activities and data collection, arranging and leading the discussion to conduct the activities and drafting the manuscript. W.C. Nugroho provided scientific input in study methods, collecting data, recommendations to concept the manuscript, drafting, and revising the manuscript. I.W.S. Dharmawan provided scientific input in study methods, collecting data, recommendations to concept the manuscript, drafting, and improvement of the manuscript. H.L.Tata provided scientific input in study methods, collecting data, recommendations to concept the manuscript, and improvement of the manuscript. S. Suharti provided scientific input in study methods, collecting data, recommendations to concept the manuscript, and improvement of the manuscript. H.H. Rachmat provided scientific input in study methods, collecting data, recommendations to concept the manuscript, and improvement of the manuscript. E.M. Lim reviewed and edited the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
ΔC	Annual change in carbon stock in each pool
K	Kelvin
A	Carbon stocks per land cover
AFoCO	Asian Forest Cooperation Organization
A0	The area at the time of initial observation
A1	The area at the subsequent observation
AB	Aboveground biomass
AGB	Aboveground biomass
B	Annual activity data/land cover area
Bov	Overall vegetative biomass
C	Amount of carbon stored
CART	Classification and regression tree
cm	Centimeter
cm/year	Centimeter per year
CO_2	Carbon dioxide
Corganic	Default carbon fraction, using a carbon content of 0.47 kgC per kg of dead matter
Ct1	Carbon stock in each pool at the beginning of the observation
Ct2	Carbon stock in each pool at the end of the observation
Cv	Carbon content in kilogram of vegetation biomass
DBH	Diameter at breast height
E	East
FOLU	Forestry and other land use
FFG	Forest farmer group
GGE	Google earth engine
GIS	Geographic information system
Gt	Gigaton

GtC	Gigaton carbon
IPCC	Intergovernmental panel on climate change
KgC	Kilogram carbon
kJ/m²/d	Kilo joule per square meter per day
mm	Millimeter
mm/year	Millimeter per year
MoEF	Ministry of Environment and Forestry
MPTS	Multipurpose tree species
m/s	Meter per second
N	North
NDC	National determined contribution
PRA	Participatory rural appraisal
PTH	The change in forest/land cover per year in a certain period
RSP	Regional spatial plans
SE	Standard error
SNI	Standard Nasional Indonesia (Indonesian National Standard)
SPFA	Specific purpose forest area
T0	Year of initial observation
T1	Year of subsequent observation
tC	Ton carbon
TOA	Top of atmosphere
USGS	United States Geological Survey

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