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ORIGINAL RESEARCH ARTICLE

Estimation of mangrove carbon stocks using unmanned aerial vehicle over coastal vegetation

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ABSTRACT

BACKGROUND AND OBJECTIVES: *Mangroves play a crucial role in mitigating climate change by absorbing carbon stocks. However, there is a lack of information on mangrove distribution and their carbon absorption abilities. Therefore, this study aimed to bridge this gap by gathering data on the ability of mangrove forest areas to absorb carbon stocks. Specifically, this study aims to assess the carbon absorption potential of the Lantebung mangrove ecosystem through field surveys, allometric calculations, and unmanned aerial vehicle imagery.

METHODS: *The methodology employed in this study consisted of field surveys, allometric calculations, and multispectral aerial imagery processing along the coastal of Makassar City, South Sulawesi, within the Lantebung mangrove ecosystem. Field surveys were conducted to determine the species composition of each mangrove stand and measure their diameter at breast height. The allometric formula was then used to calculate mangrove biomass, which was subsequently converted into carbon stock values. Aerial imagery was processed using the normalized difference vegetation index, followed by a regression analysis between normalized difference vegetation index and carbon stock values to obtain a carbon stock estimation model.

FINDINGS: *The results of the analysis of red-green-blue aerial imagery from the multispectral unmanned aerial vehicle has provided valuable insights into the extent of mangrove vegetation cover in the Lantebung mangrove forest area, revealing it to be 14.18 hectares. The normalized difference vegetation index results indicated that mangrove objects fall within a value range of 0.21–1, categorized into three density classes: high-, medium-, and low-density mangroves. The field surveys confirmed the presence of three types of mangroves in Lantebung Makassar, namely Rhizophora apiculata, Rhizophora mucronata, and Avicennia sp. The regression analysis conducted to assess the relationship between the normalized difference vegetation index value and carbon stocks yielded the equation model carbon stock = 474.61, vegetation Index value + 17.238, with a linear regression value of 0.7945. The carbon stock values for low-density class mangrove areas were predicted to range between 17.24 and 288.64 tons carbon per hectare, medium-density mangroves' carbon stocks to be between 126.04 and 391.14 tons carbon per hectare, and high-density mangrove areas' carbon stocks to range from 258.04 to 491.85 tons carbon per hectare.

CONCLUSION: The utilization of drones as a technique for monitoring carbon stocks has offered significant benefits. Drones equipped with multispectral sensors enable the collection of precise and comprehensive data on vegetation and elevation in many ecological systems. The survey and subsequent analysis highlighted the wide variation in the density of mangrove forests in the Lantebung mangrove ecosystem. This study demonstrated a strong correlation between the normalized difference vegetation index extracted using unmanned aerial vehicle and mangrove carbon levels obtained [illegible] measurements.

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INTRODUCTION

Mangroves contribute to fostering a flourishing environment in several ways: physical (trapping sediment, protecting land from storms and floods, and stabilizing shoreline geomorphology), ecological (providing habitat flora and fauna and controlling pollution), and economic (serving as a habitat for commercial fisheries) (Barbier, 2017; Basyuni *et al.,* 2021; Sumarga *et al.,* 2023). One significant environmental contribution of mangroves is their function as a blue carbon ecosystem, which is a coastal ecosystem that absorbs and stores carbon over the long term (Taillardat *et al.,* 2018). Mangroves have the ability to store biomass made up of dead plant parts like stems, branches, and litter that accumulate on the ground (Eslamdoust and Sohrabi, 2018). Additionally, mangroves play a crucial role in mitigating global climate change, primarily through carbon sequestration in coastal areas, and are effective on both national and regional scales (Alongi, 2020). Mangrove ecosystems are pivotal in sequestering and storing carbon, a key factor in mitigating climate change impacts. Quantifying the carbon stored in mangroves is essential to understanding the crucial role mangrove ecosystems play in mitigating climate change. Moreover, data on carbon storage can serve as an indicator of successful mangrove rehabilitation efforts, leading to wider public support for mangrove protection. The excessive amount of carbon dioxide (CO_2) in the atmosphere is a significant trigger for global warming. Deforestation is a leading cause for this excessive amount of CO_2 in the atmosphere, functioning as CO_2 sinks (Segaran *et al.,* 2023). Mangrove forests can absorb and reduce CO_2 from the air, with absorption rates reaching 77.9%. This absorbed carbon is stored in the form of biomass within the leaves, stems, and soil (Dewiyanti *et al.,* 2019). Despite being at the frontlines of climate change mitigation in tropical seas, mangroves still face a serious problem due to their vulnerability to logging (Dewiyanti *et al.,* 2019). Indonesia, a nation composed of over 17,504 islands, is home to the world's largest mangrove forest, spanning 2.7 million hectares (ha) in 2020 (Basyuni *et al.,* 2022). Unfortunately, the global rate of mangrove destruction is estimated to be between 0.7 and 3% per year (Richards *et al.,* 2016). In 1980, Indonesia's coastline, stretching over 95,000 kilometers, contained 4.2 mega hectares (Mha) of mangrove forests. However, by 2005, this mangrove forest cover had decreased to 2.9 million ha. Data from the Food and Agriculture Organization (FAO) reveals that Indonesia experienced a cumulative loss of 30% of its mangrove forests from 1980 to 2005, corresponding to an annual deforestation rate of 1.24% (Mudiyarso *et al.,* 2015). A recent study indicated that the country's mangroves faced a net deforestation rate of 12,818 ha per year from 2009 to 2019 (Arifanti *et al.,* 2022). The primary driver of mangrove conversion in Indonesia is for aquaculture activities, leading to carbon loss from the mangroves themselves and a 48% depletion of soil carbon stocks (Hashim *et al.,* 2021); by 2012, only 22.6% of mangroves had been regrown (Dewiyanti *et al.,* 2019). The drivers of mangrove deforestation in Indonesia from 2009 to 2019 varied by region, with conversion for aquaculture accounting for 31%, agriculture for 19%, infrastructure development for 3%, and conversion into low-statured vegetation for 46% (Arifanti *et al.,* 2021; Arifanti *et al.,* 2022). The ongoing deterioration in the functionality of mangrove forests is leading to various negative consequences, such as increased carbon emissions, loss of biodiversity, heightened vulnerability to erosion and land subsidence, and diminished livelihoods within communities (Cahyaningsih *et al*., 2022). This degradation can be predominantly attributed to population growth and land use change, especially on the southern coast of South Sulawesi. The preservation of mangrove forests is crucial for the future protection of the megapolitan area in South Sulawesi Province, namely the Mamminasata Region, which includes Makassar City and several other satellite districts, including Maros, Gowa, and Takalar regencies. Based on data obtained from the map of the distribution of changes in Indonesian mangrove forests during the 2016–2017 period by the Center for Utilization of Remote Sensing of the National Aeronautics and Space Institute, the area of mangrove forests on the southern coast of South Sulawesi decreased from 874.58 ha in 2016 to 754.91 ha in 2017. This reduction greatly contributes to an increase in CO_2 concentrations in the atmosphere. The Lantebung mangrove forest area stands as the last remaining mangrove forest in Makassar City, boasting healthy mangrove conditions. Since 2010, the Makassar City government and local community have been actively planting mangroves along the coast, aiding in increasing the number of individual mangroves each year. However, data on mangrove distribution and carbon stock potential in the Lantebung mangrove forest area is still scarce. The levels of mangrove carbon stock can be estimated using remote sensing technology. Remote sensing serves as an effective method for monitoring and estimating mangrove carbon, particularly when applied to larger areas, resulting in significant time and cost savings (Hamilton *et al.,* 2016). Global organizations such as Ikonos, Quickbird, and Worldview provide free downloadable high-resolution satellite imagery (Malik *et al.,* 2017). Very high spatial resolution (VHSR) optical satellite images offer essential information that can aid in tree identification and the differentiation of mangrove species (Viennois *et al.,* 2015; Proisy *et al.,* 2018; Viennois *et al.,* 2016). However, the use of VHSR comes with several disadvantages, such as cloud cover constraint and low flexibility in terms of acquisition time and coverage area. Alternatively, unmanned aerial vehicle (UAV) imagery has been used to analyze the extent of mangrove vegetation (Malik *et al.,* 2017) for aboveground biomass (AGB) estimation (Basyuni *et al.,* 2023) and mangrove species classification (Tian *et al.,* 2017). Wirasatriya *et al.* (2022) investigated mangroves' AGB and carbon stocks using UAV imagery in conjunction with field research. The ability to adjust the height of image acquisition when using a drone allows for highly detailed photo resolution (Sun *et al.,* 2023). The investigation into carbon stocks involved the application of a combination of vegetation index methodology and statistical regression analysis to estimate and distribute them. The biomass values of mangrove forests were then obtained through the utilization of allometric equations. Following the determination of biomass quantity, a regression model was constructed incorporating a vegetation index (Siddiq *et al.,* 2020). This study aims to assess the carbon stock of the Lantebung mangrove forest using UAV multispectral aerial photography to generate a vegetation index estimating the distribution of carbon stocks in the area. The study was conducted in the Lantebung mangrove forest on the northern coast of Makassar City in 2023.

MATERIALS AND METHODS

Study area

The Lantebung Mangrove Area spans two sub-districts within Makassar City, namely Biringkanaya Sub-district (covering Untia Village) and Tamalanraea Sub-district (covering Bira and Parangloe Villages), situated at 5°3'24.60" - 5°5'16.95 "S latitude and 119°27'7.97''-119°29'13.01 "E Longitude. Data on average rainfall and temperature conditions from 1993 to 2023 were sourced from the Merra 2 Climate Satellite. The mangrove species found in this area include *Rhizophora apiculata*, *Rhizophora mucronata*, and *Avicennia* sp. (Fig. 1).

Research stage

The methodology employed for estimating carbon stocks in the Lantebung mangrove forest area involved various stages. This included calculating carbon stocks above the surface using UAV multispectral aerial photographic images, conducting field surveys for the identification of mangrove species and their diameters, estimating biomass and carbon, and creating carbon stock distribution maps. During the field survey, key parameters such as species composition, diameter at breast height (DBH), and mangrove biomass were assessed. These variables are essential in the calculation of carbon stock values (Fig. 2).

Data analysis

Field data collection

Field data collection was carried out in late September 2023 as part of our study. This step involved two primary activities: taking aerial photographs and measuring mangrove vegetation at 30 designated sample points in the field. In terms of remote sensing techniques utilized during the fieldwork, the flight altitude was set at 120 m, with a front and side overlap percentage of 75%. The camera angle was positioned at 90° and image capture took place between 8:00 am and 10:00 am and 4:00 pm and 5:00 pm. The flying speed ranged from 15 to 20 m/s, with the area divided into 10 missions, each covering approximately 25 to 29 ha. For aerial photography, we employed a Da-Jiang innovations (DJI) Phantom 4 Multispectral UAV fitted with a red-green-blue (RGB) camera and a multispectral camera array with five global shutter cameras covering blue, green, red, near-infrared (NIR), DJI, and infrared bands. The flight altitude for image capture was set at 120 m with a camera angle of 90° and front and side overlap percentage of 75%. The flight speed was estimated at

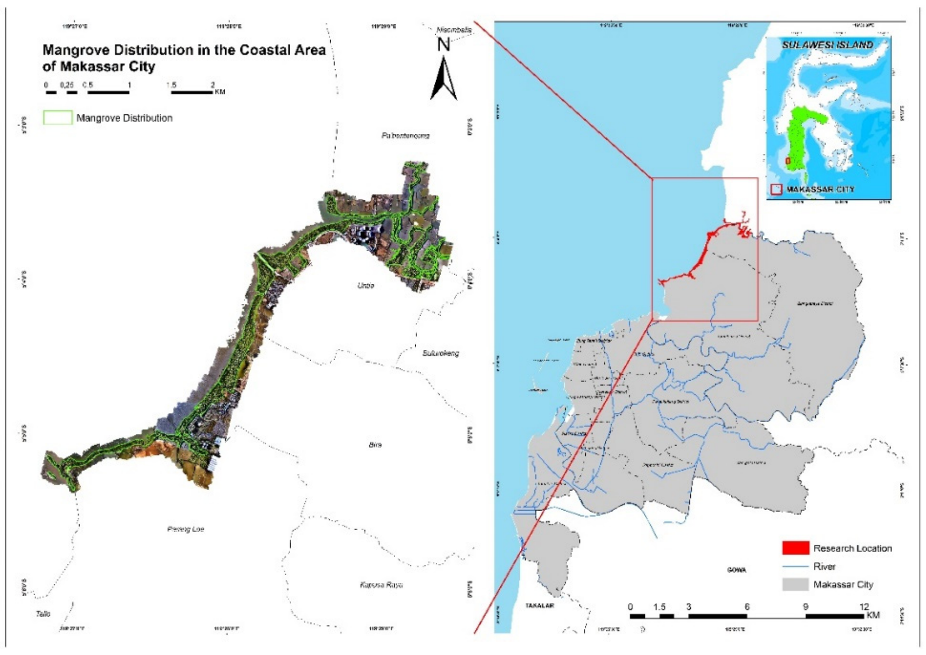

Fig. 1: Geographic location of the study area in Indonesia's Lantebung mangrove forest in Parangloe, Bira, and Untia villages

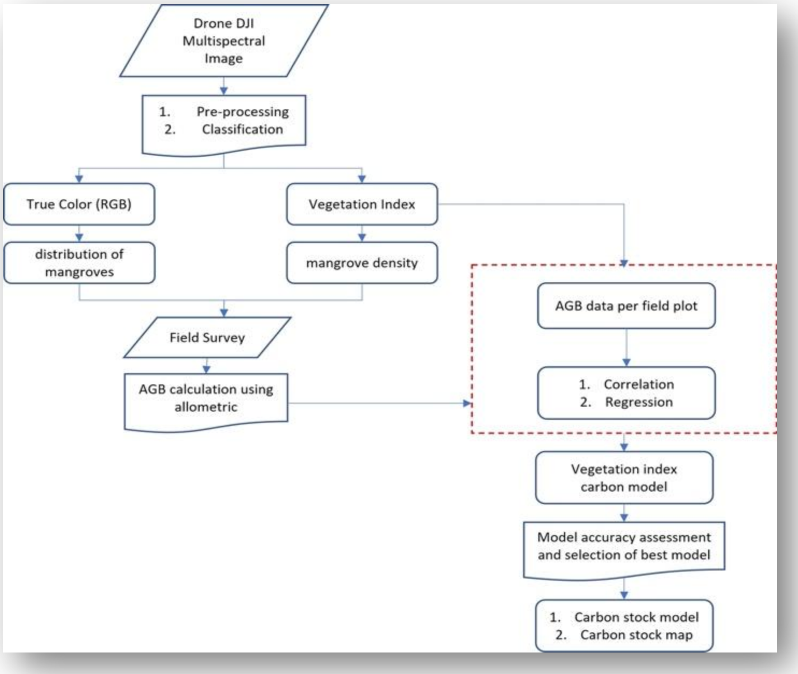

Fig. 2: The study framework for mapping mangroves' carbon stock using multispectral drone/UAV

Table 1: NDVI classification for vegetation density

Class	Value Range	Classification
1	−1.00–0.00	Clouds and Water
2	0.00–0.21	Non-vegetation
3	0.21–0.42	Low Density
4	0.42–0.63	Medium Density
5	0.63–1.00	High Density

20 m/s and image capture took place between 08:00 and 10:00 hours and 16:00 and 17:00 hours Central Indonesian Time. The selection of field sample plot points was carried out using the purposive sampling method, based on the level of mangrove density levels from the normalized difference vegetation index (NDVI) vegetation index. The sample plot size adhered to the Indonesian National Standard Number 7724/2019, based on the measurement and calculation of land-based carbon stocks, measuring 20 X 20 meters (m) in a square shape. To identify mangrove species and calculate carbon stocks, we utilized allometric equations to estimate biomass (Zulkifli *et al.,* 2021). The assessment of carbon stock involved the examination of several dimensions of mangrove species, including diameter and height (Andari *et al.,* 2023). DBH measurements were taken at three different locations: tree level, where the stem diameter was less than 10 cm and the size was 20 x 20 m; stake level, where the stem diameter was between 2.1 cm and 10 cm and the size was 10 x 10 m; and seedling level, where the stand height was less than 2 cm and the size was 5 x 5 m. Sampling mangrove species involves quantifying biomass within the subsoil, specifically the stem. Tree samples are measured in parallel with the DBH, which is situated at an elevation of 1.3 m above ground level. Additionally, the allometric formula is employed in data processing to determine the biomass beneath the surface, specifically in the stem (Baderan *et al.,* 2017).

UAV data processing and image classification

UAV data processing was conducted to extract the RGB aerial imagery data and compute the NDVI. The data processing was performed using the Agisoft Metashape application, which involved various stages including the Add Photo and Align Photo to Build Dense Clouds, Build Mesh, Build Texture, and Build Orthomosaic. The processing of RGB aerial imagery was required to identify the distribution of mangroves in the Lantebung mangrove forest area. Visual mangrove identification is a task that involves the interpreter's ability to recognize objects—assisted by image interpretation elements—based on color, texture, size, shape, pattern, shadow, and association (Situmorang *et al.,* 2016). The NDVI processing was carried out to determine a mangrove stand density level, which was then used to establish the distribution of sample plots and carbon stocks. Based on research by Tran *et al.* (2022), the NDVI index was determined to be the most extensively utilized measure in the study of mangroves. According to Laksono *et al.* (2020) and Razali *et al.* (2020), NDVI is divided into four classifications for vegetation density (Table 1).

Estimation of above ground carbon

The biomass values are calculated using allometric equations 1, 2, and 3 to obtain the value of carbon stocks above the surface in mangrove forests (Komiyama *et al.,* 2005):

1. *R. apiculata*

$$B = 0,0275(DBH)*3,22 \tag{1}$$

2. *R. mucronata*

$$B = 0,128(DBH)*2,60 \tag{2}$$

3. *Avicennia* sp.

$$B = 0,308(DBH)*2,11 \tag{3}$$

Here, B is the biomass in kilogram (kg) and DBH is in cm.

The carbon stock values were calculated using biomass values based on the Indonesian National Standard No. 7724 of 2019 on the measurement and calculation of land-based carbon stock, using Eq. 4 (Komiyama *et al.,* 2005):

$$C_v = B_{ov}\, x\, \%C\, organic \tag{4}$$

Here, C_V is the carbon content of biomass (kg), B_{ov} is the total biomass (kg), and % C organic is the percentage value of carbon stock, which is 0.47.

Carbon stock distribution

The carbon stock distribution map was created based on a statistical regression model. The relationship between aboveground carbon stocks and NDVI values was analyzed using a mathematical equation (Eq. 5) with a linear regression model (Jin *et al.,* 2020):

$$Y = a + bX \tag{5}$$

Here, Y is the carbon stock (ton C/ha), X is the vegetation Index value, and *a* and *b* are the coefficient values.

The Pearson correlation coefficient quantifies the magnitude and direction of the linear association between two numerical variables that fall within a specific interval (Baak *et al.,* 2020). Gunawan *et al.* (2023) indicates that values of the coefficient of determination falling between 0.00 and 0.199 are considered extremely low. Additionally, the values between 0.20 and 0.399 are considered low, between 0.40 and 0.599 medium, between 0.60 and 0.799 strong, and between 0.80 and 1.000 very strong. The linear regression model obtained was used to create a carbon stock distribution map using a geographic information system (GIS) software and the Map Algebra tool or Raster Calculator. Furthermore, to obtain the value of carbon stock per density, an analysis was carried out using the Zonal Statistics table in the GIS software, where the mangrove forest density level raster and carbon stock raster made previously constituted the data entered. The study employed a regression analysis between NDVI values and carbon stocks to develop a carbon stock estimation model, facilitating a detailed examination of their relationship.

RESULTS AND DISCUSSION

Image classification and extraction of mangrove forests

The results of the interpretation of RGB aerial imagery from the multispectral UAV revealed the extent of mangrove vegetation cover in the Lantebung mangrove forest area as 14.18 ha. Mangrove delineation interpreted in the study area was then analyzed to determine the level of mangrove density. Based on the NDVI transformation results, the index value for mangrove objects was obtained; the value range was between 0.21 and 1. The NDVI data on the image was analyzed, and subsequently, the mangroves were split into three density classes: high, medium, and low. The results are presented in Fig. 3 and Table 2.

Identified mangrove species characteristics

Based on the field survey results, three species of mangroves were identified in Lantebung Makassar, namely *R. apiculata* found in plots 1, 2, 3, and 4 (4 plots), *R. mucronata* found in plots 6, 7, 8, 9, 10, 11, 21, 22, 23, 24, 25, 28, and 29 (13 plots), and *Avicennia* sp. found in plots 2, 5, 6, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 26, 27, 28, and 30 (21 plots). The diameter of each species of mangrove varied, ranging from 2.55 cm for *Avicennia* sp. to 43.31 cm for *R. apiculata*. Data on the mangrove vegetation prevalence (numbers) and characteristics in the various observation plots are presented in Table 3.

Table 3 presents the prevalence numbers for each species, with the highest being *R. mucronata* (961), followed by *Avicennia* sp. (919) and *R. apiculata* (286). *Avicennia* sp. is a mangrove species that was found in 21 observation plots. However, the *R. mucronata* species was present in the highest numbers. Both species are true mangrove types located in the front zone with a 7 to 13 Part per thousand (PPT) salinity and a pool height of around 20 to 76 cm (Hilmi *et al.,* 2021). The area facing the sea is called the mangrove zone with a sandy mud substrate, which is covered with *R. mucronata* and *Avicennia* sp. (Yuliana *et al.,* 2019). Meanwhile, the mid zone was mostly covered by *Rhizophora, Bruguiera, Ceriops, Lumnitzera,* and several species of *Avicennia* such as *A. alba* and *A. officinalis* (Rahmandhana *et al.*, 2022). *R. apiculata* is generally found in the middle zone with a salinity of 13.5 to 19.5 PPT and a pool surface height of 15to 57 cm (Hilmi *et al.,* 2021). The zonation description of temporal dynamics in diversity during successional processes offers insights into recent differences in forest species, structure, and their interactions with various ecological processes (Pimple *et al.,* 2022). *R. mucronata* is known to exhibit high density in the

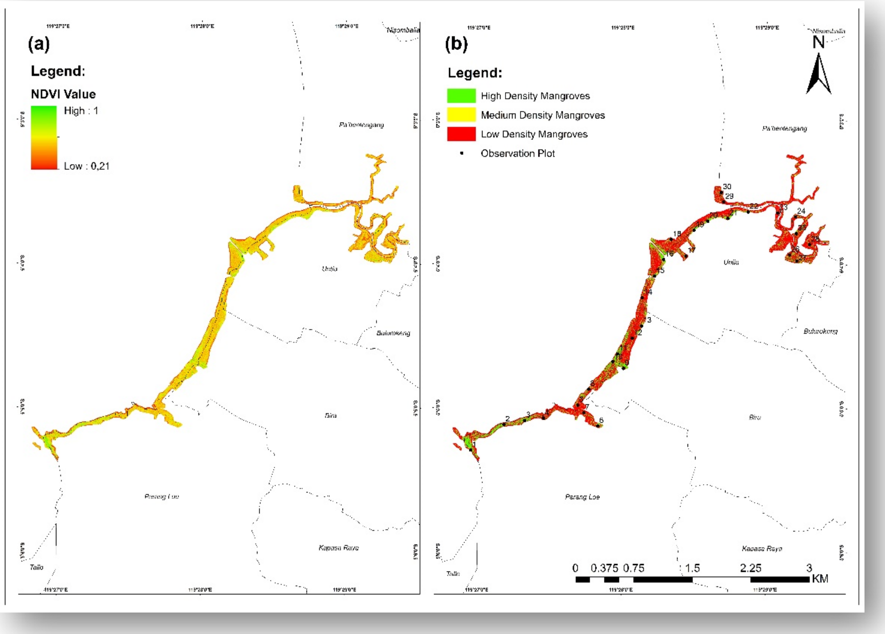

Fig. 3: (a) NDVI index from UAV multispectral and (b) mangrove density map

Table 2: Mangrove density distribution

No.	Mangrove density level	Area	
		ha	%
1	High density	0.69	5%
2	Medium density	2.41	17%
3	Low density	11.08	78%
Grand total		14.18	100%

South Sulawesi mangrove ecosystem. Its vegetation composition indicates strong substrate support for its growth, with soil types such as silt (dust) and clay playing supporting roles in the regeneration process. Clay particles, in particular, form mud that traps fallen fruit, significantly influencing mangrove density in the area. This favorable environment allows for the growth of a diverse range of mangrove species (*Avicennia marina*, *Avicennia alba*, *Rhizophora mucronata*, and *Avicennia officinalis*), highlighting the species' high adaptability to various environmental conditions (Windusari *et al.,* 2014). Among these species, *R. mucronata* stands out with its higher average height and diameter range compared to *Avicennia* sp. and *R. apiculata*. The tree's CO_2 sequestration capacity is directly linked to its biomass value and age, with larger trees absorbing more CO_2 (Muthmainnah *et al.,* 2021). The greater biomass resulting from photosynthesis not only influences the growth of both primary and secondary plants but also underscores *R. mucronata's* superior biomass compared to the two other species found on the coast of the Lantebung area of Makassar City. Mangrove vegetation has been verified in coastal regions across 124 tropical and subtropical nations, as well as certain warm temperate coastlines, spanning approximately 30° N to 30° S latitude (Bunting *et al.,* 2018). The growth and distribution/zoning of mangroves are significantly influenced by salt stress, which is determined by the salinity levels present in the substrate. The sodium/potassium (Na/K) ratios serve as valuable screening techniques

Table 3: Mangrove vegetation characteristics in each observation plot

Plot	Quantity per species			Average height (m)	Average diameter (cm)	Height range (m)	Diameter range (cm)
	R. mucronata	*R. apiculata*	*Avicennia* sp.				
1	-	94	-	11,23	9,74	5–13,5	2,87–22,61
2	-	40	7	7,63	11,69	3–14,3	3,82–43,31
3	-	94	-	8,07	9,52	5–10	3,18–25,48
4	-	58	-	10,48	11,34	4–13	4,46–22,29
5	-	-	53	11,22	16,83	6–13	6,05–35,03
6	6	-	74	10,71	11,78	5–13,5	4,14–34,39
7	50	-	-	9,28	11,18	6–10	4,78–21,02
8	53	-	-	8,87	10,71	5–10	4,7818,79
9	82	-	-	8,90	12,07	5–10	6,69–22,29
10	175	-	17	5,90	6,25	5–7	3,18–16,24
11	175	-	17	8,10	6,25	7,5–10	3,18–16,24
12	-	-	15	8,35	22,97	5–10,6	5,73–34,39
13	-	-	32	10,46	18,92	6–13,4	3,82–40,76
14	43	-	2	6,38	14,43	5–7	4,94–28,03
15	-	-	32	10,48	24,35	7–13	7,01–37,26
16	-	-	52	9,08	18,43	7–11	7,96–31,53
17	-	-	111	8,16	12,93	5–10	4,14–28,34
18	-	-	44	8,84	17,86	7,5–10	6,37–28,98
19	-	-	72	10,54	15,93	5,5–13	4,78–28,34
20	-	-	92	11,08	14,37	6–13	3,82–28,34
21	7	-	36	11,35	18,74	6–13	6,05–33,44
22	53	-	17	10,76	12,65	7–12	3,82–28,03
23	13	-	44	9,17	14,76	7,5–10,5	5,1–28,03
24	120	-	-	8,75	10,85	5–10	4,14–22,29
25	135	-	-	8,73	10,65	5–10	4,78–21,66
26	-	-	23	11,52	18,99	7–14	7,64–32,01
27	-	-	125	5,72	11,99	5–7	2,55–28,34
28	23	-	1	6,46	14,15	6–7	8,28–20,06
29	26	-	-	8,28	11,62	5–10	4,78–21,34
30	-	-	53	10,84	15,53	6–13	4,78–31,85
Grand total	961	286	919				

for assessing salt tolerance in mangroves at specific levels (Farooqui *et al.,* 2016). The co-enrichment of nitrogen (N) and phosphorus (P) has frequently demonstrated a higher yield of plant biomass compared to the individual addition of either N or P (Soons *et al.,* 2017). The biomass value represents the carbon content of a plant and serves as an indicator of its capacity to sequester CO_2 from the atmosphere. Plants absorb carbon from the atmosphere, which is then utilized for physiological functions and stored as cellulose in various plant structures, including leaves, twigs, branches, stems, and roots (Trissanti *et al.,* 2022). The *Rhizophora* genus is a mangrove species that exhibits adaptability to diverse environmental factors, including substrate composition, tidal patterns, salinity levels, and nutrient accessibility, hence allowing it to thrive in a wide range of habitats (Henri *et al.,* 2024). Preserving the mangrove ecosystem amidst environmental contamination from various sources requires a multifaceted approach. First, implementing stringent regulations to control pollution sources, such as agricultural runoff, industrial discharges, and urban wastewater, is crucial. Adopting sustainable agricultural practices, proper waste management, and treatment systems can significantly reduce the influx of contaminants into mangrove areas. Second, promoting community engagement and education on the importance of mangroves and impact of pollution can foster a collective effort toward conservation. Involving local communities in mangrove restoration projects and pollution monitoring activities enhances stewardship and accountability. Furthermore, establishing buffer zones around mangrove forests can mitigate the impact of terrestrial pollutants, serving as a physical barrier that filters out contaminants before they reach the mangroves. Restoration efforts should also consider the planting of mangrove species that have demonstrated resilience to pollutants, thereby enhancing the overall health and ability of the ecosystem to withstand environmental stressors. Moreover, continuous monitoring and research are essential to fully understand the extent and impact of contamination on mangrove habitats. This knowledge can inform adaptive management strategies that address emerging threats and ensure the long-term health and sustainability of mangrove ecosystems. Collaborative efforts between governments, non-governmental organizations, research institutions, and local communities are pivotal in effectively implementing these strategies.

Aboveground carbon stocks

The results of biomass calculations with the allometric equations were then used to calculate the carbon stocks in each plot. The carbon stock assessment assumed that 47% of the biomass is carbon. The amount of carbon stock is usually represented in tons C/ha. Based on the calculation results, plot 25 has the highest carbon value of 457.71 tons C/ha, while plot 11 has the lowest carbon value of 113.54 tons C/ha (Fig. 4). AGB values from several locations categorized based on species are depicted in Table 4.

Plot 11 exhibits a low carbon stock, primarily due to the prevalence of small diameter stands within the area. Small stands tend to have lower carbon stock compared to mature trees, as young stands are usually smaller in size and have not yet reached their full growth potential. The variations in carbon stocks across different geographical areas can be attributed to several factors such as the age of mangroves, soil fertility, growth of individual trees, species composition, biotic and abiotic factors, and the local climate; these factors distinguish restored mangroves from wild mangrove forests (Suprayogi *et al.,* 2022). The low carbon stock in plot 11 is due to the small diameter of the mangrove vegetation, which averages around 6.25 cm. In contrast, plot 25 exhibits a high carbon stock due to the substantial average diameter of 10.65 cm and a diverse array of mangrove species, totaling 135 trees. This high carbon stock is a result of the significant tree diameter and abundance of various mangrove species within the plot. According to Istomo *et al.* (2017), the number of trees, density, basal area, and volume of mangroves were directly proportional to carbon stock. Moreover, the location of the plots also plays a significant role in carbon stock levels. Plot 25, located in the inner part of the estuary and at a higher elevation, exhibits higher carbon stock compared to plot 11, which is located directly opposite the sea. This findings aligns with previous research by Komiyama *et al.* (2007), which suggests that carbon stock tends to be higher in inland mangroves than in areas near the sea. The carbon stock measured in this study reflects the amount of CO_2 removed from the atmosphere and stored by the mangrove trees in the study area throughout their growth. This highlights the crucial ecological service provided by the mangrove ecosystem in terms of climate regulation. Mangrove ecosystems act as significant carbon sinks, effectively sequestering carbon from the atmosphere and storing it in various forms. The carbon sources within mangroves include the biomass above and below the ground, encompassing living components like trees, shrubs, and understory vegetation, as well as non-living components such as litter and soil organic matter. The carbon sequestered

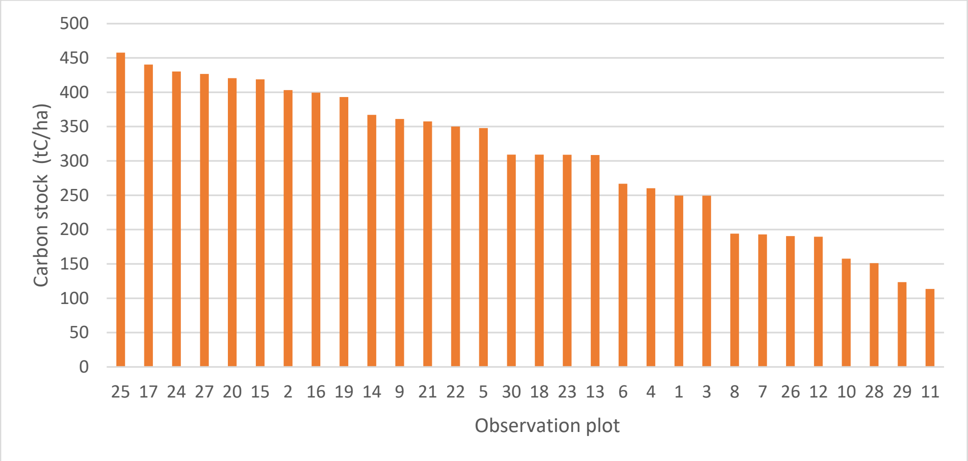

Fig. 4: Carbon stock level of Lantebung mangrove forest in each observation plot

Table 4: Comparison of AGB values obtained in Indonesia through field measurements

Sites	Dominant species	AGB (Mg/ha)	Sources
Rawa Aopa Watumohai National (RAWN) Park	*R. apiculata*	651.6	Analuddin *et al.,* 2016
	R. mucronata	232.1	Analuddin *et al.,* 2016
Baluran National Park, East Java	*Avicennia marina*	36.7	Zulhalifah *et al.,* 2021
Jor Bay, Lombok	*R. apiculata*	148.9	Zulhalifah *et al.,* 2021
Tritih, Central Java	*A. marina*	52.5	Widyastuti *et al.,* 2018
Mentawir Village, East Kalimantan	*R. apiculata*	55.2	Kristiningrum *et al.,* 2019
	R. mucronata	19.2	Kristiningrum *et al.,* 2019
Lubuk Kertang, Langkat Regency, North Sumatra	*R. apiculata*	8.76	Basyuni *et al.,* 2023
	R. mucronata	0.22	Basyuni *et al.,* 2023
	A. marina	0.22	Basyuni *et al.,* 2023
Pulau Sembilan Village, Langkat, North Sumatra	*R. apiculata*	3.25	Basyuni and Simanjuntak, 2021
	A. marina	2.42	Basyuni and Simanjuntak, 2021

by mangroves is utilized in several key processes and functions within the ecosystem:

Biomass growth

The carbon absorbed through photosynthesis from the atmosphere is used in the formation of new plant tissues, contributing to the growth and development of mangrove vegetation. This process enhances the ecosystem's capacity to store carbon over time, reinforcing its role as a carbon sink.

Soil formation and stabilization

Carbon in the form of dead plant material, such as leaves, branches, and roots, accumulates on the forest floor and gradually becomes incorporated into the soil. This organic matter contributes to soil formation, enriches soil fertility, and increases its capacity to store carbon. Additionally, the accumulation of carbon-rich sediments in mangrove soils plays a crucial role in stabilizing the coastal shoreline, preventing erosion, and maintaining the structural integrity of the ecosystem.

Habitat provision

The carbon stored in the biomass of mangrove ecosystems provides essential habitat and nourishment for a diverse array of species, including fish, crustaceans, and birds. The complex root systems of mangroves, enriched by carbon deposits, offer breeding and nursery grounds for marine and terrestrial species, supporting biodiversity and ecological balance.

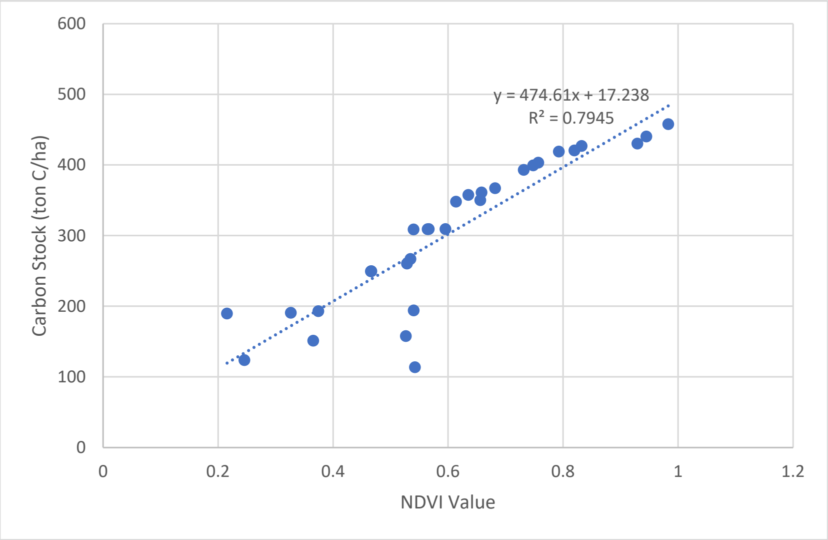

Fig. 5: Relationship between carbon stock and NDVI values using a linear regression model

Climate regulation

By sequestering and storing significant amounts of carbon, mangroves contribute to climate regulation and mitigate the effects of global warming. The reduction of carbon dioxide levels in the atmosphere helps in stabilizing global temperatures and diminishing the impacts of climate change. The results of the carbon stock calculation were analyzed using regression analysis, specifically employing a linear regression model to illustrate the relationship between carbon stock and NDVI values, as presented in Fig. 5.

The regression analysis results, as depicted in Fig. 5, reveal a quadratic relationship between the NDVI values and carbon stock: y = 474.61x + 17.238, with an R2 of 0.7945 or 79.45%. This strong correlation underscores the relationship between actual biomass values and NDVI values. The coefficient of determination of 79.45% indicates that the NDVI can account for changes or variations in carbon stock values, with the remaining 20.55% of the mangrove diversity explained by other variables. From the model, the distribution of mangrove carbon stock based on the NDVI images was conducted to determine the overall carbon stock at the study site. Carbon stock values were calculated based on the density of each mangrove forest to assess the potential value of carbon stock in each class of mangrove vegetation density, categorizing them into low dense, medium dense, and high dense classes. The low-density class has a carbon value that ranges from 17.24 to 288.64 tons C/ha, the medium-density class from 126.04 to 391.14 tons C/ha, and the high-density class from 258.04 to 491.85 tons C/ha. For further details on the distribution of carbon in the Lantebung mangrove forest area, please refer to Table 4 and Fig. 6. Furthermore, the developed model proves to be valuable tool for estimating the carbon stock of mangrove forests over time. Its high accuracy enables the prediction of future carbon stock levels based on UAV-derived NDVI values. The empirical data collected in this study serves as a crucial foundation for ascertaining the potential of mangrove ecosystems in storing carbon. By establishing current carbon stock baselines within the Lantebung mangrove ecosystem, we are able to create a reference point against which future changes can be measured. This data enables us to model carbon sequestration trajectories under various scenarios, including conservation efforts, restoration activities, and potential threats such as land-use change or climate variability. The integration of UAV technology, coupled with field survey data, offers a replicable method for the continuous monitoring of mangrove health and carbon storage capacity. By regularly updating this empirical dataset, we can track the effectiveness of conservation strategies and detect early signs of ecosystem degradation to adapt

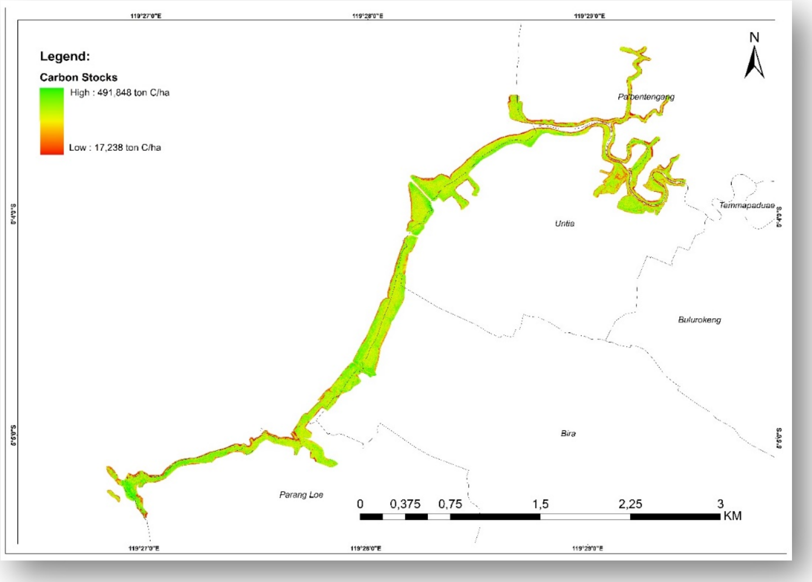

Fig. 6: Map of carbon stock distribution in Lantebung mangrove forest

management practices accordingly. Furthermore, this empirical data can be used to inform predictive models that simulate the impacts of environmental changes on mangrove carbon dynamics. These models can help explore the potential outcomes of different conservation and restoration scenarios, offering valuable insights for decision-makers and stakeholders on the most effective strategies to enhance the carbon storage function of mangrove ecosystems.

The Lantebung area boasts am average mangrove carbon content of 266.34 tons C/ha, covering a total area of 14.18 ha. This carbon stock surpasses that of restored mangroves in Lubuk Kertang (26.4 tons C/ha), Pulau Sembilan (42.5 tons C/ha), and North Sumatra (Basyuni *et al.*, 2023). The findings of this study reveal a total estimated carbon stock distribution of 3,776.63 tons. According to Chatting *et al.* (2020), estimating representative values is important to showcase the substantial carbon reserves within mangrove forests (Istomo *et al.*, 2017). The estimation of sustainable mangrove carbon stock is crucial in enhancing our understanding of mangrove ecosystems in the context of climate change. This study demonstrates the effectiveness of UAVs in precise and cost-efficient mangrove carbon mapping, particularly in areas where traditional ground-based methods are impractical. However, the study also acknowledges the limitations associated with UAV usage in large forest areas, such as flight time limitations, coverage limitations, operational expenses, weather sensitivity, and regulatory restrictions. A multi-stage mapping approach that integrates UAV data with moderate-resolution satellite imagery and ground measurements shows promise in overcoming these challenges. Further research is necessary to explore potential techniques for incorporating UAVs into broader-scale forest carbon mapping efforts at the provincial or even national level. Enforcing government action to maintain sustainable mangrove ecosystems involves strategic advocacy, policy recommendations, and stakeholder engagement. The findings of this study can be leveraged to advocate for the formulation and enforcement of comprehensive mangrove conservation policies. By presenting empirical data on the carbon sequestration capabilities and ecological value of mangroves, we can highlight their critical role in climate change mitigation and coastal protection. This underscores the importance of compelling government bodies to prioritize mangrove conservation in their environmental agendas. Engaging policy makers through workshops, seminars, and policy briefs that emphasize the study's

Table 5: Carbon stock values in Lantebung mangrove forest

Mangrove density level	Minimum carbon stock (ton C/ha)	Maximum carbon stock (ton C/ha)	Average carbon stock (ton C/ha)
High density	258.04	491.85	370.58
Medium density	126.04	391.14	261.46
Low density	17.24	288.64	166.97

outcomes and the long-term benefits of mangrove conservation can facilitate informed decision-making. Recommendations may include the establishing mangrove protected areas, implementing sustainable land-use practices, and integrating mangrove conservation into national climate action plans. Moreover, fostering partnerships with international environmental organizations can provide additional leverage and resources for mangrove conservation initiatives. Collaborative projects and funding opportunities can support the implementation of conservation strategies and promote best practices in mangrove management. Finally, developing monitoring and evaluation frameworks to assess the effectiveness of conservation policies is crucial for ensuring accountability and continuous improvement in mangrove management strategies. Regular reporting on the status of mangrove ecosystems and the impact of conservation efforts can maintain governmental and public awareness and support for sustainable mangrove ecosystem management.

CONCLUSION

The primary objective of this study was to assess the carbon stock potential within the Lantebung mangrove ecosystem using an integrated approach that combines field surveys, allometric calculations, and analysis of UAV imagery. The methodology of the study involved conducting field surveys to identify species composition and measure the DBH of mangroves. Allometric equations were then applied to estimate the biomass of the mangroves, which was subsequently converted into carbon stock values. Additionally, UAV technology was utilized to capture multispectral imagery, from which the NDVI was derived. This index was instrumental in classifying the mangrove vegetation into three density classes: high, medium, and low. Quantitatively, the results of the study revealed that the Lantebung mangrove ecosystem spans an area of 14.18 ha, with carbon stock values varying significantly across different density classes. Low-density mangroves exhibited carbon stock values ranging from 17.24 to 288.64 tons C/ha per hectare, medium-density mangroves ranged from 126.04 to 391.14 tons of C/ha, and high-density mangroves showed values between 258.04 and 491.85 tons C/ha. The regression analysis executed between NDVI values and carbon stocks yielded a model with a coefficient of determination (R^2) of 0.7945, indicating a strong correlation. This suggests that approximately 79.45% of the variation in carbon stocks could be explained by the NDVI values derived from the UAV imagery. Qualitatively, the study highlights the crucial role of mangroves in carbon sequestration and their significance in combating climate change. The meticulous classification of mangrove density and subsequent estimation of carbon stocks within these classes provide valuable insights into the spatial distribution of carbon storage within the ecosystem. Furthermore, the use of UAV technology has proven to be a highly effective tool for monitoring mangrove ecosystems, offering high-resolution data that significantly enhances the accuracy and efficiency of carbon stock assessments. In conclusion, this study demonstrates the effectiveness of integrating field surveys with advanced UAV imagery analysis to evaluate the carbon storage potential of mangrove ecosystems. The findings underscore the importance of mangrove conservation in climate change mitigation efforts and establish a robust framework for monitoring and managing these vital ecosystems. Future research should prioritize expanding the application of UAV technology for mangrove monitoring and exploring the implications of mangrove conservation on a larger scale, considering the global urgency to enhance carbon sequestration capabilities in response to climate change. This study serves as a useful guideline for estimating the amount of carbon storage using UAV over coastal vegetation, providing valuable information on carbon and AGB data throughout time. This data is necessary for tracking and assessing the success of initiatives linked to Indonesia’s forest and other land uses (FOLU) net sink 2030.

AUTHOR CONTRIBUTIONS

S.H. Larekeng wrote study proposal, designed sampling technique, analyzed and interpreted the data, wrote the manuscript draft, reviewed and edited manuscript text. M. Nursaputra designed sampling technique, analyzed and interpreted the data. M.F. Mappiasse designed sampling technique, collected field data, analyzed and interpreted the data. S. Ishak designed sampling technique, collected field data, analyzed and interpreted the data. M. Basyuni wrote the study proposal, reviewed and edited manuscript text. S.H. Larekeng wrote study proposal, reviewed and edited manuscript text. E. Sumarga designed sampling technique, collected field data, analyzed and interpreted the data. V.B. Arifanti interpreted data and prepared all the tables and figures. A.A. Aznawi collected references, prepared the manuscript, and organized the text. Y.I. Rahmila did the statistical analysis and paper editing. R. Rahmania reviewed and edited manuscript text. A. Mubaraq collected references, prepared the manuscript, and organized the text. S.G. Salmo reviewed and edited manuscript text. H.M. Ali reviewed and edited manuscript text. I. Yeni reviewed and edited manuscript text.

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CONFLICT OF INTEREST

The authors declare that there are 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, were observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
%C	percentage value of carbon stock
a and b	Coefficient value
AGB	Aboveground biomass
am	Ante meridiem
B	Biomass
Bov	Total biomass
C	Carbon
cm	Centimeter
CO_2	Carbon dioxide
Cv	carbon content of biomass
DBH	Diameter at breast height
DJI	Da-Jiang innovations
Eq.	Equation
FOLU	Forest and other land uses
GIS	Geographic information system
ha	Hectar are
K	Potassium
kg	Kilogram
km	Kilometer

m	Meter
m/s	Meters per second
Mha	Megahectare
N	Nitrogen
N	North
Na	Sodium
NDVI	Normalized difference vegetation index
NIR	Near-*infrared* spectroscopy
P	Phosphorus
pm	Post meridiem
ppt	Part per thousand
R.	Rhizophora
R2	coefficient of determination
RGB	Red-green-blue
sp.	Species
S	South
UAV	Unmanned aerial vehicle
VHSR	Very high spatial resolution
X	vegetation Index value
Y	Carbon Stock

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