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MORALITY BEFORE KNOWLEDGE

Socio-ecological perspectives on the carbon absorption process of tea plants (*Camellia sinensis*): Age-based estimates at Tambi plantation

Farras M. Yusa[1]*
[1] *Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada, Sleman, Yogyakarta 55281, Indonesia.*
*Correspondence: farrasmyusa@gmail.com

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ABSTRACT
Background: Understanding the ecological role of perennial plants such as tea (*Camellia sinensis*) is crucial for climate change adaptation and supporting sustainable rural livelihoods. Tea plantations have long been part of the socioeconomic fabric of mountain communities, providing economic benefits while also possessing the potential to contribute to carbon sequestration. This study aims to estimate carbon storage variations according to plant age at the Tambi farm unit in Wonosobo and explore its relevance to sustainable land management practices. **Methods:** Samples were collected using random sampling to represent each farm plot. Three plant and soil samples were collected for each tea tree age group (10 years, 30 years, 40 years, 100 years). Biomass and carbon content were analyzed for plant components (leaves, stems, roots, litter layer) and soil layers (0–10 cm, 10–20 cm, 20–30 cm). Relationships between soil physicochemical properties (organic carbon, particle size, bulk density) and carbon storage were also investigated, along with NDVI (Normalized Difference Vegetation Index) values. **Findings:** Total carbon storage increased with plant age, reaching 63.17 tons/ha in 10-year-old plants and 69.40 tons/ha in the 100-year-old plantation. The most influential factors affecting carbon storage were soil organic carbon, particle size, and bulk density. NDVI values (0.384–0.557) showed no strong correlation with plant age due to canopy density fluctuations caused by periodic pruning. **Conclusion:** Tea farms function as both economic assets and carbon sinks, demonstrating potential to support low-carbon agricultural development. Integrating carbon stock management into farm operations can enhance the environmental and social value of tea cultivation in mountain ecosystems. **Novelty/Originality of this article:** This study highlights the socio-ecological role of tea plants as a perennial crop contributing to climate mitigation and community sustainability. It provides new insights into reconfiguring traditional tea farm systems within modern low-carbon, sustainable land management frameworks.

KEYWORDS: carbon stock; NDVI; tea plant.

1. Introduction

Climate change is a significant issue for human life today, as it is related to socio-environmental changes (Azizah et al., 2019). Increasing concentrations of carbon dioxide and other greenhouse gases cause global warming and climate change (Balasubramanian, 2017). In 2022, global carbon dioxide emissions from fossil fuels and industry totaled 37.15 billion metric tons ($GtCO_2$) and are projected to increase by 1.1% in 2023, reaching a record high of 37.55 $GtCO_2$ (Basuki et al., 2018). Overall, global CO_2 emissions have increased by more than 60% since 1990 (Budhisurya et al., 2013). One way to reduce carbon emissions through the REDD (Reducing Emissions from Deforestation and Forest Degradation)

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scheme is through a system called MRV (Measurable, Reportable, and Verifiable) to document, report, and verify changes in land carbon stocks in a transparent, consistent, comparable, complete, and accurate manner (Chen et al., 2013). One satellite image used for forest biomass and carbon estimation is Sentinel-2A imagery with a 10-meter resolution (Dahlan, 2005). Higher resolution images can reveal smaller landforms, resulting in more accurate digitization results (Effendi et al., 2012).

Tea plants absorb carbon dioxide from the air during photosynthesis and store it in the form of biomass distributed in the roots, stems, leaves, and litter (Europen Space Agency, 2015). According to Ferdeanty et al. (2019) tea carbon reserves in Pagilaran Cooperation tea plantations averaged 32.8 tons C/ha. In research conducted by Fiantis et al. (2005), carbon reserves produced by tea plantations in the Mount Halimun National Park area were 22.13 tons/ha. Fitra (2020) obtained carbon reserves in Kerinci tea plantations using Sentinel-2A imagery, namely 1.33 tons/ha. Another study by Gatti & Bertolini (2015) found that the average carbon reserves in tea plantations in China ranged from 28.02 to 31.31 tons C/ha. In addition, measurements of carbon reserves in agroforestry tea plantations in Northeast India at the ages of 6.14 and 22 years were 44.8 ± 1.3, 50.2 ± 4.6, and 56.7 ± 4.9 Mg C/ha, respectively (Gebrehiwot et al., 2018). This study concluded that tea agroforestry systems store and sequester carbon, contributing to climate change mitigation in northeastern India (Handayanto et al., 2017). Soil carbon storage can increase soil organic matter content, which significantly impacts soil properties (Hikmatullah, 2010). According to Indrahayu & Setiawan (2023), carbon stored in soil can support pedological development, helping stabilize soil against erosion and creating pathways for greater water infiltration. It also forms organic matter that contributes to cation exchange and pH buffering. Carbon reserves are also a key determinant of soil biological activity, such as the diversity and activity of soil fauna and microorganisms, which are directly related to organic matter (Johan, 2001).

Tea is a suitable commodity for transforming towards low-carbon production because perennial crops like tea can absorb and store more carbon than seasonal crops (Lal, 2009). Variation in plant age at Tambi Tea Plantation Cooperation is thought to affect tea plant biomass and ultimately the stored carbon stock (Langi, 2011). Therefore, this study aims to estimate carbon stocks across several tea plant ages. The approach using satellite imagery is highly relevant as a basis for research on biomass and carbon estimation at the Tambi Plantation Unit, particularly in the General View Block. The phenomenon of global warming is increasingly worrying, requiring the global community to reduce GHG emissions (Mandala et al., 2020). In 2019, 22% of global greenhouse gas emissions, or 13 gigatonnes of CO_2, came from the agriculture, forestry, and other land use (AFOLU) sector (Mansyur et al., 2023). This data gap impacts the effectiveness of climate change mitigation strategies. Therefore, further research is needed to identify and understand the components that more deeply influence carbon stocks. Developing reliable methods is also crucial for efficiently measuring and monitoring carbon stocks.

In efforts to mitigate current climate change, research on the carbon stocks of tea plants is essential (Mardiana et al., 2018). Tea plants have long been considered an agricultural crop capable of storing carbon (Matchhavariani, 2019). Furthermore, the capacity to store carbon and associated emissions can be affected by changes in tea plantation management systems, such as increased production and changes in land use (Monde, 2009). Tea is a commodity that has the potential to reduce atmospheric emission concentrations (Nursanti et al., 2023). The Oktaviona et al. (2017) lists tea as a suitable commodity for transforming to low-carbon production. Depending on the plantation, according to Pang et al. (2019), tea plantations typically produce 0.4 to 1.5 tons of CO_2 per ton of tea produced. This figure is also influenced by several additional factors, such as fertilizer use, transportation during crop processing, and energy consumption. Tea, a perennial crop, can absorb and store more carbon than other annual crops (Putri & Wulandari, 2015). Carbon remains stored in plant biomass and soil organic matter as long as it is not cut down and decomposed (Ririska et al., 2023). Furthermore, tea cultivation does not require intensive land management, thus preventing damage to the carbon structure stored in the soil (Ruddiman, 2007). Carbon stock measurements are necessary to obtain data on the carbon reserves stored in a given area, allowing for the calculation of the extent to which tea plants and soil in the Pemandanan Block of the Tambi UP can store carbon.

2. Methods

The research carried out included direct field observation, soil sampling at various ages of tea plants using the drill and ring method, sampling of tea plants (leaves, stems, and roots), litter sampling, analysis of soil and vegetation samples in the laboratory, primary data processing, and preparation of the final report. The block number map of the Perkebunan Tambi Cooperation landscape is shown in Figure 1.

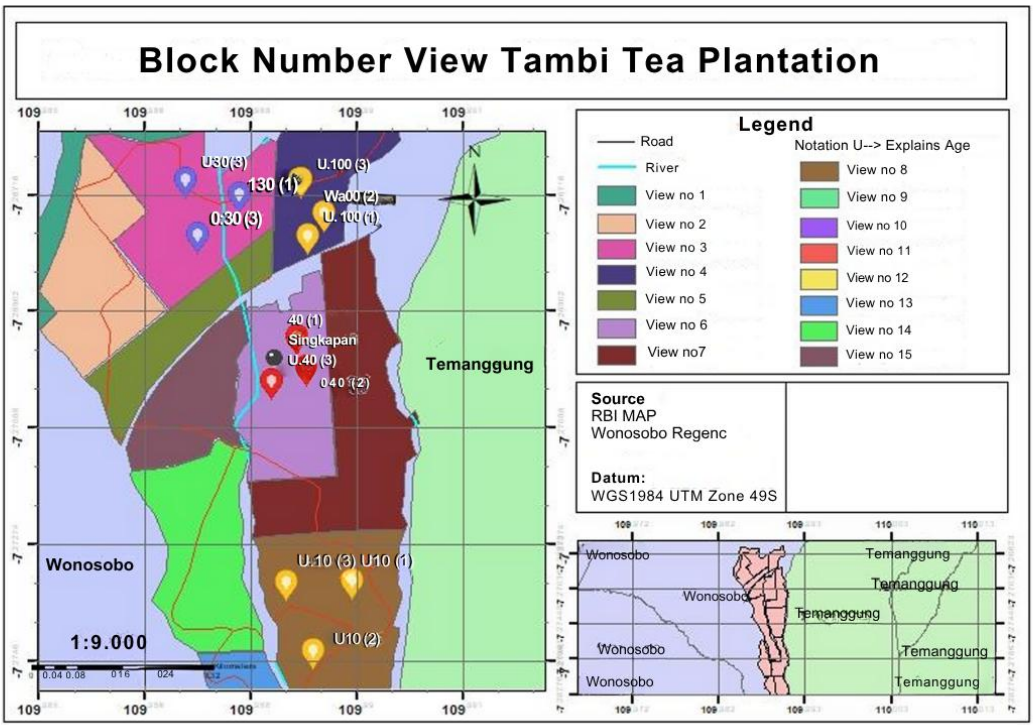

Fig. 1. Map of sampling points

The research tools and materials used covered all stages of the research activities, starting from field surveys, field observations, sampling, image analysis, and laboratory analysis. The tools and materials used for data collection and map creation are shown in Tables 1.

Table 1. Tools and materials for data collection

No	Tool	Utility
1.	Ground drill	Disturbed soil sampling at a depth of 0-30 cm
2.	Ring drill	Undisturbed soil sampling
3.	Pedology mix	Undisturbed soil sampling tool
4.	Ziplock Plastic	Storage place for soil and plant samples
5.	Clonometer	Reading slope and slope direction
6.	Stationery	Recording field results
7.	Dagger	Cleaning and taking soil samples
8.	GPS	Knowing the coordination of sampling points
9.	ArcMap Application	Creation of sampling and NDVI maps
10.	Avenza Maps	Knowing the coordinates and height of the sampling location
11.	Web Coppernicus	Source of Sentinel-2A imagery
12.	Hoe	Assist in taking soil and root samples
13.	Excel	Calculating field data results
14.	Branch shears	Plant sampling aids

2.1 Field survey, sampling method, and sampling techniques

The first step in conducting this research is to conduct a field survey and observation. Field surveys and observations are necessary to determine the location description and characteristics of the land, as well as the surrounding environmental conditions at the research site. The next survey and observation activities include interviews and questions and answers with the person in charge of the Tambi Plantation Unit to obtain recommendations for sampling points and information on the location and age of tea plants at Perkebunan Tambi Cooperation.

Data collection for this study began with soil and plant samples. Random sampling was used to select samples to represent a population. This data served as a reference for determining the age of the plants to be used in the study. The block numbers grouped the tea plants based on their age, as follows: 10-year-old tea plants were in block 8, 30-year-old tea plants were in block 3, 40-year-old tea plants were in block 6, and 100-year-old tea plants were in block 4. Soil samples were taken at three locations at each age range of the studied plants. At each location, soil samples were taken from each layer (0-10 cm, 10-20 cm, and 20-30 cm), resulting in a total of 36 soil samples. The random sampling method represented the age variation within the General View Block.

After conducting a field survey, side plots were identified under the guidance of a mentor from Perkebunan Tambi Cooperation. According to Hairiah et al. (2013), tea plant biomass measurements can be conducted using destructive or non-destructive methods. Non-destructive methods are used if the allometric formula of the plant species being measured is known, while destructive methods are used to develop allometric formulas, especially for tree species with unique branching patterns for which the allometric equation is generally unknown. Soil and plant samples were taken based on the age of the tea plants within the Tambi Plantation Unit, Tambi Tea Plantation Cooperation. At each location, plant and soil samples were taken at random depths of 0-10 cm, 10-20 cm, and 20-30 cm. Soil from the three locations was mixed at each depth (0-10 cm, 10-20 cm, and 20 cm-30 cm). The soil was then mixed and stirred evenly in a plastic bag (distubed soil sample) for testing soil texture, organic carbon, pH, and CEC. Some soil samples were taken using the ring method at each depth at each location (undisturbed soil sample) for soil volumetric weight (BV).

2.2 Measurement of biomass carbon stocks (tea plants and litter)

In tea plants, a destructive method is carried out by dismantling all parts of the tea plant including the stem, leaves, and roots. Next, the mixture of stems, leaves, and roots of the tea plant is weighed for its wet weight with a sample of 300 grams. The plant sample is dried at a temperature of 85°C for 48 hours in an oven until it reaches a constant weight. The plant sample is then weighed for its dry weight, the carbon reserves of the tea plant (leaves, stems, and roots) can be calculated after knowing the dry weight with the following formula:

$$Ctn = BK \ x \ Fraction \ C \tag{Eq. 1}$$

According to BSN (2011), the parameters used in the calculation include Cs, which represents the carbon reserves of tea plants measured in tons per hectare; BK, which denotes the dry weight or biomass expressed in kilograms; and the C Fraction, which is set at 0.47. The sampling process was conducted within a 1 m × 1 m plot located beneath the tea plant canopy. Each sample was first weighed to determine its wet weight, then oven-dried at a temperature of 85°C for 48 hours until a constant weight was achieved, ensuring that all moisture was removed. The estimation of carbon in dead organic matter was calculated using the formula proposed by Rusdiana and Lubis (2012).

$$Cs = BKs \ x \ 0.47 \tag{Eq. 2}$$

Next, the total carbon content of tea plants and litter per hectare is calculated using the following Equation 3. The calculation of carbon content in the litter pool was based on several parameters. Ct represents the organic carbon content of the litter, measured in kilograms, while Lplot refers to the area of each plot within the respective pool, expressed in square meters. The resulting value, Cs, indicates the carbon content per hectare in each carbon pool for every plot, measured in tons per hectare.

$$Cs = \frac{Ct}{1000} VS \frac{1000}{Lplot} \quad \text{(Eq. 3)}$$

2.3 Measurement of soil carbon stocks

Using a formula that refers to the national standardization body (2011), namely Equation 4. According to Sahfiitra (2023), the calculation of soil carbon stock at each depth involves several key parameters. Ct represents the soil organic carbon content measured in grams per square centimeter, while Kd denotes the soil mass in cubic centimeters. BV refers to the bulk density of the fine soil fraction with particles smaller than 2 mm, expressed in grams per cubic centimeter. Meanwhile, % Organic C indicates the percentage value of soil organic carbon content. These variables are then used to determine the carbon stock value at each soil depth.

$$Ct = Kd \ x \ BV \ x \ \%C \ Organic \quad \text{(Eq. 4)}$$

In the book written by Sahfiitra (2023), to obtain the carbon stock value at each depth (Ct) in tons/ha, a conversion must be carried out so that the units of C-organic content (COt) become 'ton C/ton' and the soil bulk density (the result of multiplying Kd and BV) becomes tons/ha.

2.4 Measurement of total carbon stocks

Using a formula that refers to the National Standardization Agency (2011), namely Equation 5. The total carbon reserve (Ctotal) is obtained by combining the carbon reserves contained in biomass and those found in the soil. In this calculation, Cn represents the carbon reserves per hectare derived from biomass (expressed in tons per hectare), while Ct denotes the soil organic carbon reserves per hectare. Together, these components provide a comprehensive estimation of the total carbon reserves in a given area.

$$Ctotal = Cn(Ctn + Cs) + Cland \quad \text{(Eq. 5)}$$

2.5 Soil sample preparation and soil analysis methods

Soil samples collected from each sampling point were prepared by air-drying. After the air-drying process, they were then sieved using 2 mm and 0.5 mm sieves. The sieved soil samples were placed in plastic bags and labeled, ready for laboratory analysis. Soil sample analysis was conducted at the Laboratory of the Department of Soil, Faculty of Agriculture, Universitas Gadjah Mada. Soil sample analysis used air-dried soil samples with a diameter of 2 mm and 0.5 m on disturbed soil and then the ring method with undisturbed soil samples.

The physical and chemical analyses carried out included. Soil physical analysis: Determination of Soil Texture by the pipetting method (Soil Research Institute, 2022). Determination of Soil Volume Weight by the Ring method (Soil Adjusted Vegetation Index, 2022). Soil chemical analysis: Determination of Soil Acidity Degree (pH H_2O and pH NaF) with a pH meter (BPSI Soil and Fertilizer, 2023). Determination of Organic C by the Muffle Furnace method (Soil Survey Staff, 2003). Determination of Cation Exchange Capacity (CEC) (Soil Survey Staff, 2014).

2.6 Image data processing

The imagery used in this study is Sentinel 2A satellite imagery sourced from the official Copernicus Space Data website. The imagery was taken at the PT Tambi tea plantation research site on October 28, 2023. The satellite imagery was selected on that date because it has a low cloud cover percentage of 9.3%. The Sentinel-2A imagery used in this study was not subjected to geometric correction, because the Sentinel-2A imagery used was the result of development of the geometrically corrected level 1C (Europian Space Agency, 2015). Radiometric correction is also not required in Sentinel-2A, which has been corrected and has a Bottom of Atmosphere reflectance value (Satohadi et al., 2022). NDVI is a mathematical combination of the red band and the NIR (Near Infrared Radiation) band which has long been used as an indicator of the presence and condition of vegetation (Sinaga et al., 2018).

$$NDVI = \frac{pIMD - pM}{pIMD + pM} \quad \text{(Eq. 6)}$$

The analysis uses two spectral channels, namely the Near Infrared (NIR) channel represented by pIMD (Band 8) and the Red channel represented by pM (Band 4). The values derived from these channels are then classified into five categories based on the Regulation of the Minister of Forestry of the Republic of Indonesia No. P.12/Menhut-II/2012, as presented in Table 2.

Table 2. Range of NDVI classification values

Class	NDVI	Information
1.	-1 to -0.1	Non-vegetated land
2.	-0.03 to 0.1	Very low vegetation
3.	0.15 to 0.25	Low vegetation
4.	0.26 to 0.35	Moderate vegetation
5.	0.36 to 1.00	Tall vegetation

2.7 Data analysis

Laboratory test results for each soil sample are in the form of raw data processed using Ms. Excel to calculate laboratory test results based on the formula for each parameter and the processed data can be displayed in tables, graphs, and bar charts. The sample point map that has been combined with the NDVI map will identify the pixel value at each sample point and be made in tabular form, then the accuracy of the Sentinel 2A image used can be determined. After that, a regression analysis is carried out to measure how much the independent variables are able to explain the dependent variable, where the independent variable is the NDVI value used and the dependent variable is the carbon content value in each sample.

3. Result and Discussion

3.1 Analysis of soil properties (physical and chemical) at varying plant ages

The results of the analysis of physical and chemical properties of the soil at the age of 10 years, 30 years, 40 years, and 100 years are explained in Table 3. Soil texture with values ranging from 16–20% for the clay fraction, 67–56% for the silt fraction, and 17-28% for the sand fraction. The texture of the research soil is classified as silty clay. The volume weight of the research sample soil has a value range of 0.56 to 0.69 g/cm^3. The soil pH consisting of pH H_2O with a range of 4.7–5.6 is classified as acidic and slightly acidic and pH NaF with a range of 10.33-11.68. The soil organic carbon content in the range of 8.45–1.74% is classified as very high. The soil CEC has a range between 8.71–16.20 cmol(+)/kg which is classified as low. The grading and determination of classes for each physical and chemical soil property is based on the assessment criteria of the technical guidelines for soil chemistry, aquatic plants and fertilizers (2023). The average values of soil laboratory tests on several samplings are shown in Table 3.

Table 3. Average values of soil laboratory tests at several sampling points

Age	Depth	Texture (%)			Bulk Density	pH		Organic C	CEC
	(cm)	Clay	Silt	Sand	(g/cm^3)	H_2O	NaF	(%)	(cmol(+)/kg)
10 years	0-10	16	56	27	0.64	4.65	11.40	9.52	10.23
	10-20	16	56	28	0.65	5.21	11..43	8.65	8.71
	20-30	15	59	26	0.69	5.27	11.48	8.45	12.08
30 years	0-10	17	60	22	0.59	4.71	11.30	10.92	11.77
	10-20	16	62	22	0.64	4.88	11.40	9.73	11.63
	20-30	15	66	19	0.66	5.69	11.68	9.15	10.79
40 years	0-10	12	67	21	0.56	5.37	10.33	11.74	14.33
	10-20	15	59	26	0.58	5.42	10.44	10.52	12.16
	20-30	15	67	17	0.61	5.24	11.25	10.04	11.85
100 years	0-10	20	61	19	0.57	4.93	11.00	11.25	16.20
	10-20	19	64	17	0.59	5.24	11.30	10.68	14.31
	20-30	16	65	19	0.64	5.60	11.41	9.85	10.62

3.1.1 Soil texture

The sand fraction has a diameter between 2-0.05 mm. The clay fraction has a smaller surface area, namely less than 0.02 mm. The soil fraction with a particle size between 0.02–2 mm is called the silt fraction (Siringoringo, 2014). Soil texture is an important characteristic that influences water, biological, chemical, fertility, erosion, microtopography, workability, aeration, and climate properties of the soil. To date, soil texture has been considered an important control for a number of soil processes, including structure development, carbon sequestration, nutrient retention (e.g., N), and water infiltration and storage (Sismiyanti et al., 2018). The diagram is divided into units of area that define various textural classes, and the soil is given the textural class name of the area in which the diagram is plotted.

The percentage of sand, silt, and clay particles in each soil depth and the age of the Tambi tea plants varied, ranging from 16–20% for the clay fraction, 67–56% for the silt fraction, and 17–28% for the sand fraction. Furthermore, Sorbu et al. (2021) also stated that the high silt content in Andisol soil is due to the presence of volcanic materials such as volcanic ash and lava, dominated by short-structured minerals, namely allophane, immogillite, and fehiferhydride. Volcanic ash consists of fragments measuring less than 2 mm to silt-sized and can compact when accumulated on the ground for a long time (Tisdale et al., 1999). This also aligns with the conclusion of Tiseo (2024), who stated that soil texture is not affected by land use type or age, as changes in soil texture require a considerable time span. Therefore, the texture class at the research site is the same for each tea plant age variation: silt loam. The silt loam texture influences the amount of organic matter in the soil. This statement is supported by research by Uthbah et al. (2017), who explained that soil with a silt loam texture has a larger surface area, allowing it to retain water and provide high levels of nutrients. The soil structure type found in the Tambi UP's Landscape Block across all age and depth variations is consistent: silt loam. This is consistent with research conducted by Wada (1989), which found that Andisol soils have a texture classified as silty loam, characterized by a general dominance of coarser particles.

The silt + clay fraction, as the finer particles in soil texture, in this study showed a higher ratio compared to the sand fraction. At each soil depth and across varying tea plant ages, the silt + clay fraction dominated the soil texture, accounting for more than 72–82% of each sample, in contrast to the sand fraction, which only ranged from 18–28%. The dust-to-clay ratio at this research site ranged from 3.4 to 4.3, indicating a very high value. The dust-to-clay ratio in this study indicates that the surface layer of the soil (0–10 cm) has a higher value than the underlying soil layer. This data is similar to research by Wowor (2013), which concluded that the dust-to-clay ratio is also higher in the upper soil layer. Wulansari et al. (2022) also added that the low dust-to-clay ratio in the lower layer is due to the weathering of the dust fraction into clay, with clay being added to the underlying layer due to illuviation. According to FAO (1990), a lower silt-to-clay ratio indicates more intensive soil weathering in the area. Therefore, it can be concluded that the soil conditions at the research location can be described as young soil that has not yet developed further.

3.1.2 Soil volume weight

Xia et al. (2020) stated that soil a high BV value will inhibit plant growth compared to soil with a low BV value, even with sufficient nutrient content. In addition, soil bulk density also affects soil porosity, where the higher the BV value, the lower the total pore space (Yaya et al., 2005). Therefore, the soil BV value plays an important role in estimating soil productivity and quality as well as carbon storage in the soil (Yusra et al., 2023). The graph of bulk density at different soil depths and plant age variations is shown in Figure 2.

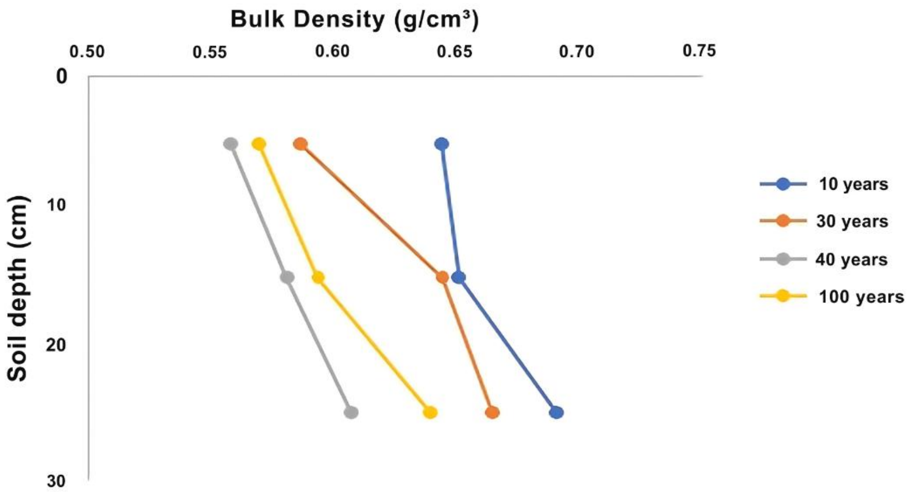

Fig. 2. Soil volume weight at different soil depths and variations in plant age

The average BV value at this research location was 0.66 g/cm^3 at 10 years old; 0.63 g/cm^3 at 30 years old; 0.58 g/cm^3 at 40 years old, and 0.60 g/cm^3 at 100 years old. These values indicate that the highest BV value is in tea plants aged 10 years. Yusra et al. (2023) stated that bulk density is one indicator of evaluating the possibility of roots penetrating the soil. However, there is an increase in the BV value at 100 years old. The increasing BV value at 100 years old occurs due to human activities such as walking on the topsoil. This occurs because the Tambi UP's Vista Block is a tourist attraction, and the 100-year-old block is one of the most frequently visited areas. The soil volume (BV) values at each soil depth and varying plant ages in the Tambi PT Vista Block ranged from 0.56 to 0.69 g/cm^3. This value is classified as low BV according to Xia et al. (2020) because the soil at the study site was formed from volcanic ash. BV values at the study sites ranged from highest to lowest, respectively, from 40 years, 100 years, 30 years, and 10 years.

The low BV values are attributed to the dominant amorphous mineral content, which results in a significant number of micropores, particularly intra-and inter-particle allophane (Yaya et al., 2005). Allophane particles are porous spheres, with diameters between 3 and 5 nm, resulting in a large surface area (specific surface area ranging from 400 to 900 m^2/g) and high porosity (Yusra et al., 2023). The highest soil BV values for each plant age range were found in the lowest layer (20-30 cm), at 0.57–0.64 g/cm^2. This was followed by a consistent increase in BV values with increasing soil depth. Soil bulk density is closely related to pore space, root penetration, microbial activity, and increased organic matter (Mansyur et al., 2023). The decomposition of various soil organic materials can reduce the soil's bulk density, reducing the compacted structure to crumbs, making it easier to work

(Mansyur et al., 2021). This research demonstrates that the levels of soil organic matter and organic carbon also increase in the topsoil.

3.1.3 Soil acidity (pH) H_2O and NaF

The actual pH value (H_2O) shows the amount of Hydrogen ion concentration (H^+) in the soil. Several factors influence the soil pH value, one example is the content of soil organic matter, soil cation exchange capacity, and soil clay fraction. The pH value (H_2O) of Andisol soils in Indonesia ranges from 3.8 – 6.4. Very acidic or very alkaline pH values can affect the availability of nutrients in the soil, which can cause element imbalances in plants. According to Uthbah et al. (2017), soil pH has an indirect effect on carbon reserves in the soil. Andisol pH affects the overall soil depth. Soil with a NaF pH value ≥ 9.4 indicates the presence of andic materials (allophane) that dominate the exchange complex. This is due to the relatively high content of amorphous allophane materials in Andisol, which is indicated by a high NaF pH. The image of the pH value of H_2O and NaF soil at different soil depths and variations in plant age is shown in Figure 3.

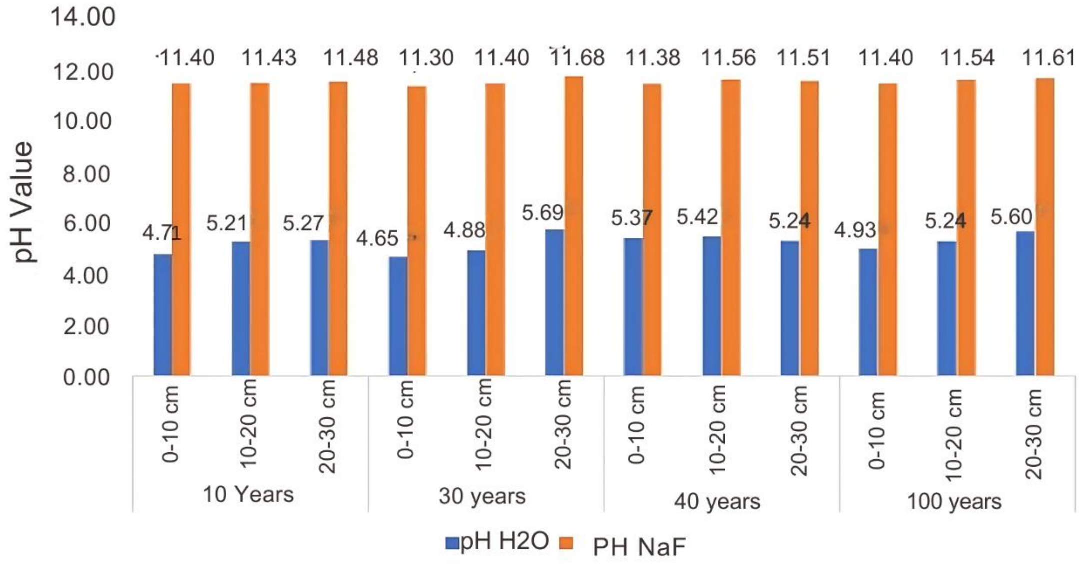

Fig. 3. pH values of H_2O and NaF in soil at different soil depths and plant age variations.

The pH values at each soil depth and varying plant ages in the Tambi UP's Vista Block ranged from 4.65 to 5.69 for pH H_2O and from 10.33 to 11.68 for pH NaF (Figure 3). The pH H_2O values at the study site were classified as slightly acidic to acidic. According to Ririska et al. (2023), acidic and slightly acidic pH values are caused by vegetation contributing organic matter through decomposing litter. The decomposition process typically causes a decrease in soil pH because it releases organic acids, which lower the pH (Ririska et al., 2023). The highest pH H_2O values were found in 30-year-old plants, at 4.65; and has the highest NaF pH value at 11.68. This is closely related to the abundance of allophane minerals in the soil. Soil pH also plays a role in allophane mineral formation (Wada, 1989). This finding is also supported by Fiantis et al. (2002), who stated that the availability of allophane minerals in the lower layers is greater than in the upper layers. Therefore, an increase in NaF pH in the lower layers will affect the pH of the soil.

The pH of the soil in the 0-10 cm layer for each age variation is 4.71 at 10 years, 4.65 at 30 years, 5.37 at 40 years, and 4.93 at 100 years. This occurs due to the higher concentration of H^+ and $Al3^+$ ions in the topsoil compared to the layers below, which are formed from the weathering of clay minerals. Acidic soils are usually dominated by Al, Fe, and Mn adsorption complexes (Ririska, 2023). The NaF pH values in the study showed uniformity, with the highest values in the lowest layer (20-30 cm). Plants aged 10 years, 30 years, 40 years, and 100 years, respectively, had NaF pH values of 11.48; 11.68; 10.44; and 11.61. The NaF pH of each plant age tended to have a higher pH value in the lower layer than in the upper layer. Stated that the high allophane mineral content in the lower layers is caused by the high amount of active Silanol (Si) and active Aluminum (Al) in the subsoil. The leached Si will be removed from the layer and accumulate in the lower layers.

3.1.4 C-Organic soil

Organic C, also known as soil organic carbon, originates from the decomposition of animals and plants, which serves to improve the physical and chemical properties of the soil, as well as increase fertility, productivity, and soil quality. The carbon cycle and climate change will also be affected by changes in the circulation of organic C in the soil. (Rusdiana & Lubis, 2012). High levels of soil organic C can improve soil physical properties, increase soil biological activity, improve mineral soil quality, and increase nutrient availability for plants. At higher temperatures, the increase in soil organic C stocks and decomposition will be faster, and will be lower at lower temperatures. Prasetyo (2005) stated that the organic carbon content of Andisol soils in Indonesia ranges from 6–15%. Figure 4 shows the organic carbon values of soil at different soil depths and plant age variations.

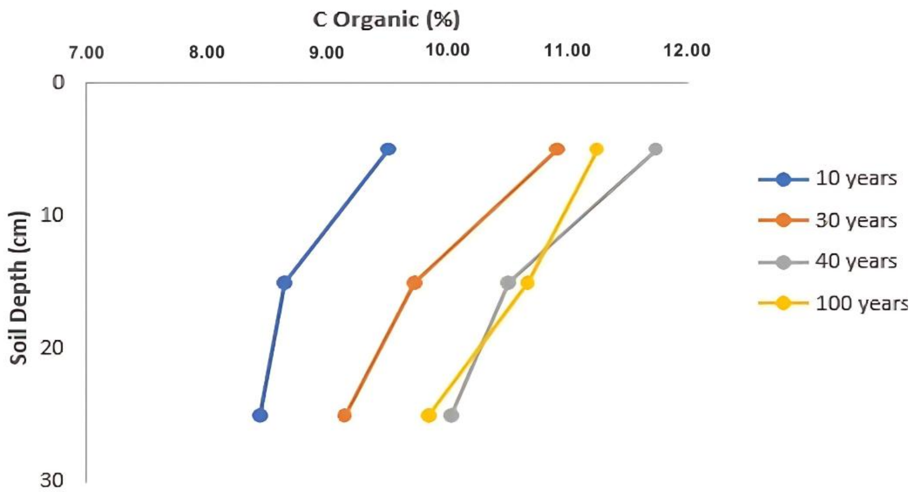

Fig. 4. Soil organic C value at different soil depths and plant age variations

The percentage of C-Organic in various plant ages has the highest value in sequence from 40 years, 100 years, 30 years, and then 10 years. Tea plants aged 40 years have a C-Organic content of 10.77%; then aged 100 years with a value slightly below that, namely 10.59; and ages 30 and 10 years respectively, namely 9.93% and 8.87%. Tea plants aged 10 years have the lowest C-Organic value compared to other plant ages because the amount of tea plant litter contribution to the soil is not as much as that of older plants. Litter is one of the contributors of soil organic matter, especially in the top layer. C-Organic will later become the main ingredient in the composition of soil organic matter. The C-Organic content of 40-year-old plants has a C-Organic value similar to that of 100-year-old plants. This is because the 40-year-old plant block has a large canopy density. The dense canopy of tea plantations protects the soil from direct rain impact, thus reducing the potential for soil erosion and loss of organic matter. Mardiana et al. (2018) stated that the biomass produced by necromass is greater than that of litter, which in turn contributes organic matter to the soil.

Organic carbon values at each soil depth and varying plant ages in the Tambi UP's Scenery Block ranged from 8.45 to 11.74%. The high organic carbon content is due to the Andisol soil type at the study site, which is pedogenically formed from mineral-rich volcanic ash and high accumulation of organic matter. Andisol soils with good aeration and soil respiration also enhance the performance of microorganisms, resulting in higher levels of organic matter production. Organic C values at different soil depths and ages at the study sites tend to be consistent, with the highest organic C levels in the upper layers and decreasing with increasing soil depth. The litter and animal remains on the surface then undergo a decomposition process to form humus and mix with the topsoil. Furthermore, organic matter decomposition occurs more rapidly due to climatic factors such as better temperature, humidity, and oxygen at the surface, which allows for optimal microbial activity.

3.1.5 Cation exchange capacity (CEC)

Cation exchange capacity (CEC), also commonly referred to as CEC, is the ability of a soil to adsorb and exchange cations in the soil adsorption complex with cations in the soil solution, expressed in units of cmol(+)/kg. The CEC value of the soil is influenced by soil properties such as soil texture, organic matter, and clay mineral type (Ririska et al., 2023). Soil with a high CEC content means it is able to absorb and provide nutrients well. The CEC value of Andisol soil in Indonesia ranges from 6.5–52.0 cmol(+)/kg with very low to very high values. The image of the CEC value at different soil depths and plant age variations is shown in Figure 5.

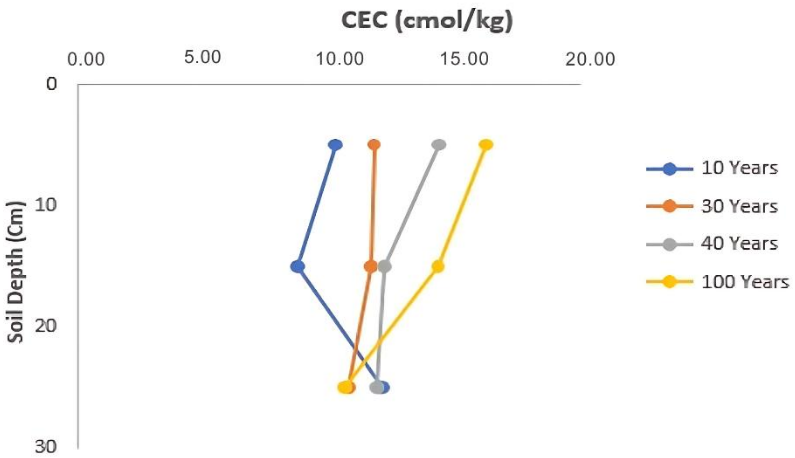

Fig. 5. Soil cation exchange capacity (CEC) values at different soil depths and plant ages

The average soil CEC values for varying plant ages of 10 years, 30 years, 40 years, and 100 years were 10.34 cmol/kg, 11.39 cmol/kg, 12.78 cmol/kg, and 13.71 cmol/kg, respectively. The highest CEC value in the study was for 100-year-old plants, which was 13.71 cmol/kg. The biomass produced by 100-year-old plants is greater than that of younger plants, which will also affect the increase in organic matter and C-Organic (Bimsakti et al., 2017). 100-year-old tea plants have more necromass dead organic matter than other age tea plants, indicating that the biomass and organic carbon content of the soil will also be higher. The CEC values for each soil depth and plant age ranged from 8.71 to 12.16 cmol(+)/kg in the Pemandangan Block, Tambi UP. The highest to lowest CEC values were for tea plants aged 100 years, 40 years, 30 years, and 10 years, respectively. The CEC values are determined by the clay and organic matter content (Nursanti et al., 2023). The CEC value depends on the availability of clay minerals in each soil type, the organic matter content, and the humus content (Sahfitra, 2023).

Tea plants aged 10, 30, 40, and 100 years had values in the top layer of 10.23 cmol/kg, 11.77 cmol/kg, 14.33 cmol/kg, and 16.20 cmol/kg, respectively. The CEC values of this study tended to be uniform at each soil depth with different age variations. The highest CEC values were found in the top layer (0-10 cm) of each plant age and decreased with increasing depth. This causes the soil cation exchange capacity (CEC) value to increase

(Tisdale et al., 1999). Also stated that soil organic matter is one of the best types of soil colloids, possessing a higher CEC capacity than clay colloids. The average CEC levels at the study sites were ranked from highest to highest at 100-year-old, 40-year-old, 30-year-old, and 10-year-old plants. However, there were differences in organic carbon levels: the highest at 40 years old, followed by 100-year-old, 30-year-old, and 10-year-old plants. Soil CEC levels are also influenced by Na^+ and H^+ ions, which can influence CEC levels without a direct relationship to organic carbon levels (Safitra, 2023). This is further supported by the average soil pH value of 5.34 for 40-year-old plants. Meanwhile, the pH value of soil H_2O in 100-year-old plants is lower at 5.26. A high cation value indicates the high availability of base cations in the soil.

3.2 Analysis of carbon reserves in variations in tea plant age

The physical and chemical properties of the soil and soil management can affect carbon reserves in the soil (Haryati et al., 2014). Carbon stored in plants is stored in the form of biomass distributed in stems, leaves, and roots. The table of biomass carbon reserves (plants and litter), soil carbon reserves, and total carbon reserves is shown in Table 5. Figure of biomass and soil carbon reserves at various plant ages in the UP Tambi Landscape Block.

Table 5. Biomass carbon stocks (plants and litter), soil carbon stocks, and total carbon stocks

Plant Age	Biomass C-Stock (ton/ha)	Soil C-Stock (ton/ha))	Total C-Stock (ton/ha)
10 year	4.50	58.84	63.20
30 year	4.72	62.53	66.76
40 year	5.32	62.55	67.34
100 year	588	63.52	68.70

Carbon stock values at various plant ages in the Tambi UP Scenery Block range from 58.67 to 63.52 tons/ha of soil carbon stock; 4.50 to 5.88 tons/ha of biomass carbon stock, and 63.17 to 68.70 tons/ha of total carbon stock. This is because the soil can store much more carbon than the cumulative stock in the atmosphere and vegetation up to more than 2000 Pg carbon (C) in the top 100 cm of soil depth (Gebrehiwot et al., 2018). Biomass carbon reserves (tea plants and litter) in the Tambi UP Vista Block were 4.36 tons/ha at 10 years old; 4.23 tons/ha at 30 years old; 4.78 tons/ha at 40 years old; and 5.73 tons/ha at 100 years old, totaling . Necromass contributes more carbon reserves than dead plant leaves (Sorbu et al., 2021). Heriyanto et al. (2020) stated that the water content of each plant organ (stem, roots, branches, and leaves) can directly affect the biomass or weight of each plant part. Wood components cause the stem cell cavities to be filled with wood components rather than water, resulting in a higher biomass weight (Widyasari, 2010). Leaf area increases with age (Uthbah et al., 2017). In this study, the larger the leaf area, the greater the potential for CO_2 absorption. Putri & Wulandari (2015) also stated that the larger the stem diameter of a stand increases the biomass and carbon storage. This research, conducted with tea plants, demonstrated that stem diameter increases with age. A diagram of soil carbon at each soil depth and variations in plant age in the Tambi landscape block is shown in Figure 6. The carbon stock value for each soil depth and variation in plant age in the Block Pemandangan UP Tambi has a value ranging from 58.84–63.52 tons/ha. The carbon stock value at the research location has a value that tends to be uniform, namely the largest carbon stock is in the top layer (0-10 cm). There is a decrease in the value of soil carbon stocks along with increasing soil depth. Soil carbon stocks are directly proportional to the content of organic matter and soil C-Organic. The total carbon stock content of the Block Pemandangan UP Tambi has the highest content in 100-year-old tea plants, namely 69.40 tons/ha; followed by 40-year-old plants, namely 67.87 tons/ha; 30-year-old plants, 67.26; then 10-year-old plants with a lower content, namely 63.34 tons/ha. Furthermore, stand density and pruning are also important factors in carbon storage. Chen et al. (2013) concluded in their research that routine pruning of tea plants can increase the plant's carbon storage capacity.

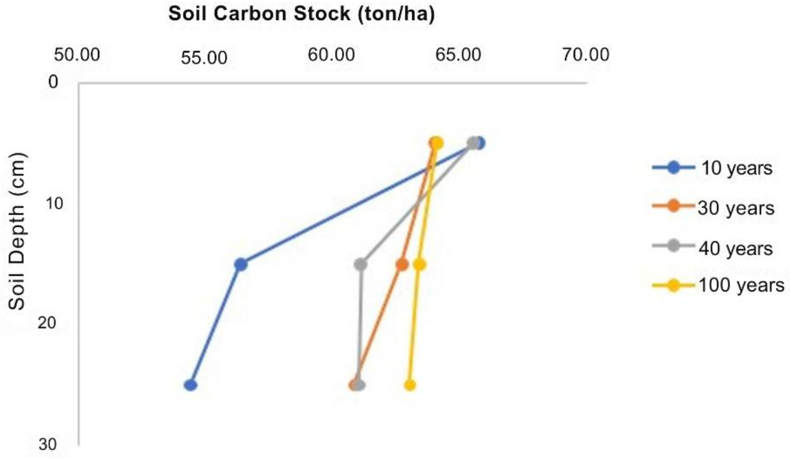

Fig. 6. Soil carbon reserves at each soil depth and variations in plant age in the landscape block

The total carbon reserves of tea plants at 100 years, 40 years, 30 years, and 10 years, respectively, were 69.40 tons/ha; 67.87 tons/ha; 67.26 tons/ha; and 63.17 tons/ha, respectively. Considering the change in total carbon storage capacity, the change in carbon storage capacity between 100-year-old and 40-year-old plants was 0.03 tons/ha, while the change in carbon storage capacity between 40-year-old and 30-year-old plants was 0.06 tons/ha. and the change in total carbon stock capacity between 30-year-old and 10-year-old plants was 0.2 tons/ha. The levels of organic carbon content and bulk density in 30-year-old and 10-year-old soils differ significantly. This results in higher carbon stock changes in 30-year-old and 10-year-old plants compared to other ages.

3.3 Analisis nilai normalized difference vegetation index (NDVI) pada perkebunan the Tambi

The NDVI analysis conducted in this study is linked to biomass carbon stocks because it is derived from image processing based on the plant greenness index. However, NDVI, as a vegetation indicator, can be linked to the level of plant greenness and biomass productivity, which indirectly influence carbon accumulation in the soil through photosynthesis and organic matter deposition. NDVI essentially uses the near-infrared and red bands. This is because leaves reflect light specifically with a green wavelength of 0.55 µm, but maximum reflection from leaves occurs in the near-infrared (NIR) wavelength. The human eye can only perceive light at wavelengths of 0.4–0.7 µm, also known as visible light. In healthy plants, near-infrared light reflection can occur significantly in the 0.7–1.2 µm spectrum due to internal scattering on the cell walls within the leaves. Healthy leaves generally have a light reflection of 40%–60%, with a relative absorption of 5%-10%.

The range of values obtained was the threshold range of the resulting NDVI value between -1 to 1 (Sulastri, 2015). The results of the NDVI transformation showed that the redder the color, the lower the NDVI value, and the greener the color, the higher the NDVI value. NDVI values with a value of -1–0.03 indicate information about unvegetated land; 0.03 - 0.15 indicates very low greenness; 0.15–0.25 indicates low greenness; 0.25–0.35 indicates moderate greenness; and 0.35–1 indicates high greenness. Sentinel 2A image raster data that had been transformed into NDVI images were then calculated using a raster calculator to obtain the distribution of carbon stock values represented by pixel values. The table of biomass carbon stock values and NDVI for each sampling point is shown in Table 6.

The NDVI value for the General Landscape Block of the Tambi UP ranges from 0.384 to 0.557. The lowest NDVI value is found at the first point of the 100-year-old tea plant (U 100 (1)), while the highest NDVI value is found at the second point of the 30-year-old tea plant (U 30 (2)). The average NDVI value for all sample points is 0.471, thus categorizing it as high greenness.

Table 6. Biomass carbon stock and NDVI values for each sampling point

Sample Points	NDVI	NDVI Value Classification	Biomass Carbon Stock (tons/ha)
U.10.1	0.509	High Vegetation	9.52
U.10.2	0.493	High Vegetation	8.65
U.10.3	0.464	High Vegetation	8.45
U.30.1	0.492	High Vegetation	10.92
U.30.2	0.557	High Vegetation	9.73
U.30.3	0.425	High Vegetation	9.15
U.40.1	0.466	High Vegetation	11.74
U.40.2	0.477	High Vegetation	10.52
U.40.3	0.476	High Vegetation	10.04
U.100.1	0.384	High Vegetation	11.25
U.100.2	0.462	High Vegetation	10.68
U.100.3	0.451	High Vegetation	9.85

According to Faizal & Amran (2005), the higher the vegetation index for NDVI transformation, the higher the density, and vice versa. This results in a narrow spectral index range (0.4–0.5) for tea plants, even with significantly different plant ages (10 to 100 years). Tea plants, as a production crop, require leaf pruning to achieve maximum shoot production. Furthermore, the tea plant ages of 10, 30, 40, and 100 years in the Landscape Block do not reflect the actual age of the plants, but rather the age of the replanted plants. The tea plants in the Tambi UP have been in existence since 1830, with a rejuvenation process to maintain their productive phase. NDVI values obtained from image processing are based on the wavelength values emitted from vegetation. Nirmala & Santosa (2018) also stated that pruning also affects plant density, which is a parameter required for NDVI. This low density can also be caused by the pruning period which is usually carried out every 3-4 years, because as is known, tea plants require approximately 3 months average tea shoots in the same pruning area to be easily harvested. The polynomial regression analysis graph between NDVI and biomass carbon reserves is shown in Figure 7.

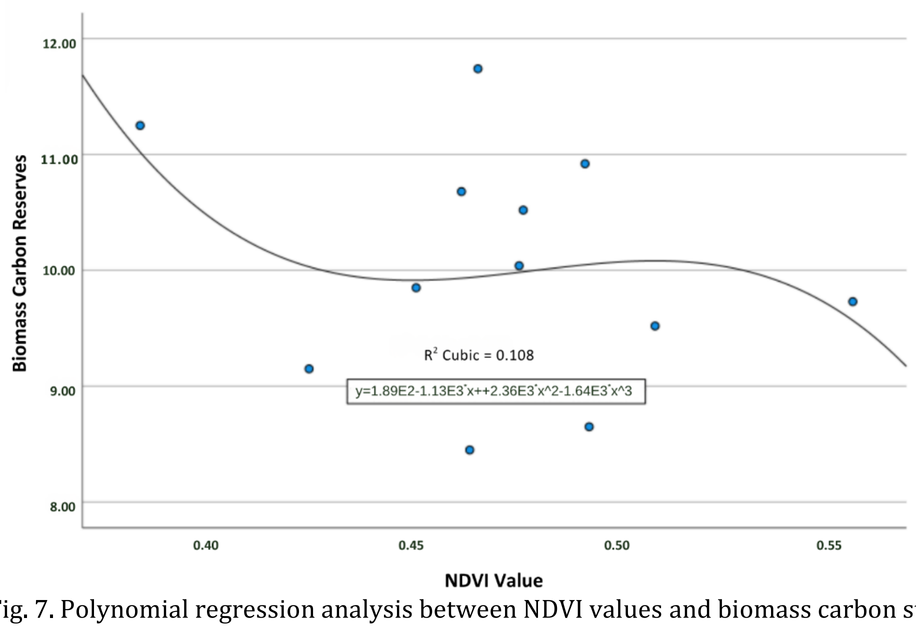

Fig. 7. Polynomial regression analysis between NDVI values and biomass carbon stocks

Based on polynomial regression analysis, the relationship between NDVI values and tea plant biomass carbon stocks has a correlation coefficient of 0.108 with the equation $y = 188.83 - 1127.3x + 2359.8x^2 - 1640.3x^3$. The use of Order 3 is also done to prevent overfitting of existing data. The relationship between the two variables (NDVI values and biomass carbon stocks) which is in the form of an up-down curve shows the highest curve at the starting point, then experiences a decrease and a slight increase in the middle of the curve, then decreases again at the end. According to Yaya et al. (2005) stated that the magnitude of the correlation coefficient moves between -1 to 1. The R^2 value = 0.108 indicates that changes or variations in biomass values can be explained by the index value can be explained by 10.84%. This occurs because of special treatment on tea plants, namely pruning carried out every 4 years. This results in biased NDVI values because satellite imagery captures images of the Earth's surface (Latue et al., 2023). In a study conducted by Purba et al. (2012) on estimating aboveground carbon stocks in oil palms based on stand age, they concluded that NDVI values increase with increasing age of the oil palm stands. Therefore, the carbon stock estimation model interpreted using NDVI in this study did not provide optimal results.

4. Conclusion

Based on the research that has been conducted, it can be concluded as follows: The Tambi UP Landscape Block has tea plants with varying ages of 10 years, 30 years, 40 years, and 100 years and has a range of NDVI values of 0.384–0.557. Satellite image vegetation index capture does not reflect the actual age of the plant due to the replanting and pruning process in tea plants and is not suitable for use in the study of carbon stock estimation in the soil. The total carbon stock value of tea plants stored in the Tambi UP Landscape Block is 63.17 tons/ha in 10-year-old tea plants; 67.26 tons/ha in 30-year-old tea plants; 67.87 tons/ha in 40-year-old tea plants; and 69.40 tons/ha of 100-year-old tea plants. Soil properties that play a role in influencing the content of carbon stocks in the soil and biomass from the most influential respectively, namely, C-organic, soil texture, and soil volume weight.

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Biography of Author

Farras M. Yusa, Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada, Sleman, Yogyakarta 55281, Indonesia.

- Email: farrasmyusa@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A