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Valuation of Carbon Stocks in Forest Area with Special Purpose Gunung Bromo: Efforts to Achieve Indonesia's FOLU Net Sink 2030

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ABSTRACT

Achieving the 2030 FOLU Net Sink target requires accurate carbon stock estimation and integrated forest health assessment. This study quantified carbon stocks in the Forest Area with Special Purpose (FASP) Gunung Bromo UNS using the USDA nested-plot design within assessing aboveground tree biomass, litter, understory vegetation, and necromass through tropical allometric equations. Canonical Correspondence Analysis (CCA) examined relationships between carbon stocks and environmental variables, including soil temperature, light intensity, air humidity, and soil pH. Dry secondary forest stored the highest carbon (57.79 tC/ha; 22,582.81 tC across 106.58 ha), followed by shrubland (36.79 tC/ha; 84.19 tC across 0.62 ha) and dryland agriculture (7.36 tC/ha; 487.59 tC across 18.07 ha). Higher stocks were associated with more stable microenvironmental conditions, while open and disturbed areas had lower stocks. These results underscore the need to protect secondary forests, restore shrublands, and strengthen agroforestry systems to support the implementation of FOLU Net Sink 2030.

HIGHLIGHTS

- FASP Gunung Bromo stores the most extensive carbon stocks in dry secondary forest.
- Dryland agriculture holds the lowest carbon stocks.
- CCA analysis confirms high stocks are associated with more favorable micro-conditions.

1. INTRODUCTION

Climate change poses a complex risk to the global environment, including higher temperature, extreme weather and imbalances in natural ecosystems (IPCC, 2023). The mitigation of climate change requires improved natural carbon sequestration and storage in forests (Chazdon and Uriarte, 2016; Pan et al., 2011). In this sense, forests need to be protected to keep their natural functions optimal. A healthy forest has optimal carbon sequestration ability by photosynthesis, a stable plant structure against disturbances, and strong resistance to natural disturbances such as drought and diseases (Morin and Compiler, 2020; USDA-FS, 1999). Forest health should be measured to support accurate decision-making in forest management.

In Indonesia, the importance of secondary forests has been overlooked, even though they continue to regenerate naturally following human-induced disturbances or natural calamities (Chazdon and Uriarte, 2016). Secondary forests, especially in drylands, are high-quality environment with strong carbon sequestration capacity, good soil quality, and natural resources (Chazdon et al., 2016; Poorter et al., 2021). Unlike primary forests, carbon stocks in secondary forests are essential for carbon cycling when restored and managed sustainably and adjusted to climate change (Poorter et al., 2016; Rozendaal et al., 2019). More diverse tree structures and pioneer species can enhance carbon stocks in secondary forests, especially in drylands when carbon sequestration and biomass accumulation are

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accommodated (Poorter et al., 2016). Research on carbon stock dynamics in secondary forests should be performed, since these ecosystems mitigate the impacts of climate change (Poorter et al., 2021). Two major tests are required to evaluate forests' ability to sequester carbon: biomass and carbon stock. Carbon stocks are calculated by summing aboveground biomass, including necromass, litter, and understory vegetation. Reliable carbon stock data to forecast forests' potential in greenhouse gas emissions reduction and develop evidence-based management plans for their activities are required (Krug et al., 2006). Carbon stock monitoring protects the environment while also advances the social and economic benefits from the sustainable forest management (Suich et al., 2017).

The 2030 National Forest and Other Land Use (FOLU) Net Sink objective requires the forestry industry to reduce emission producing activities and increase carbon sequestration through carbon stock conservation (Government of Indonesia, 2022). Calculation of above-ground biomass and above-ground carbon shows the mitigation readiness towards the impacts of climate change (Ayer et al., 2022). Forest Area with Special Purposes (FASP) potentially contributes as a carbon storage area that aligns with the Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), through climate change mitigation initiatives (Madjid et al., 2025). This condition is supported by various studies that estimate carbon storage and sequestration in FASP (Nandini et al., 2023; Paradika et al., 2021; Ramadhani et al., 2025). Although research related to carbon sequestration and storage in FASP is quite diverse, research conducted in FASP Gunung Bromo is still limited. Therefore, this research is important to conduct which aims to determine the contribution of FASP to climate change mitigation efforts, through analysis of carbon storage in FASP Gunung Bromo as an indicator of forest health and the result of this research provide carbon sequestration capability database in FASP Gunung Bromo. The novelty of this study is the integration of forest health, carbon-pool accounting, and micro-environmental ordination to produce a baseline for FASP Gunung Bromo. The study addresses three research questions: (1) how do carbon pools differ among dry secondary forest, shrubland, and dryland agriculture; (2) which biomass components contribute most to total carbon stocks in each land-cover class; and (3) how are carbon-stock patterns associated with micro-environmental conditions relevant to forest health and FOLU planning?

2. METHODOLOGY

2.1 Research site

The research was conducted at FASP Gunung Bromo in Karanganyar, Central Java. The site is located at 7°34'56" S 110°59'26" E - 7°35'38" S 111°00'49" E, 244-362 masl. The land area designated for a mitigation action plan at the site is 122.91 hectares. FASP Gunung Bromo UNS is mostly within the administrative area of Delingan Village, and some parts are within Gedong Village, Karanganyar District. Measurement plots were created to estimate biomass in dryland secondary forests in the area. Plots were determined based on the distribution of stand density, while carbon stock was calculated to quantify various carbon pools. Several tools were used, including raffia rope, a compass, a digital camera, stationery, a phiband, scales, a GPS device, and a personal computer (PC). The laboratory analysis was undertaken from June 10th to July 13th, 2025. Figure 1 shows the carbon sampling sites. The dry secondary forest plots (H1-H5) were associated with points 2, 3, 9, 10, and 11; shrubland plots (S1-S3) were associated with points 5, 6, and 7; and dryland agriculture plots (P1-P3) were associated with points 1, 4, and 8.

2.2 Data collection

This study used nested plots (Figure 2) to identify the growth levels of seedlings (2×2 m), saplings (5×5 m), poles (10×10 m), and trees (20×20 m). Data collection was conducted on 11 plots spread across 5 secondary forest plots, 3 shrub plots, and 3 dryland agricultural plots. Plot points were determined via random sampling in Microsoft Excel. Data collected in this study were diameter at breast height or DBH (130 cm), tree height, and litter collected specifically on 2×2 m plots (BSN, 2011).

2.3 Data analysis

2.3.1 Tree and pole biomass

Tree and pole biomass calculations were conducted on stands scattered across secondary forests, shrublands, and dryland agriculture. An allometric approach was used to calculate tree and pole biomass values (Ketterings et al., 2001). The specific gravity value of each species is different, namely *Pinus merkusii* (0.58 g/cm^3); *Swietenia macrophylla* (0.61 g/cm^3); and *Parkia speciosa* (0.5 g/cm^3).

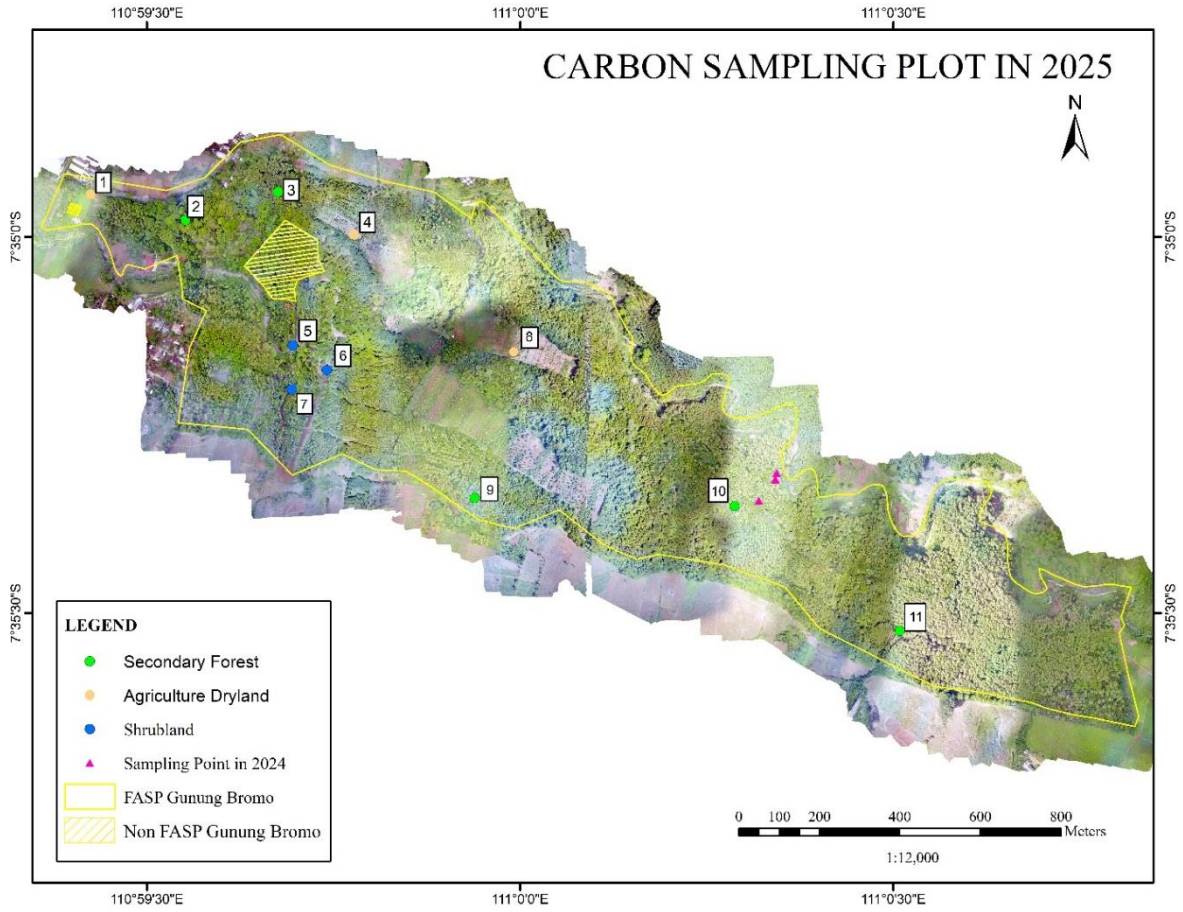


Figure 1. Sampling points for carbon stock measurements

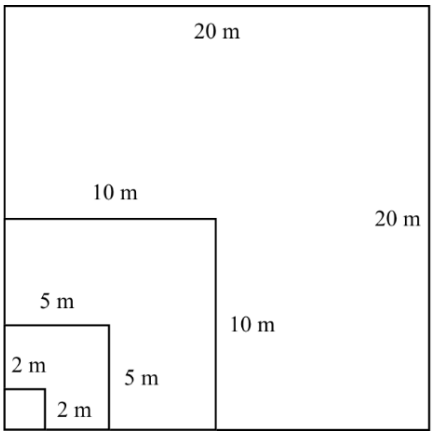


Figure 2. Nested plot sampling design

$$B = 0.11 \times p \times D^{2.62}$$

Where; B: total biomass (kg); D: diameter at breast height 1.3 m (cm); ρ: wood density (g/cm^3).

2.3.2 Below ground biomass (BGB)

Calculating belowground biomass values is rarely done directly by researchers, as it is synonymous with the use of destructive methods. This is because allometric estimation models for belowground biomass are not yet widely available and developed. Therefore, this study calculated belowground biomass values using the universal root biomass allometric approach developed by Cairns et al. (1997).

$$BGB = RSR \times AGB$$

Where; BGB=belowground biomass (kg); RSR=root-to-shoot ration (0.27); BGB=aboveground biomass (kg).

2.3.3 Seedling biomass, understory plants, and litter

The calculation of the Biomass Expansion Factor (BEF) value is carried out by comparing the wet weight and dry weight values of the sample. The BEF equation was used to estimate the biomass of litter and understory plants (Toru and Kibret, 2019).

$$\text{Total BK} = \frac{\text{BK sub sample (g)}}{\text{BB sub sample (g)}} \times \text{total BB}$$

Where; BB: wet weight (g); BK: dry weight.

2.3.4 Calculation of dead trees

Calculation of dead tree necromas is performed using the geometric method (SNI 7724-2011).

$$Vpm = \frac{1}{4} \times \pi \left(\frac{dbh}{100}\right) \times t \times f$$

Where; Vpm=volume (m^3); Dbh=diameter at breast height 1.3 m (cm); t=total height (m); f=shape factor (0.6).

The shape factor value varies depending on the wood species. If a shape factor is not available, use a shape factor value of 0.6 and perform the calculation (BSN, 2011).

$$Dom = Dv \times Dsg$$

Where; Dom=Deadwood organic matter (kg); Dv=Deadwood volume (m^3); Dsg=Deadwood spesific gravity (kg/m^3).

2.3.5 Deadwood calculation

Deadwood value is measured using the tree volume calculation approach (BSN, 2011).

$$V = \frac{1}{4} \times \pi \times \left(\frac{dt+db}{2} \times 100\right)^2 \times l$$

Where; V=volume (m^3); Db=deadwood base diameter (cm); Dt=deadwood tip diameter (cm); l=length (m).

After calculating the volume, the specific gravity of the deadwood is calculated. Determining the specific gravity of deadwood in the field can be done by empirically observing the decay rate of deadwood and finally calculating the deadwood biomass using the formula (BSN, 2011).

$$Dom = Vd \times Dd$$

Where; Dom=dead tree organic matter (kg); Vd=volume of dead trees (m^3); Dd=density of dead tree wood (kg/m^3).

2.3.6 Calculation of carbon value

Carbon potential could be estimated based on the amount of biomass obtained from vegetation, necromass, litter, and undergrowth, with a conversion of 0.47 from biomass and necromass (BSN, 2011):

$$C = B \times 0.47$$

Where; C: Carbon (kg); B: Plant biomass (kg); 0.47: factors for carbon estimation.

2.3.7 Canonical correspondence analysis (CCA)

Canonical correspondence analysis (CCA) was used to explore the associations between carbon-stock components and microenvironmental conditions. The response matrix consisted of litter biomass, litter input, total aboveground biomass, total belowground biomass, necromass, total carbon stock, and CO_2 equivalent for each plot. The explanatory matrix consisted of soil temperature, light intensity, air humidity, and soil pH. Land-cover classes were included as grouping variables to facilitate comparison among secondary forest, shrubland, and dryland agriculture. CCA constrains the ordination axes to measured environmental gradients and produces a biplot showing the relative relationships among plots, carbon-stock variables, and environmental factors. In the CCA biplot, vectors pointing in similar directions indicate positive associations, vectors pointing in opposite directions indicate negative associations, and approximately perpendicular vectors indicate weak associations. Longer vectors represent variables with stronger contributions to the displayed ordination pattern. Because the analysis included only eleven plots, the CCA was interpreted as an exploratory visualization, without causal inference or permutation-based significance claims.

3. RESULTS AND DISCUSSION

3.1 Species Identification

Firstly, sampling points were determined based on several observed parameters, including tree type, dry and wet litter weight, litter biomass, tree diameter, circumference, and density, as well as total carbon and total CO_2 at the site. The land cover of FASP Gunung Bromo was categorized into secondary forest, shrubs, and dryland agriculture. Meanwhile, the diversity of species at both the pole and tree levels was also examined, as seen in Table 1.

This study found that *Pinus merkusii* and *Dalbergia latifolia* dominate several plots. *Swietenia macrophylla* was also found in one secondary forest plot, while *Artocarpus heterophylla* was found in the dryland agriculture plot. In detail, some plots did not have individuals at the pole level (“None”), for example, plots H5, S1, and S2 (Figure 3). Hence, the gaps in the vertical structure of the stand potentially affect the regeneration processes and medium-term carbon storage capacity due to the distribution of size classes (seedling-sapling-pole-tree) in the recruitment continuity (Anhar et al., 2025; Poorter et al., 2008; Rocky and Mligo, 2012). In tropical secondary forests,

the composition and abundance of the pole strata are strongly influenced by disturbance history and site conditions that determine the rate of biomass accumulation and carbon stocks (Rahayu et al., 2022). Weaker or empty pole strata shows slower biomass recovery trajectory as fewer individuals are ready to move up the diameter class to become trees (Poorter et al., 2008).

Table 1. Complete species inventory by land-cover and growth stage (number of individuals)

Growth stage	Species	Family	Number of individuals			Total
			Secondary forest	Shrubs	Agriculture dryland	
Pole	*Pinus merkusii*	Pinaceae	2		3	5
	Swietenia macrophylla	Meliaceae	4			4
	Dalbergia latifolia	Fabaceae		1	4	5
	Artocarpus heterophyllus	Moraceae			1	1
Tree	*Pinus merkusii*	Pinaceae	44	18		62
	Swietenia macrophylla	Meliaceae	22	4		26
	Senna siamea	Fabaceae	1			1
	Parkia speciosa	Fabaceae			1	1
Total						105

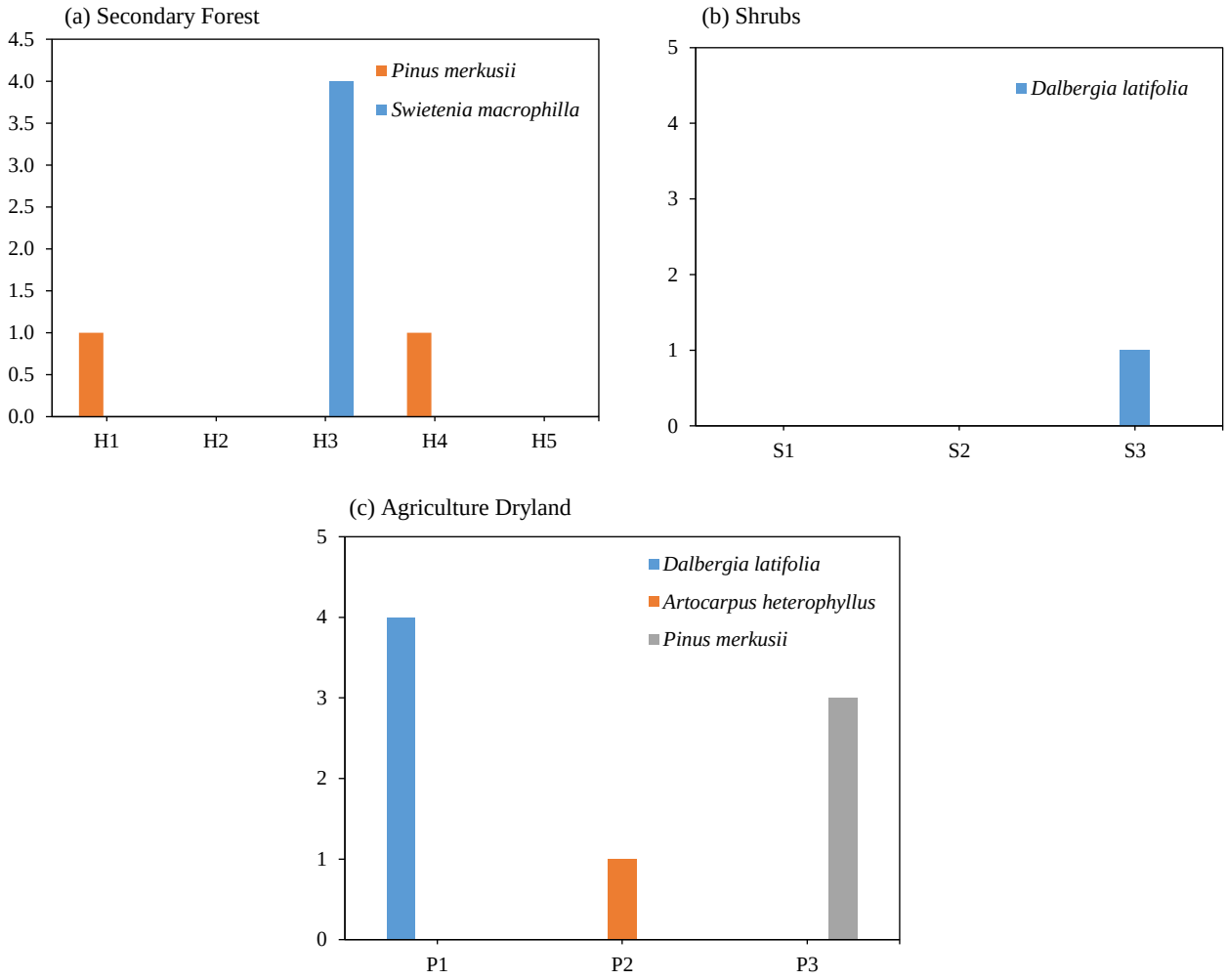


Figure 3. Number of species at the pole level in (a) secondary forest, (b) shrubs, (c) agriculture dryland

Pole-level abundance was low in several plots, indicating discontinuity in the intermediate stand layer. This condition can reflect either mature stands with few stems in the pole class or disturbance histories that limit recruitment into larger diameter classes. Such structural gaps may affect future carbon accumulation because pole individuals represent the transition from regeneration to tree-size biomass pools. The presence of *Dalbergia latifolia* in shrubland and dryland agriculture suggests that some non-forest plots already have woody components that can support restoration or agroforestry enrichment.

The dominance of *Pinus merkusii* and *Dalbergia latifolia* in several secondary forest and dryland plots reflects a history of planting and land rehabilitation using introduced and locally valuable species. *Pinus merkusii* is popular species in reforestation programs in Java due to its rapid growth and adaptability to drylands (Imanuddin et al., 2020; Udayana, 2019). *P. merkusii* is known as a bright, heat-drought-tolerant species (IPGRI, 2003). *Dalbergia latifolia* as poles in plots S3 and P1 (Figure 3) indicate that some areas of scrubland and dryland agricultural land exhibit semi-agroforestry characteristics, where valuable hardwoods are retained or planted among other vegetation (Kartawinata and Satjapradja, 1983). *Dalbergia* is a genus with dense wood and high density (≈750-880 kg/m³ at MC 12%), and it stores greater carbon per individual once it reaches tree size (Chopra et al., 2023). *D. latifolia* exhibits good carbon sequestration potential at young to medium ages (Chopra et al., 2023). These conservational and economically valuable species can positively affect the forest health. However, the low number of poles in some plots suggests uneven regeneration (ITTO, 2001).

Swietenia macrophylla is a preferred choice for quality carpentry timber, thereby it is commonly planted on a large scale for carpentry wood (Krisnawati et al., 2011). The pole-level structure is dominated by these three species. This dominance indicates stand regeneration which could maintain or increase aboveground biomass (AGB) carbon stocks in the future. Carbon stocks increase sharply as tree diameter and height increase, while Higher wood density also contributes to greater carbon stocks. These changes occur during the transition phase toward mature trees (Chave et al., 2014), However, this outcome depends on controlling anthropogenic disturbances. The absence of individual poles in some plots (e.g., H2, H5, S1, S2) in Figure 3 may also reflect two contrasting conditions: (1) mature stands where most individuals are already at the tree level, or (2) sites experiencing stress, such as selective logging, land conversion, or fire which interrupted the regeneration and the formation of the pole strata (Harrison et al., 2024; Pinagé et al., 2019). Selective logging and fire increase the frequency of canopy gaps, reduce the density of intermediate strata, and shift the composition of regenerants, thereby affecting medium- to long-term carbon stocks (Pinagé et al., 2019). In Indonesian, the interruption slows down the recovery of size structure unless followed by consistent rehabilitation practices (Imanuddin et al., 2020). This structural imbalance can lead to long-term carbon stock declines, even though current carbon stocks are still high in the mature tree strata (Morin, 2020).

Figure 4 illustrates species diversity at the tree level. The species composition at this level clearly demonstrates the dominance of *Pinus merkusii* and *Swietenia macrophylla* in almost all secondary forest plots (H1-H5) and shrub plots (S1-S3), with some presence of Johar (*Senna siamea*) and agroforestry species such as *petai* (*Parkia speciosa*) in agricultural land. This stand structure is typical of mixed plantation forests or community forests in Java. These forests usually combine economically valuable species with fast-growing species. This combination helps accelerate canopy closure and restore ecosystem services. The dominance of pine and mahogany reflects the history of forest planting and management in Java. *Pinus merkusii* is widely used for land rehabilitation and resin production. *Swietenia macrophylla* is commonly grown in community forests and mixed plantations as valuable timber (Imanuddin et al., 2020; Krisnawati et al., 2011). The compositional variation was also confirmed in findings of studies on pine stands in Java, where a spectrum of associated species within tree strata correspond to site conditions and natural forest (Supartono et al., 2022).

This type of stand structure is common in mixed-use plantations and community forests in Java. These forests usually have one or two dominant economically valuable species and multipurpose species. These species help accelerate canopy closure, restore ecosystem services and support production functions (Center for International Forestry Research-World Agroforestry (CIFOR-ICRAF), 2019). Farmers often develop compositions based on teak/mahogany/pine-based compositions and then add

MPTS (fruit/fodder/firewood) according to market opportunities and land conditions (Kollert and Kleine, 2017; Pramono et al., 2011). This simple mixed-use pattern effectively combines economic (timber and non-timber) and ecological (canopy cover, erosion reduction, and microclimate) functions in a fragmented forested agricultural landscape in Java (Prabawani et al., 2024). The dominance of *Pinus merkusii* and *Swietenia macrophilla* at the tree level has direct implications for AGB carbon stocks, since these two species generally have relatively straight trunks and large wood volumes (Chave et al., 2014). Community forests/mixed stands can store ~40-70 tC/ha in AGB, even greater than >70 TC/ha in some areas, depending on species, age, and stand density (Arianasari et al., 2021).

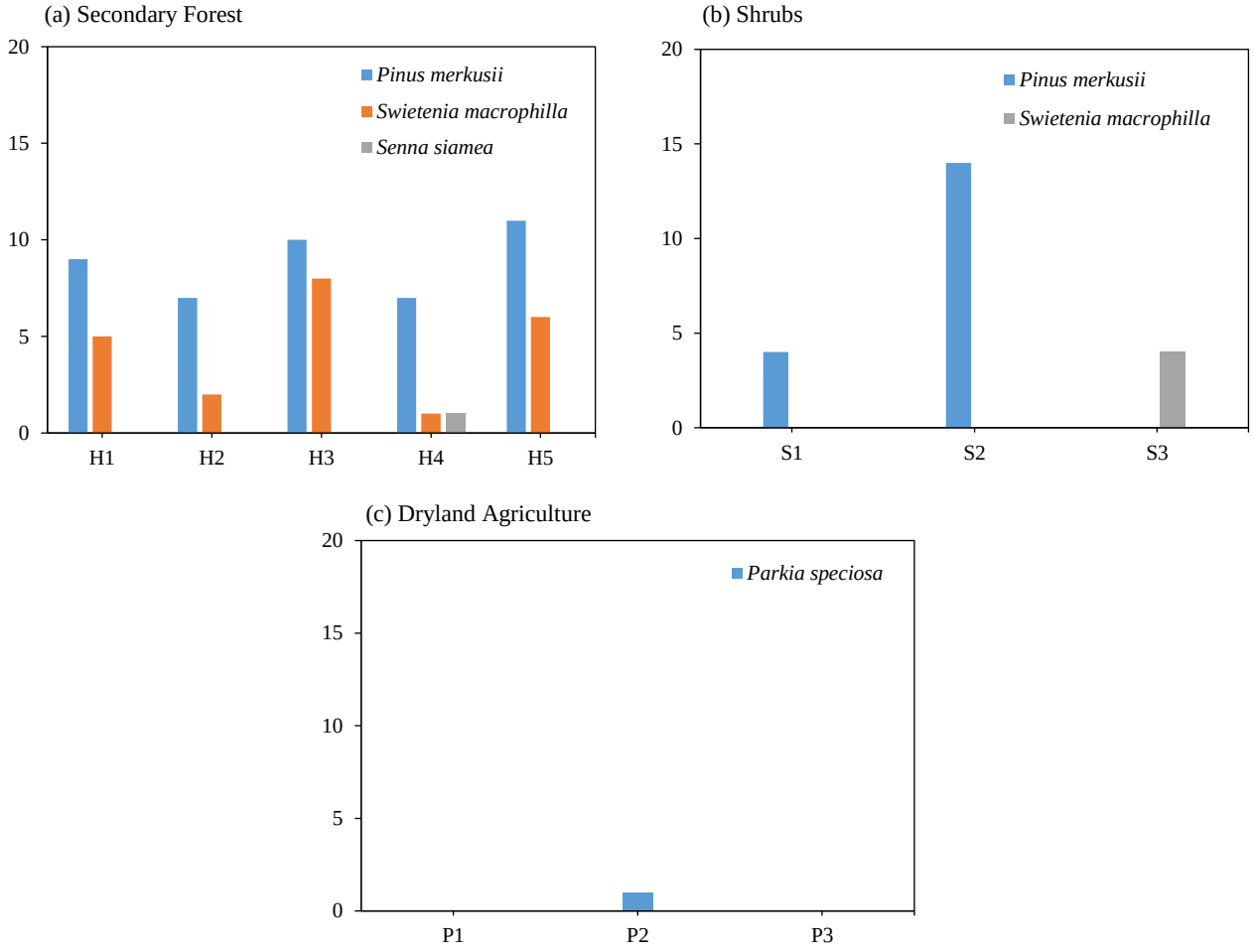


Figure 4. Number of species at the tree level in (a) secondary forest, (b) shrubs, (c) dryland agriculture

In terms of forest health and long-term sustainability of forest, having only a few species lowers the ecosystem resilience to biotic and abiotic disturbances. Homogenous forests are more likely harmed by pests, diseases, and climate change (Brockerhoff et al., 2017; Isbell et al., 2015; Pan et al., 2011). Therefore, FASP management options should include the enrichment of local species and the improvement of tree composition diversity to support long-term stability while sustaining carbon stock functionality (Brockerhoff et al., 2017; Isbell et al., 2015). Several plots had *Senna siamea*, *Dalbergia latifolia*, and *Artocarpus heterophyllus* (Figure 4), hence the stand composition can be expanded using nitrogen-fixing legumes and multipurpose tree species (MPTS). Tree legumes improves soil fertility through nitrogen fixation, growth and biomass accumulation. In the context of the 2030 FOLU Net Sink, combining carbon stock enhancement and soil quality improvement through the integration of tree legumes and MPTS is an alternative to strengthening the ecological and economic functions of FASP (Montagnini and Nair, 2004; Nair et al., 2009).

3.2 Carbon stock in dry secondary forest

Table 2 shows carbon stock estimates for five dry secondary forest plots (H1-H5). Total biomass ranged from 83.34 to 214.05 t/ha (mean: 122.96 t/ha). Carbon stock ranged from 39.17 to 100.60 tC/ha (mean: 57.79 tC/ha), equivalent to 143.62-368.88 tCO_2e/ha (mean: 211.90 tCO_2e/ha; (Krug et al., 2006). Plot H3 had the highest biomass (214.05 t/ha) and carbon stock (100.60 tC/ha), indicating a denser and/or older stand. This is consistent with ecological theory, where biomass and carbon increase with tree size and wood density (Chave et al., 2014), and with secondary forest recovery dynamics showing rapid biomass accumulation during intermediate succession (Poorter et al., 2016). The FASP data in this study showed that the average total C in dry secondary forest was 57.79 tC/ha. In dense stand classes and mature secondary forest stands, the carbon stock of above-ground biomass (AGB) can exceed 100 tC/ha. The carbon stock of mature scrub vegetation is approximately 60 tC/ha. Carbon storage increase follows the forest development stages (The Forest Trust and Greenpeace, 2012).

As seen in Table 2, the average value of 57.79 tC/ha falls within the medium range. Ibrahim and Lukman (2020) demonstrated that aboveground carbon stocks in various forest types in Indonesia ranged from 16.92 to 92.73 tC/ha, depending on the forest type and level of disturbance (Ibrahim and Lukman, 2020). Poorter et al. (2016) reported that tropical secondary forests can recover their biomass and carbon quickly and, within the first few decades, can approach the values of primary forests. However, this depends on baseline conditions and subsequent disturbances (Poorter et al., 2016). The moderate FASP value indicates that the secondary forest has accumulated substantial carbon but retains potential for further recovery under proper management, such as silvicultural practices and disturbance protection (Poorter et al., 2016).

Table 2. Estimated carbon stock in dry secondary forest

Plot	Seedlings undergrowth (t/ha)	Poles (t/ha)	Trees (t/ha)	Total AGB (tC/ha)	BGB (t/ha)	Litter (tC/ha)	Dead wood (tC/ha)	Total Biomass (t/ha)	Total C (tC/ha)	Total emissions CO_2e (t/ha)
H1	0.53	5.43	83.21	89.17	24.08	4.34	2.77	120.36	56.57	207.42
H2	1.27	-	79.06	80.33	21.69	2.84	0.16	105.01	49.35	180.97
H3	0.49	20.77	141.28	162.54	43.89	4.92	2.70	214.05	100.6	368.88
H4	0.15	7.43	60.41	67.99	18.36	5.68	-	92.03	43.25	158.60
H5	0.70	-	63.27	63.97	17.27	2.10	-	83.34	39.17	143.62
			Average	92.80				122.96	57.79	211.90
			Area (Ha)	106.58						
			Total carbon stock	9,890.03				13104.15		22,582.81

The FASP's total secondary forest carbon is primarily derived from tree AGB, followed by BGB. At the same time, litter and necromass makes significant contribution. The AGB in Plot H3 reached 162.54 t/ha and BGB 43.89 t/ha, while litter and dead wood contributed roughly 4.92 t/ha and 2.70 t/ha, respectively. Likewise,Pinang Jaya community forest showed that its AGB accounted for over 95% of carbon stocks, necromass of ~4.23%, and litter/undergrowth of ~0.05% (Arianasari and Kaskoyo, 2021). Necromass and litter are critical nutritional buffers, disturbance signals, and components of forest floor carbon cycles in tropical forests (Palace et al., 2012). Increasing carbon stocks in dry secondary forests requires enhancing tree density and size, while maintaining litter and necromass to support nutrient cycling and soil health. The 106.58 hectares of dry secondary forest at the landscape scale contribute a total carbon store of 22,582.81 tC. This value substantially exceeds the carbon stored in shrubs and agricultural fields. Hence, secondary forests are the primary centers of carbon storage in FASP. Achieving the sink target can be done by increasing the most effective stock, strengthening stand protection, improving the disturbance control, and accelerating canopy closure and diameter growth (Chave et al., 2014). In the context of the 2030 FOLU Net Sink, increasing carbon stocks in secondary forests can be performed through disturbance control, enrichment planting, and implementation of silviculture that accelerates canopy closure. Because secondary forests are relatively easy to convert, policy instruments and adaptive management are needed to prevent carbon losses from

land-use change. Strengthening the AGB pool by increasing tree density and size, while maintaining litter and necromass to sustain soil fertility, aligns with IPCC carbon inventory and reporting guidelines (Krug et al., 2006).

3.3 Carbon stock in shrubs

Table 3 shows the estimated carbon stocks in three shrub plots (S1-S3). Total biomass per plot ranged from 40.95 to 140.33 t/ha, with an average of 78.29 t/ha. Total carbon stocks (Total C) ranged from 19.25 to 65.96 tC/ha, with an average of 36.79 tC/ha equivalent to 134.91 tCO_2e/ha when converted using a factor of 44/12 (≈3.67) according to the IPCC A FOLU 2006 guidelines (IPCC, 2006). Plot S2 stood out with a total C value of 65.96 tC/ha, approaching values reported for secondary forests in other locations. This is related to the dominance of tree biomass (AGB 109.59 t/ha), which remains relatively high despite the vegetation structure being classified as shrubland. The phenomenon of high AGB shrubs is common in "old shrubs" or woody shrubs that store intermediate carbon stocks between open land and secondary forest (The Forest Trust and Greenpeace, 2012). Theoretically, AGB stocks are expected to increase rapidly along with the growth in diameter/height, and density of woody species, even though the land cover category is still recorded as shrubs. Carbon stocks in tropical shrubland ecosystems are estimated to range from 30 to 40 tC/ha worldwide (Krug et al., 2006).

The shrub carbon stocks in Samarinda ranged from ~30 to 31 tC/ha, similar to the average of 36.79 tC/ha in Mount Bromo FASP shrubland (Azham, 2015). Although classified as scrub, some locations contribute to carbon storage, particularly when the forests are dominated by timber species such as *Pinus merkusii* (Lü et al., 2010). The Indonesian Forest Reference Level (FRL) report classifies old scrub as having intermediate carbon stocks between open land and secondary forest (Government of Indonesia, 2022).

Table 3. Estimation of carbon stock in shrubs

Plot	Seedlings undergrowth (t/ha)	Poles (t/ha)	Trees (t/ha)	Total AGB (tC/ha)	BGB (t/ha)	Litter (tC/ha)	Dead wood (tC/ha)	Total Biomass (t/ha)	Total C (tC/ha)	Total emissions CO_2e (t/ha)
S1	0.54	-	29.10	29.64	8.00	1.34	1.96	40.95	19.25	70.57
S2	1.27	-	108.32	109.59	29.59	1.16	0.00	140.33	65.96	241.84
S3	0.55	6.37	34.61	41.54	11.22	0.82	0.00	53.57	25.18	92.33
			Average	60.26				78.29	36.79	134.91
			Area (Ha)	0.62						
			Total carbon stock	37.60				48.85		84.19

The High Carbon Stock (HCS) study finds that old scrub often resembles regenerating forest, underscoring its restoration potential (The Forest Trust and Greenpeace, 2012). Carbon stocks are dominated by AGB, while litter and necromass are minor but ecologically important. At S2, AGB reached 109.59 t/ha, with very low litter (1.16 t/ha) and no necromass. Similarly, AGB accounts for about 95.71% of total carbon in community forests (Arianasari and Kaskoyo, 2021). IPCC guidance notes that litter and deadwood are strongly shaped by disturbance and management.

According to community forest studies, AGB accounts for around 95.71% of total carbon, while necromass and litter have lesser contribution. IPCC states that disturbance and management regimes significantly influence litter/deadwood dynamics. Despite its small size, this compartment is a valuable metric of stand health and carbon flux (Krug et al., 2006). Scrubland in FASP is beyond a collection of low vegetation, instead it is a transitional stage between degraded and recovering secondary forest. Scubland phase is a reserve for forest recovery when maintained properly.

At the landscape level, FASP's scrubland area is relatively tiny (0.62 ha) with a total carbon of 84.19 t, significantly smaller than that of secondary forest and agricultural land. However, in terms of FOLU Net Sink and landscape restoration planning, shrubland areas are strategic priority targets for rehabilitation or carbon stock enhancement through tree species enrichment due to their moderate initial carbon stocks and quicker response to rehabilitation treatments (Chazdon and Uriarte, 2016; Indrajaya et al., 2022). Shrubland rehabilitation can generate large additional

carbon reserves in a relatively short timescale (Indrajaya et al., 2022; Mangueira et al., 2019).

3.4 Carbon stock in dryland agriculture

Table 4 presents carbon stocks in three dryland agricultural plots (P1-P3). The total biomass per plot ranged from 9.44 to 21.80 t/ha, with an average of 15.65 t/ha. Whereas, the total carbon stocks (Total C) ranged from 4.44 to 10.24 tC/ha with an average of 7.36 tC/ha that is equivalent to 26.98 tCO_2e/ha. These values are significantly lower than those in dry secondary forests and shrublands, reflecting the significant loss of tree carbon stocks from the dryland agriculture conversion (Krug et al., 2006). The presence of several species (e.g., *Dalbergia latifolia*, *Parkia speciosa*, or *Pinus merkusii*) has not been sufficient in increasing the stock due to their small dimensions and low numbers (Chave et al., 2014).

Table 4. Estimation of carbon stock in dryland agriculture

Plot	Seedlings undergrowth (t/ha)	Poles (t/ha)	Trees (t/ha)	Total AGB (tC/ha)	BGB (t/ha)	Litter (tC/ha)	Dead wood (tC/ha)	Total Biomass (t/ha)	Total C (tC/ha)	Total emissions CO_2e (t/ha)
P1	0.01	16.42	0.00	16.43	4.44	0.93	0.00	21.80	10.24	37.56
P2	0.10	1.25	5.90	7.25	1.96	0.06	0.17	9.44	4.44	16.27
P3	0.01	12.17	0.00	12.18	3.29	0.26	0.00	15.73	7.39	27.10
			Average	11.95				15.65	7.36	26.98
			Area (Ha)	18.07						
			Total carbon stock	216.05				282.94		487.59

Studies on the carbon stock dynamics due to the conversion to agricultural land and plantations reveal showed an average decline from 0.7 to 16.43 tC/ha, depending on the cultivation system and the presence of shade trees. The average value of 7.36 tC/ha in the Mount Bromo FASP (moderate) indicates that some agricultural land still retain some tree components at the pole and tree level (e.g., rosewood in P1, jackfruit and *Parkia speciosa* in P2, and pine in P3) (Figure 4). However, their density and size are insufficient to bring high carbon stocks (Figure 4). In terms of process, stock decline occurs due to the loss of AGB and reduced litter input, which then suppresses soil carbon accumulation in the medium term (Don et al., 2011; Guo and Gifford, 2002). Thus, preserving and increasing the shade tree component is the determinant to higher carbon stocks in the agricultural dryland (Chave et al., 2014; Krug et al., 2006).

Coffee agroforestry with adequate shade tree density and diversity can achieve carbon stocks comparable to those of secondary forests. Therefore, practical reference for tree-based intensification strategies in drylands should be provided (Anhar et al., 2025; Lugo-Pérez et al., 2023). In Gayo Highlands, the carbon stocks in shaded coffee plantations ranges from 10 to over 100 Mg C/ha, depending on the composition and structure of the canopy strata, showing a substantial range compared to unshaded systems (Anhar et al., 2025). Both classical and modern studies on agroforestry confirm the significant potential of tree-based systems for carbon sequestration along with soil quality and the microclimate cultivation as the carbon stock rehabilitation strategy in dryland agriculture (Nair et al., 2009). Because tree AGB is the main determinant of aboveground carbon, increasing shade tree density through MPTS enrichment, field-edge planting, and optimized spacing is essential to raise tC/ha without reducing production (Chave et al., 2014; Nair et al., 2009). From a landscape health and 2030 FOLU Net Sink perspective, the 18.07 ha of dryland agriculture stores only about 487.59 tC, far less than secondary forest (22,582.81 tC) (Table 1).

Coffee agroforestry can create carbon stores comparable to secondary forests when managed with high tree densities and appropriate species diversity. Low-carbon storage in dryland agricultural areas can impact soil fertility and ecosystem function. A decline in aboveground biomass is typically accompanied by a decrease in litter and soil organic matter inputs, which reduces the soil's ability to store carbon and nutrients over time. In the context of FASP, these findings emphasize the importance of a landscape approach that integrates secondary forests, shrublands, and agricultural lands into a coherent management strategy. This allows for increasing carbon stocks in a particular component (for example, shrubland restoration or agroforestry enrichment on agrarian lands) to contribute carbon sequestration and meet the 2030 FOLU Net Sink target.

3.5 Statistical comparison among land-cover classes

The summarized statistical table shows that dry secondary forest had the highest mean values for total AGB, BGB, litter, total biomass, total C, and CO_2e, followed by shrubland and dryland agriculture (Table 5). Kruskal-Wallis tests indicated significant differences among land-cover classes for total AGB, BGB, litter, total biomass, total C, and CO_2e ($p<0.05$). Deadwood did not differ significantly, likely because deadwood was absent or low in several plots and because the sample size was limited.

Table 5. Summary statistics of biomass and carbon pools by land-cover class

Variable	Dry secondary forest (n=5)	Shrubland (n=3)	Dryland agriculture (n=3)	Kruskal-Wallis H	p-value
Seedlings/understory	0.63±0.41	0.79±0.42	0.04±0.05	6.50	0.039
Poles	6.73±8.51	2.12±3.68	9.95±7.83	2.29	0.319
Trees	85.45±32.72	57.34±44.23	1.97±3.41	6.62	0.036
Total AGB	92.80±40.25	60.26±43.14	11.95±4.59	6.59	0.037
BGB	25.06±10.87	16.27±11.65	3.23±1.24	6.59	0.037
Litter	3.98±1.48	1.11±0.26	0.42±0.46	8.24	0.016
Dead wood	1.13±1.47	0.65±1.13	0.06±0.10	1.01	0.604
Total biomass	122.96±52.80	78.28± 54.10	15.66±6.18	6.59	0.037
Total C	57.79±24.82	36.80±25.43	7.36±2.90	6.59	0.037
CO_2e	211.90±91.00	134.91±93.24	26.98±10.65	6.59	0.037

Values are mean±standard deviation. AGB, aboveground biomass; BGB, belowground biomass. Kruskal-Wallis tests were based on the plot-level values reported in Tables 1-3; $p<0.05$ indicates a significant difference among land-cover classes. The cross-cover analysis confirmed significant differences in tree biomass, total AGB, BGB, litter, total biomass, total carbon, and CO_2 equivalent ($p<0.05$), with dry secondary forest consistently highest and dryland agriculture lowest. Pole and dead-wood biomass did not differ significantly. Because the land-cover groups contained small and unequal numbers of plots, these results should be interpreted as plot-level evidence rather than landscape-wide causal estimates.

International comparisons place the FASP results in context. Mean AGB in the dry secondary forest (92.80 t/ha) was below the 122 t/ha mean reported for 20-year-old Neotropical secondary forests (Poorter et al., 2016). The mean FASP secondary-forest carbon stock (57.79 tC/ha, excluding soil carbon) was also lower than the 183.72-207.58 tC/ha reported for community forests in Nepal and the 303 Mg C/ha total ecosystem stock reported for a mature tropical seasonal forest in southwestern China (Ayer et al., 2022; Lü et al., 2010). These contrasts are indicative because stand age, disturbance history, sampled carbon pools, and estimation methods differ among studies.

Agroforestry with adequate shade-tree density and diversity can substantially increase biomass and carbon storage relative to unshaded agriculture (Lugo-Pérez et al., 2023; Montagnini and Nair, 2004; Nair et al., 2009). Because tree AGB is the principal aboveground pool, increasing multipurpose tree species through enrichment, field-edge planting, and optimized spacing can raise carbon stocks while maintaining production. In the FASP landscape, 18.07 ha of dryland agriculture stores only about 487.59 tC, compared with 22,582.81 tC in dry secondary forest, highlighting the potential value of tree-based intensification.

3.6 Comparison with other studies

The dry secondary forest carbon stock at FASP Gunung Bromo (57.79 tC/ha, excluding soil) was lower than aboveground tree carbon reported for old secondary lowland limestone forest in Seram, Indonesia (70.3 tC/ha; Stas, 2014) and far below total ecosystem carbon in a mature tropical seasonal forest in southwestern China (303.3 tC/ha, including mineral soil to 1 m; Lü et al., 2010). Community forests in Kanchanpur, Nepal stored 207.58 and 183.72 tC/ha under scientific and conventional management, respectively (Ayer et al., 2022). These differences reflect forest age, tree size, species composition,

management, and especially the carbon pools included. Cross-study comparison is therefore contextual rather than a direct performance ranking (Table 6).

Table 6. Comparison of FASP Gunung Bromo carbon stock with other studies

Study/location	Land-cover/forest type	Carbon pool compared	Reported carbon stock (tC/ha)	Interpretation for FASP Gunung Bromo
FASP Gunung Bromo, Indonesia (this study)	Dry secondary forest	Total biomass C, excluding soil	57.79	Moderate value; lower than mature tropical forests because soil C was not included and the stand is secondary/dry.
Seram, Moluccas, Indonesia (Stas, 2014)	Old secondary lowland limestone forest	Aboveground tree carbon	70.3	Slightly higher than FASP secondary forest, consistent with older secondary structure.
Kanchanpur, Nepal (Ayer et al., 2022)	Community forest	Forest biomass carbon	207.58 (scientific management); 183.72 (conventional management)	Shows carbon stock increases with scientific/community forest management and tree diversity.
Southwestern China (Lü et al., 2010)	Tropical seasonal rain forest	Total ecosystem carbon including soil	303.3	Much higher because it includes mature forest structure and mineral soil carbon to 1 m.
Puerto Rico coffee region (Lugo-Pérez et al., 2023)	Coffee agroforestry	Farm carbon storage	Higher with shade trees	Supports enrichment of dryland agriculture with shade/MPTS trees.

3.7 CCA Analysis

CCA was used to identify parameters influencing carbon stock estimates in FASP Gunung Bromo, including litter stock biomass, litter input biomass, total AGB, total BGB, and total emissions. Soil temperature, light intensity, air humidity, and soil pH are environmental explanatory variables in the CCA. CCA is a multivariate statistical method that examines the relationship between biological communities and ecological variables to examine how specific environmental gradients influence community composition. Unlike Principal Component Analysis (PCA) which reduces data dimensionality by capturing maximum variance, CCA explicitly associates environmental variables with species data. Therefore, CCA is applicable in ecological data analysis. It is particularly useful for integrating multidimensional data and revealing how environmental factors influence soil health and ecosystem function (Souza, 2025).

Figure 5 presents the results of the CCA analysis. Environmental variables such as soil temperature, light intensity, air humidity, and soil pH were used to interpret the research results. The use of CCA allowed for the analysis of ecological gradients that influence carbon stock fluctuations between plots for more comprehensive understanding of forest health and ecosystem conditions in FASP Gunung Bromo. CCA also selects the ordination axis as a linear combination of environmental variables that best explains the variation in response data (Peck, 2011). Because large tree carbon stocks are typically associated with dense canopies, lower light intensity on the forest floor, and relatively stable soil temperatures, plots with high AGB and BGB values are expected to be located near the AGB and BGB vectors on the ordination diagram (Chen et al., 1999; De Frenne et al., 2019). Whereas, dry agricultural plots (P1-P3) with low carbon stores tend to have higher light intensity and greater variations in soil temperature due to their open canopies (Chen et al., 1999).

Shrubland plots (S1-S3), especially S2 with intermediate carbon stocks, likely occupy transitional positions between secondary forest and agricultural land in the CCA ordination. Although exact coordinates are not provided, this pattern aligns with observed carbon stock differences among land covers (De Frenne et al., 2019). Air humidity and soil pH also regulate litter and necromass dynamics, influencing surface carbon stocks. Higher humidity and lower soil temperatures slow decomposition, allowing greater litter accumulation and carbon storage (Brockerhoff et al., 2017; Nair et al., 2009).

In open areas with high light intensity and extreme soil temperatures, litter dries and decomposes faster, resulting in lower carbon stocks (Sayer, 2006). Temperature, moisture, and soil pH are the main

controls of decomposition, and lower pH often slows this process in forest ecosystems (Prescott, 2010; Shen et al., 2021). CCA integrates these relationships and helps managers identify environmental conditions that promote or limit carbon accumulation. High carbon stocks in dry secondary forests reflect not only stand structure and species composition but also favorable microclimates, including stable moisture, suitable soil pH, and moderate temperatures (De Frenne et al., 2019). On the contrary, agricultural areas and some shrublands with low stocks reflect harsher conditions that constrain carbon storage. Within the FOLU Net Sink 2030 framework, this insight supports targeting restoration and adaptive management to sites with low carbon stocks and unfavorable environmental conditions.

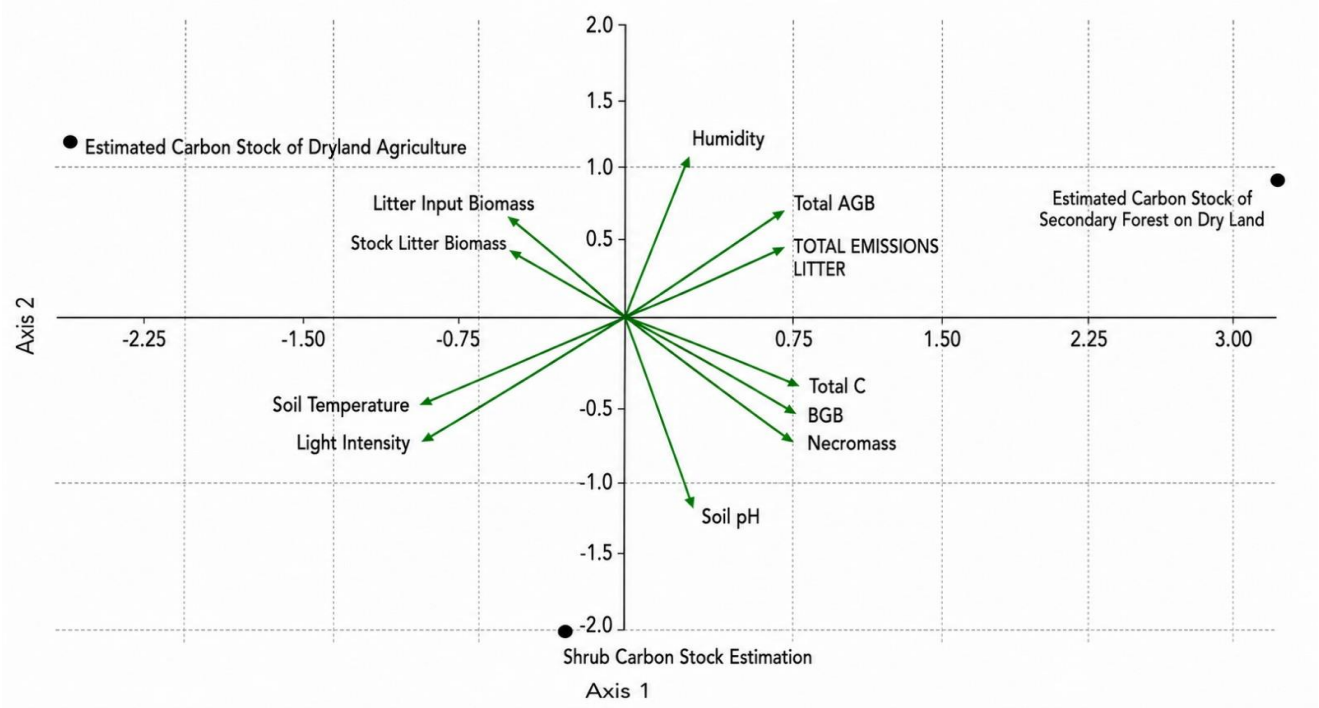


Figure 5. CCA analysis results graph

4. CONCLUSION

This study found that carbon stocks differ among three land cover types in FASP Gunung Bromo. The most extensive carbon stocks were found in dry secondary forest (average 57.79 tC/ha; total 22,582.81 tC in 106.58 ha), followed by shrubland (36.79 tC/ha; 84.19 tC in 0.62 ha) and dryland agriculture (7.36 tC/ha; 487.59 tC in 18.07 ha). AGB shows the dominant contribution, while litter and necromass play a smaller role in carbon stocks. The results of CCA analysis confirm that high carbon stocks are associated with ideal micro-conditions (closer canopy, more stable soil temperature/ moisture), while low stocks are located along a gradient of openness. Based on the results of this study, effective strategies towards FOLU Net Sink 2030 include protecting and enhancing secondary forests as the "sink core," rehabilitating shrubland as a transitional phase that responds quickly to enrichment, and adopting agroforestry in dryland agriculture using the permanent plot for repeated monitoring and evaluation of carbon stocks.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.A.A. and S.; Methodology, M.A.A. and M.I.N.M.; Software, A.F.L. and W.A.; Validation, S, M.M.A.R.R., and P.; Formal Analysis, S.; Investigation, A.F.L. and W.A.; Writing-Original Draft Preparation, M.A.A., M.I.N.M., and M.N.; Writing-Review and Editing, M.A.A. and M.M.M.A.R.R.; Visualization, A.F.L. and W.A.; Project Administration, A.F.L. and W.A.; Funding Acquisition, S., M.M.A.R.R., P., M.A.A., M.I.N.M., and M.N.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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