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Carbon Sequestration and Environmental Service Assessment in the Special Purpose Forest Area of Mount Bromo, Indonesia

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ABSTRACT

This study aimed to evaluate the carbon and environmental service potential in the natural tourism zone of special purpose forest areas Mount Bromo. The study focused on understanding how this area, with its specific tree compositions and sizes, contributes to carbon absorption and environmental benefits, which can also translate into carbon credits, a form of state revenue. The methodology involved purposive sampling to create observational sample plots (OSP) of varying sizes based on tree diameter. These plots were designed to measure the biomass, carbon potential, and environmental service potential of the trees in a given area. The collected data included the composition of tree species, the number of each type of tree, their diameters, and heights. The study applied specific formulas to determine the potential of biomass, carbon, and environmental services in the area. Key findings revealed a dominance of mahogany trees (83 trees per hectare) among ten identified plant species, indicating a specific but lower biodiversity in this zone. The significant results of the study include the quantification of biomass potential, which was found to be 787.84 tons/ha above-ground and 228.47 tons/ha below-ground, totaling 1016.31 tons/hectare. The study also evaluated the environmental service potential, including CO_2 absorption and O_2 production. The CO_2 absorption capacity of the area was estimated at 1753.04 tons/ha, with a corresponding high O_2 production of 1279.72 tons/ha. Additionally, the potential for carbon credits in the area was calculated at approximately 70.12 US$/ha. This research is crucial in understanding how specific forest areas, like special purpose forest areas Mount Bromo, can play a significant role in global environmental sustainability efforts.

Keywords: carbon sequestration, environmental services, forest ecosystem, sustainable forest management.

INTRODUCTION

Global warming and climate change are currently among the most pressing issues in the world, leading to various negative environmental impacts, such as extreme weather events, rising sea levels, effects on agriculture, wildlife & plant life, and human health (Stefanakis 2019; Koul et al. 2022; Suryawan and Lee 2023a). These climate changes are caused by greenhouse gases originating from anthropogenic activities, such as the use of fossil fuels, livestock/agricultural activities, deforestation, and organic waste (Kath et al. 2020; Lee et al. 2020; Suryawan et al. 2021). Among these anthropogenic activities, carbon emissions, which contribute to climate change, need to be reduced (Huang and Zhai 2021). This is in line with the statements of other studies (Shahbaz et al. 2020; Huang and Zhai 2021; Suhardono et al. 2023), who emphasize the significant role of human activities in the production of carbon emissions. Carbon storage refers to the carbon contained within the Earth's surface (Ramesh et al. 2019), including plant biomass, dead plant residues, and soil as organic matter. The transformation of carbon is the basis for calculating emissions, where most decomposed carbon (C) in the air usually binds with O_2 (oxygen) to become CO_2 (carbon dioxide). This is why when one hectare of forest disappears (the trees die), the biomass of these trees will decompose over time, and the carbon content will be released into the air as emissions. Conversely, when a barren land is planted with vegetation, the process of carbon binding from the air occurs, and this carbon becomes part of the plant biomass as the plants grow. The volume of the plants in the area then becomes the measure of the amount of carbon stored as biomass (carbon stock) (Vashum and Jayakumar 2012). This process can reduce the greenhouse effect caused by CO_2, as the CO_2 content in the air is reduced, thereby lowering the potential for climate change (Ewunetie et al. 2021). One way to mitigate the impact of global warming is by controlling carbon concentrations through the development of carbon sinks, where organic carbon from photosynthesis is stored in the biomass of forest stands or woody trees. Forest biomass contains a significant amount of carbon, with nearly 50% of forest vegetation biomass consisting of carbon (Dumitrașcu et al. 2020). The high carbon absorption capacity of a tree is influenced by the carbon stock, which is in turn affected by the diameter of the trunk and the density of the trees (Hayati et al. 2023).

On the basis of Basic Forestry Law No. 41 of 1999, a forest can be defined as a unified ecosystem consisting of a land area with natural resources dominated by trees within their natural environment, where each component is interdependent and inseparable. The presence of forests in a region plays a substantial role if they are understood and managed effectively. Forests are also viewed as multifunctional ecosystems, providing a variety of goods and services for human well-being (Martínez Pastur et al. 2018; Baciu et al. 2021). Forests contribute to environmental services in terms of provisioning, regulating, and cultural aspects (Ahammad et al. 2021; Suhardono et al. 2024). One of the most crucial roles of forests is their contribution to carbon. Forests provide environmental services as absorbers of carbon dioxide and contributors of oxygen production, as well as offer economic value through carbon credits.

Effective forest management in a region can enhance the benefits provided. This management can be achieved by designating forest areas for specific purposes, commonly known as SPFA (special purpose forest areas). One such forest classified as SPFA is Mount Bromo forest. The status of Mount Bromo forest as a SPFA is based on the Decree of the Minister of Environment and Forestry No. 177/MENLHK/SETJEN/PLA.0/4/2018 dated April 9, 2018. This decree allows Universitas Sebelas Maret to manage the area as the UNS Education and Research Forest (Wibowo et al. 2020). According to this decision, the forest area of 126,291 hectares can be developed in line with its natural resource potential, considering it carrying capacity and ensuring sustainable principles are adhered to. Sustainable principles aim to maintain and preserve the characteristics as well as forms of natural resources and ecosystems (Sutrisno et al. 2023). As a forest area, the most crucial aspect of its management is its ecological value contribution, ranging from its potential as a biomass store, carbon absorber, and provider of environmental services such as CO_2 absorption, O_2 production, and carbon credits. On the basis of these considerations, this study was conducted with the background of the author's interest in the potential of biomass, carbon, and environmental services in absorbing CO_2, producing O_2, and generating carbon credits in the SPFA Mount Bromo in the Tourism Zone. The location for this study was chosen due to the lack of existing data on these aspects in the area, and the tourism zone block was selected because this area will have many human activities, thus correlating with the level of vegetation present. Therefore, this research aimed to determine the carbon potential and environmental services in the natural tourism zone, SPFA Mount Bromo.

The current research landscape on forest ecosystems, particularly in the context of carbon sequestration and environmental services, shows a significant focus on broad, general forest areas. However, there is a notable gap in specific, localized studies, especially in unique forest environments like the SPFA Mount Bromo. This area represents a distinct ecosystem with potential for high carbon storage and diverse environmental services, which has not been extensively studied or quantified. Additionally, the interplay between human activities in the tourism zone and its impact on the forest carbon sequestration capability is an underexplored area. Addressing this gap will provide valuable insights into the specific contributions of such unique ecosystems to climate change mitigation and sustainable forestry practices. This study aimed to evaluate and quantify the potential of carbon sequestration and environmental services provided by the SPFA Mount Bromo, specifically within its Natural Tourism Zone, to enhance understanding of its role in climate change mitigation and sustainable forest management.

METHOD

Study location

The location of this research is in the special purpose forest area of Mount Bromo, located on Jl. Derpoyudo, Pelet, Gedong, Karanganyar District, Karanganyar Regency, Central Java. Geographically, SPFA Mount Bromo is situated at coordinates -7.581685288639392, 110.99375744321637. The total area of SPFA Mount Bromo is 126,291 hectares. Meanwhile, the area of the natural tourism zone is approximately 12.59 hectares. The research location can be seen in Figure 1. Additionally, this research was conducted in March - April of the year 2023.

Data collection method

The equipment and materials used in this study included a camera, laptop/computer, Microsoft Office software, survey stakes, a rolling meter, a Hagameter measuring tape, writing tools, and a field data tally sheet. Primary data was obtained through direct observation in SPFA Bromo by sampling various tree species, the number of trees of each species, tree diameter, and tree height. Meanwhile, secondary data supporting this article was obtained from journal literature, focusing on general conditions at the research location such as zoning maps, land cover distribution maps, types of vegetation, and forest types at the research site. The data collection location was determined using the purposive sampling method by designing observational sample plot (OSP) layouts based on the modified P.33/Menhut-II/2009 method (Fig. 2).

Data analysis method

The data analysis method used in this research is descriptive quantitative. The data processing approach involves mathematical formula calculations based on primary data, which include tree species, the number of trees of each species, tree diameter, and height. After processing using these formulas, the results are then described

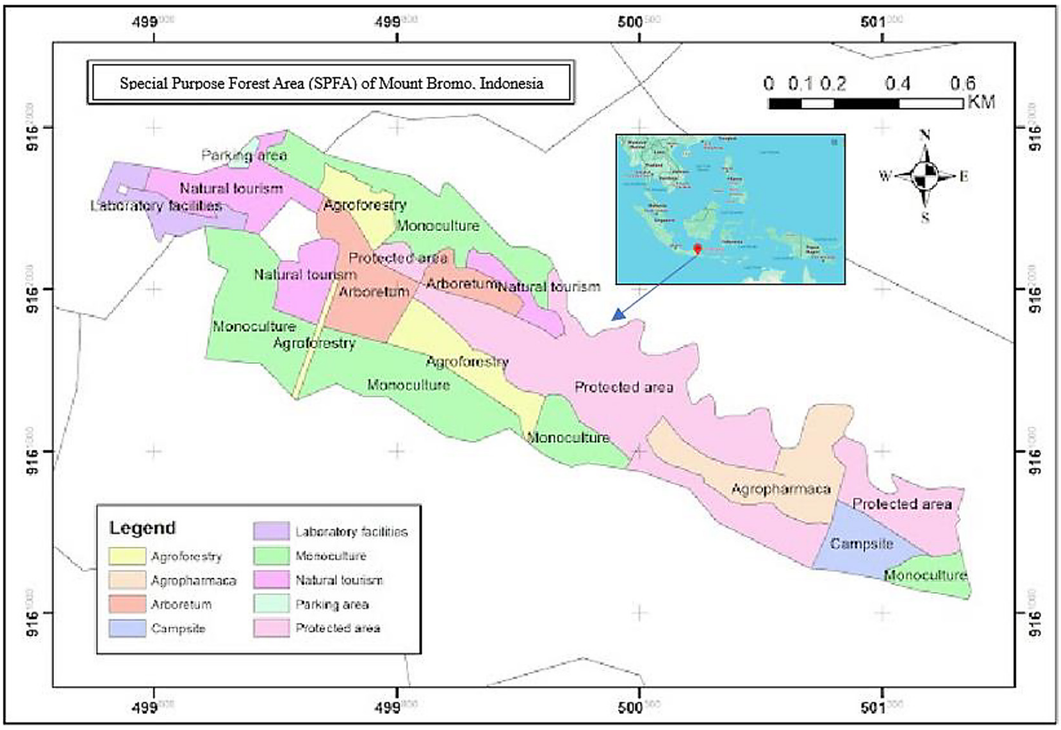

Figure 1. Study site in SPFA Bromo, Indonesia

descriptively. The calculations in this study used formulas to determine biomass potential, carbon potential, and potential for environmental services.

Biomass potential

The determination of biomass potential is based on above-ground biomass potential and below-ground biomass potential. Above-ground biomass potential is calculated using the Biomass Expansion Factor (BEF) by determining the wood volume using Equation 1.

$$V = \frac{1}{4}\pi . DBH^2 . f \tag{1}$$

where: V – tree volume (m^3), DBH – diameter at breast height (m), Phi – 3.14, H – total tree height (m), f – shape factor (0.6).

After determining the tree volume, the estimated biomass potential is calculated using the National Standardization Agency of Indonesia Number 7724 (Badan Standardisasi Nasional Indonesia (BSNI) 2011) Equation 2.

$$B_{ap} = V.BJ, BEF \tag{2}$$

where: B_{ap} – above-ground biomass (kg), V – wood volume (m^3), BJ – wood density (kg/m^3), BEF – biomass expansion factor.

Finally, the calculation of above-ground biomass is accumulated into a per-hectare area using the Equation 3.

$$B_{ap} = \frac{B_x}{1000} . \frac{10000}{L} \tag{3}$$

where: B_{ap} – biomass per unit area (ton/ha), B_x – biomass storage value (kg), L – area of the observational sample plot (m^2).

Carbon potential

The determination of carbon potential is based on above-ground and below-ground carbon potential. Above-ground carbon potential can be estimated using the formula of the National Standardization Agency of Indonesia Number (Badan Standardisasi Nasional Indonesia (BSNI) 2011).

$$C_{ap} = B_{ap} . \%C\ organic \tag{4}$$

where: C_{ap} – above-ground carbon (ton/ha), B_{ap} – above-ground biomass (ton/ha), % C organic – carbon storage percentage value of 0.47.

Below-ground carbon potential can be analyzed using the National Standardization Agency of Indonesia Number (Badan Standardisasi Nasional Indonesia (BSNI) 2011) Equation 5.

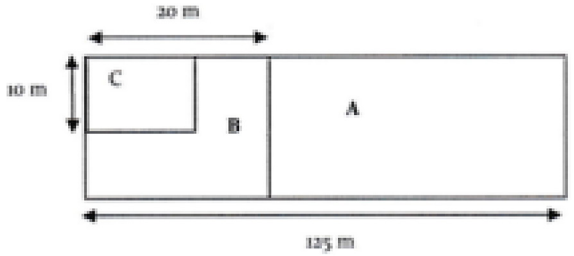

Figure 2. Design of observational sample plots: Sub OSP 20×125 m (a) for measuring DBH (diameter at breast height) > 30 cm, Sub OSP 20×20 m (b) for measuring DBH > 15–30 cm, Sub OSP 10×10 m (c) for measuring DBH > 5- <15 cm

$$C_{bp} = B_{bp} . \%\ C\ organic \tag{5}$$

where: C_{bp} – below-ground carbon (ton/ha), B_{bp} – below-ground biomass (ton/ha), %C *organic* – carbon storage percentage value of 0.47.

The calculation of total carbon stock potential can be calculated using Equation 6.

$$C_t = C_{ap} + C_{bp} \tag{6}$$

where: C_t – total carbon (ton/ha).

Environmental service potential

The determination of environmental service potential is based on absorbed CO_2, O_2 production, and Carbon Credits. The calculation of the CO_2 absorption environmental service value can be analyzed using Equation 7 (Hardjana 2010).

$$CO_2\ absorbed = C \cdot 3.67 \tag{7}$$

where: CO_2 absorbed – absorbed carbon dioxide (ton/ha), Ct – total carbon storage (ton/ha), 3.67 – equivalent number or conversion factor from C to CO_2.

Carbon credits can be obtained by multiplying the absorbed CO_2 by the prevailing carbon credit price, minus the transaction costs. The carbon credit price is based on The World Bank (2019) at USD 40/ton. Transaction costs are defined as administrative process costs, verification of emission reduction services using absorbed CO_2, and monitoring. The transaction cost for absorbed CO_2 emission reduction in the forestry sector is USD 1.23 (Antinori and Sathaye 2007). Thus, the environmental service value of carbon credits is calculated using equation 8.

$$\textit{Carbon credit} = \text{HJ CO}_2 \cdot \text{CO}_2\ \textit{absorbed} \tag{8}$$

where: *Carbon credit* – carbon dioxide compensation (ton/ha), $HJCO_2$ – carbon credit selling price (USD 40/ton), CO_2 absorbed – absorbed carbon dioxide (ton/ha)

The value of the O_2 production environmental service can be calculated using the CO_2 absorption development Equation 9.

$$O_2\ \textit{production} = CO_2 \cdot 0.73 \tag{9}$$

where: O_2 *production* – oxygen production (ton/ha), CO_2 absorbed – absorbed carbon dioxide (ton/ha), 0.73 – equivalent number or conversion factor from CO_2 to O_2.

RESULTS AND DISCUSSION

On the basis of the observations detailed in Figure 3, within the Natural Tourism Zone of the Special Purpose Forest Area (SPFA) Mount Bromo, a variety of plant species have been identified. Among these, the area is primarily dominated by Mahogany trees, accounting for 83 trees per hectare. Interestingly, despite the range of species present, the specific sample plots of the study did not record the presence of pine or rosewood trees. This lack of variety in tree species within the sampled plots suggests that the biodiversity in this zone of Mount Bromo is relatively low. It is important to note that biodiversity plays a crucial role in the health and stability of an ecosystem (Verma et al. 2020; Hong et al. 2022). Generally, the areas with higher biodiversity tend to have more stable ecosystems (Chen et al. 2021). This stability stems from diverse species performing various ecological functions, creating a more resilient environment against disturbances and environmental changes. Therefore, the observed lower biodiversity in the Natural Tourism Zone of SPFA Mount Bromo might indicate a less stable ecosystem compared to more diverse areas.

Biomass refers to the total biological material above the surface of a tree. Biomass is classified into two types, based on its location: above-ground biomass and below-ground biomass. Above-ground biomass includes the trunk, branches, leaves, flowers, and fruit, while below-ground biomass consists of roots. The amount of biomass can be expressed in units of dry weight tons per unit area. Tree biomass correlates with the absorption of CO_2. The extent of carbon absorption in a forest can be determined through the measurement of forest biomass (Trlica et al. 2020). The average biomass potential in the tourism zone of SPFA Alas Bromo can be seen in Table 1.

Table 1 shows that the biomass potential in the tourism zone of SPFA Alas Bromo is as follows: in diameter class C, it can produce biomass of 13.70 (ton/ha), in diameter class B, it can produce biomass of 34.23 (ton/ha), and in diameter class A, it can produce biomass of 968.38 (ton/ha). This amount of biomass potential can illustrate the extent of carbon absorption, considering that 47% of biomass is stored carbon (Badan Standardisasi Nasional Indonesia (BSNI) 2011). The trees with diameter class A are known to have the highest potential biomass value. The magnitude of biomass potential is influenced by two factors: tree density and the diameter of each tree (Bachmid et al., 2018). This correlates because trees with diameter class A are those with a large category diameter, namely with DBH (Diameter at Breast Height) of

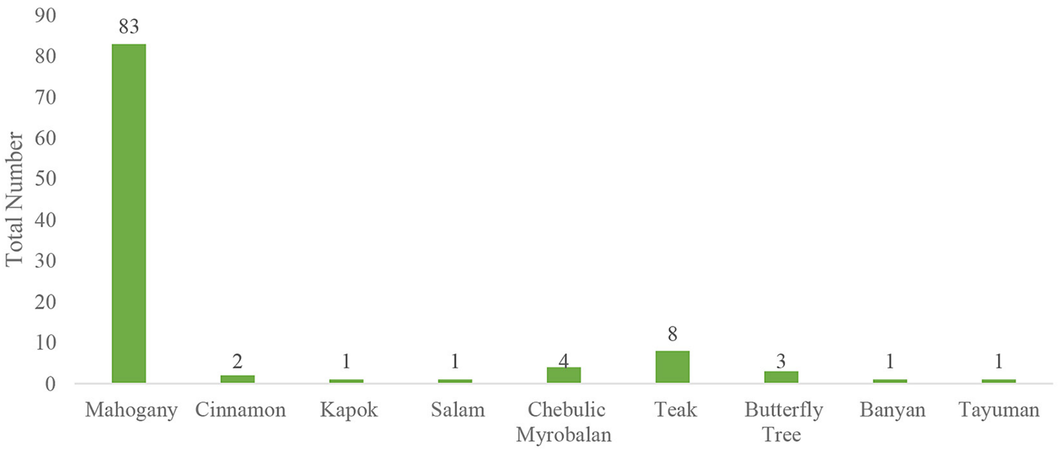

Figure 3. Composition of types & number of trees in SPFA Bromo, Indonesia

Table 1. Biomass potential

Class diameter	Biomass potential (ton/ha)		
	B_{ap}	B_{bd}	B total
C	10.62	3.08	13.70
B	26.53	7.69	34.23
A	750.68	217.70	968.38

more than 30 cm. The lowest biomass potential is in diameter class C due to having the smallest diameter category. On the basis of these results, it is known that the highest biomass potential is found in the trees with larger diameters.

The detailed analysis of biomass potential in the study, as outlined in Table 1, provides a comprehensive understanding of the biomass distribution around interest. The calculations distinguish between above-ground and below-ground biomass potentials, offering insights into the overall biomass contribution of the forest ecosystem, including:

- above-ground biomass potential – this includes all the biomass present above the soil surface, encompassing tree trunks, branches, leaves, flowers, and fruits. The calculated value for the above-ground biomass in the study area is 787.84 ton/ha. This substantial figure reflects the volume of biological matter contained in the forest canopy and other above-ground components of the trees and vegetation in the area.
- below-ground biomass potential – this refers to the biomass found below the soil surface, primarily consisting of roots. Roots play a crucial role in a tree's stability, nutrient absorption, and carbon storage. The below-ground biomass potential in the study area is quantified at 228.47 ton/ha. This value underscores the significant contribution of root systems to the overall biomass and ecological functioning of the forest.
- total overall biomass – combining these two components provides a holistic view of the forest's total biomass. The sum of the above-ground and below-ground biomass potentials gives a comprehensive total biomass value of 1016.31 ton/ha for the study area. This aggregate figure is critical in understanding the full scope of the forest biomass, which is a key indicator of the forest health, productivity, and its ability to sequester carbon.

This detailed breakdown of biomass potential is essential for ecological assessments, carbon stock calculations, as well as for formulating strategies for forest conservation and sustainable management. The high total biomass value indicates a significant capacity for carbon storage and highlights the importance of such ecosystems in global carbon cycling and climate change mitigation efforts.

The concept of carbon potential, detailed in Table 2, is essential for understanding the role of forests in carbon sequestration. It refers to the capacity of plants, particularly trees, to absorb and store carbon in their biomass, a crucial element in the global carbon cycle with significant implications for climate change mitigation. Carbon content potential is determined by converting the total carbon stored in each part of a tree, such as the trunk, branches, leaves, and roots, into a quantifiable value. The total number of trees per hectare is factored into this calculation, providing an estimate of the carbon storage potential of a specific area, following the research approach (Hardjana 2010). The calculation of carbon storage within the biomass is done using the values derived from the allometric equation. According to the National Standardization Agency of Indonesia, about 47% of the biomass in a forest comprises stored carbon. This percentage helps estimate the amount of carbon sequestered within the biomass. Table 2 differentiates between the carbon stored above and below the ground (Badan Standardisasi Nasional Indonesia – BSNI, 2011). The highest above-ground carbon storage (C_{ap}) is found in the trees with larger diameters (class A), with a Cap value of 352.82, while the lowest above-ground carbon potential is seen in the trees with smaller diameters (class C), with a value of 4.99. For below-ground carbon potential (Cbp), the largest value (102.32) is associated with the larger diameter trees (class A), and the smallest value (1.45) is linked to the smaller diameter trees (class C). The diameter of a tree significantly influences its ability to absorb carbon. Larger trees, with greater diameters, have a higher capacity for carbon absorption due to their larger biomass, which includes more extensive trunk, branch, and root systems (Verisandria et al. 2018). In essence, carbon potential, as outlined in Table 2, measures the amount of carbon that can be absorbed and stored by the trees in a given area. It varies significantly based on the size (diameter) of the trees, with larger trees having a greater capacity for carbon storage. This understanding is vital for the forest management practices aimed at maximizing carbon sequestration and for the strategies to mitigate the effects of climate change. Table

Table 2. Carbon potential

Class diameter	Carbon potential (ton/ha)		
	C_{ap}	C_{bd}	C total
C	4.99	1.45	6.44
B	12.47	3.62	16.09
A	352.82	102.32	455.14

2 explains the total carbon storage above-ground (Cap), carbon storage below-ground (Cbp), and total carbon storage in the SPFA Mount Bromo tourism zone. For above-ground carbon storage, when calculated from all Diameter classes, it is produced with a total value of 370.29 ton/ha. Next, the total below-ground carbon storage has a total value of 107.38 ton/ha. For the total carbon storage obtained from trees in the SPFA Mount Bromo area, it is 477.67 ton/ha.

Environmental services are the benefits obtained by humans and the environment from the concept of natural systems based on natural ecosystem processes (Tan et al. 2020; Lavorel et al. 2020). SPFA Mount Bromo is a forest area with a natural ecosystem, thus contributing potential environmental services. In this study, calculations were made for the potential environmental services from the absorbed CO_2 value, O_2 production, and carbon credits generated by the SPFA Mount Bromo tourism zone. The calculation results can be seen in Table 3.

On the basis of the calculations presented in Table 3, the potential environmental service value of absorbed CO_2 ranges from 23.64 (ton/ha) produced by diameter class C, 59.04 (ton/ha) produced by diameter class B, and 1670.36 (ton/ha) produced by diameter class A. On the basis of these amounts, the total CO_2 absorption potential that can be performed by the SPFA Mount Bromo tourism zone is about 1753.04 (ton/ha). The potential for carbon dioxide absorption is a calculation to estimate the value of carbon dioxide that can be absorbed by a forest stand. The amount of CO_2 absorbed is related to the carbon content in plants, as the carbon content will be directly proportional to the plant's ability to bind CO_2 in the air (Godin et al. 2021; Garcia et al. 2022). In relation to the ability of plants to absorb carbon dioxide, the diameter and height of a plant can indirectly affect the intensity of absorption produced (Liang et al. 2020; Khatoon and Kim 2022; Zarbakhsh and Shahsavar 2023).

Table 3. Environmental service potential

Class diameter	Environmental service potential		
	CO_2 absorbed (ton/ha)	O_2 production (ton/ha)	Carbon credit (US$/ha)
C	23.64	17.26	0.95
B	59.04	43.10	2.36
A	1670.36	1219.36	66.81
Total	1753.04	1279.72	70.12

According to the calculations presented in Table 3, the potential O_2 production generated by the SPFA Mount Bromo Tourism Zone has the lowest value in diameter class C at 17.26 ton/ha, followed by diameter class B with a value of 43.10 ton/ha, and the highest is produced by diameter class A with a value of 1219.36 ton/ha. Through these results, the total value of O_2 production that can be generated at the research location is about 1279.72 ton/ha. The potential for O_2 production is a calculation made to assess the estimate of the amount of O_2 that can be produced by a plant. The oxygen production value that can be generated by a plant is related to its ability to absorb carbon dioxide. This is because oxygen production is closely related to the process of photosynthesis, where CO_2 is required to be converted into O_2. In this regard, the size of the plant also becomes a factor in the oxygen production generated (Allam 2009). Additionally, the type of plant also affects its ability to produce oxygen. Thus, larger plant species will produce a greater amount of oxygen.

The calculation of carbon credits is an estimation made to calculate the trading value of carbon dioxide compensation. In this regard, carbon credits will provide an economic environmental service when an area can contribute to supplying carbon according to applicable policies. The principle of this trade practically means that more polluting parties (with high emissions) will pay for carbon emission reduction costs to less polluting parties (Irama and SE 2020). Considering the massive issue of emissions today, this trade has significant potential in global competition. In this study, calculations were made for the carbon credit value in the SPFA Mount Bromo tourism zone. On the basis of the results obtained, the total carbon credit value that can be generated is about 70.12 US$/ha. This figure is obtained from the range of calculations for the value in diameter class C of 0.95 US$/ha, diameter class B of 2.36 US$/ha, and class A of 66.81 US$/ha.

From a policy perspective, the findings emphasize the importance of forest conservation and management strategies that prioritize the preservation of larger trees due to their significant role in carbon storage. There is also a need for initiatives to enhance biodiversity in the areas with lower species variety, such as the Natural Tourism Zone of SPFA Mount Bromo. These initiatives could include reforestation and afforestation programs with a focus on adaptive management (Suryawan and Lee 2023b, a; Sutrisno et al. 2023) that introducing and nurturing a variety of species. Future research should delve deeper into understanding the specific factors that influence biodiversity in the SPFA Mount Bromo and similar ecosystems. Additionally, studies could focus on the impact of human activities, especially tourism, on the carbon sequestration capacity and overall health of the forest. This would provide valuable insights for developing more effective conservation strategies and sustainable tourism practices that align with environmental preservation goals.

CONCLUSIONS

The tourism zone in SPFA Alas Bromo can produce 1279.72 tons of oxygen per year with a total CO_2 absorption value of 1753.04 tons/ha. The amount of oxygen produced during a certain period correlates with the amount of carbon absorbed by plants. The higher the carbon absorption value, the higher the oxygen production. Furthermore, the total carbon credit value that can be generated is approximately 70.12 US$/ha. The size of the carbon reserve and CO_2 absorption correlates with the biomass value, where the larger the biomass of a plant, the greater its carbon reserve and CO_2 absorption. Thus, it is understood that if the CO_2 absorption of a plant is high, then the environmental service value of CO_2 absorption in the plant is also high.

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