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This study found varied vegetation diversity, timber production, and biomass accumulation in each compartment. The relative contribution of commercial species to wood production and carbon stock was substantially higher than non-commercial species. Interestingly, our study did not record a significant correlation between vegetation diversity and stand productivity. It was contrary to other studies that reported a strong relationship between biodiversity and forest productivity.

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Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Borneo

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Abstract. Sustainable management in secondary tropical rainforests requires basic information about stand characteristics, mainly related to productivity and biodiversity. This study aimed to quantify vegetation diversity, timber production, and carbon storage from various sites of secondary forests in South Borneo. Forest inventory was conducted using a census method at seven different natural forest management unit compartments. Four parameters were measured from each tree, including the type of species, commercial categories, tree diameter, and tree height. Individual tree volume and biomass were estimated using allometric equations, while carbon storage was determined using a conversion factor from biomass. Three indicators were used to evaluate vegetation diversity: richness, heterogeneity, and evenness. The analysis of correlations was applied to examine the relationship between vegetation diversity and stand productivity with a significant level of 5%. Results found that there were 41 tree species in the study site comprising 20 commercial and 21 non-commercial species. The highest richness (*R′*) was recorded in compartment 18X by approximately 4.0, while the most increased heterogeneity (*H′*) and evenness (*E′*) were observed in compartment 18Y by around 2.4 and 0.7, respectively. The accumulation of timber production varied in each site, with a range of 45.46−68.32 m^3 ha^{-1}. The highest carbon storage was noted in compartment 19Y (38.74±1.79t ha^{-1}), while the lowest was found in compartment 18W (20.76±0.93 t ha^{-1}). The relative contribution of commercial species to timber production and carbon storage was substantially higher than non-commercial species at all sites. However, there was not a significant correlation between vegetation diversity and stand productivity ($P>0.05$). Overall, our study concluded that the secondary tropical forest ecosystems in the site had good vegetation diversity, timber production, and carbon storage.

Keywords: biodiversity, ecosystems, inventory, natural forest, productivity

Running title: Spatial distribution of vegetation diversity

INTRODUCTION

Biodiversity conservation, climate change mitigation, and economic development are essential issues in sustainable forest management, particularly in Indonesia. In this context, the management of forests is expected to stabilize wood supplies for commercial industries, support species conservation, and reduce carbon emissions in the atmosphere (Wirabuana et al. 2021b). To tackle these challenges, information about stand dynamics is required as baseline considerations to determine alternative forest management strategies (Pretzsch et al. 2014). It is related to timber production and includes vegetation diversity and carbon storage.

In general, the quantity of timber production will provide adequate information about the economic value of the forest and its capacity for supporting industry viability (Simmons et al. 2021). It also determines the maximum annual allowable cutting from the forest ecosystem (Asamoah et al., 2020). The number of timber production also describes the regeneration stock from different life stages of trees to maintain business sustainability (Zambiazi et al. 2021). Meanwhile, vegetation diversity information indicates the stability of environmental health and forest ecosystems (Pan et al. 2018). It also shows how many species live in the forest and their relative contribution to ecological functions (Matatula et al. 2021). The vegetation diversity can also be used to understand the natural competition in the ecosystems (Duan et al. 2021). On another side, the accumulation of carbon storage indicates the ability of the forest ecosystem to support climate change mitigation, primarily for reducing carbon emissions (Sadono et al. 2021a). Many studies explain forest vegetation generally absorbs CO_2 through the photosynthesis process. First, it converts it into biomass (Sasaki et al. 2016, Ma et al. 2017, Kocurek et al. 2020, Wirabuana et al. 2020, Sadono et al. 2021b, Setiahadi 2021). Then, the biomass will be distributed in components like roots, stems, branches, and foliage (Poorter et al. 2012, Yue et al. 2018, Altanzagas et al. 2019, Wirabuana et al. 2021a). Higher biomass indicates excellent carbon storage wherein the carbon absorption in forests will increase along with vegetation age (Arora et al. 2014). Another study report the critical role of vegetation on carbon absorption is also a part of the balance in biogeochemical cycles (Taillardat et al. 2018). To collect this information, forest inventory is necessary to support forest managers in monitoring the stand dynamics in each forest ecosystem, including secondary tropical rainforest (STR).

Before the 1990s, STR played an essential role in economic development. It provided wood materials for forest industries like furniture, veneer, and plywood. STR also occupied the second position of important sectors contributing to country revenue. However, the occurrence of deforestation has declined its contribution significantly to the gross domestic product. Most STR currently have low productivity and high biodiversity loss (Gaveau et al. 2014). To anticipate this condition, the government has conducted the effort of reforestation to recover forest productivity and prevent vegetation extinction. However, this program is not easy to implement because STR commonly has high variation in land configuration with low accessibility (Wardhana et al. 2020).

Moreover, soil quality in these sites is also dominated by mature soil with low fertility, like oxisols and ultisols (Fujii et al. 2018). Therefore, it causes the low survival rate of vegetation generated from the reforestation program. Nevertheless, several concession areas of STR still exist and maintain their functions for economic development, biodiversity conservation, and climate change mitigation. One of them is a secondary tropical rainforest area managed by PT Aya Yayang Indonesia (AYI) located in South Borneo. Although it has been managed for over 30 years, the information about forest dynamics in this location is still limited, mainly related to vegetation diversity and carbon storage. Therefore, it is essential to provide more comprehensive details on stand dynamics in this area to support better forest management efforts.

This study aims to document vegetation diversity, timber production, and carbon storage from several compartments of secondary tropical rainforests managed by AYI. This information will help forest manager to determine the forest planning strategy, mainly related to yield regulation and harvesting schedules. Thus, even though it is managed as a production zone, forest regeneration is still maintained and minimizes the risk of biodiversity loss. We hypothesize that:

(a) Every compartment has a different value for vegetation diversity, timber production, and carbon storage.
(b) Higher vegetation diversity significantly increases timber production and carbon storage.
(c) The contribution of non-commercial species on stand productivity is higher than commercial species.

MATERIALS AND METHODS

Study area

This study was conducted in the secondary tropical rainforest concession area managed by PT Aya Yayang Indonesia. It is situated in Tabalong District, approximately 270 km from Banjarmasin, the capital city of South Borneo province. The geographic coordinates of this area are located in S1°39'−1°40' and E115°29'−115°30'. Altitude ranges from 225 to 470 m above sea level. Land configuration is dominated by hills with a slope level of 15−40%. The average daily temperature is 27.6°C with a minimum of 25.7°C and a maximum of 30.3°C. The mean annual rainfall during the past ten years is 2,589 mm year^{-1}, with an average air humidity of 87.6%. The highest rainfall is recorded in November. Dry periods are relatively short, only around two months from July to August. Oxisols and ultisols dominate soil types with high acidity levels.

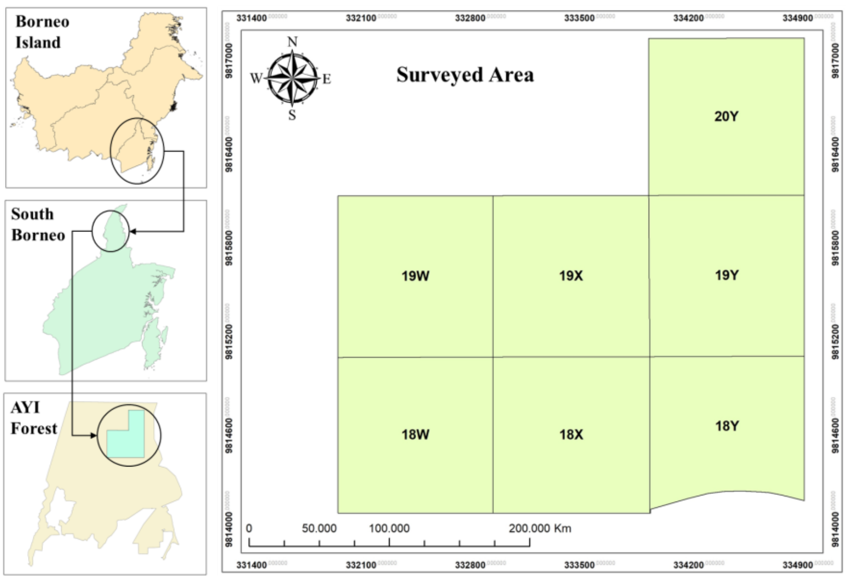


Figure 1. The study area of secondary tropical rainforest in South Borneo

Data Collection

Forest inventory was conducted using a census method at seven compartments of the secondary tropical rainforest management unit, namely 18W, 18X, 18Y, 19W, 19X, 19Y, and 20Y. The total surveyed area reached 700 ha, with each site 100 ha. To facilitate the measurement process, the field survey was conducted step by step using sub-plots of 20 m x 20 m. These sub-plots were arranged systematically; all trees in compartments could be covered and measured correctly. Four parameters were measured from each tree, i.e., type of species, commercial categories, tree diameter, and tree height. The determination of commercial and non-commercial species was undertaken, referring to the guidance from the company. Tree diameter was measured using a phi band at 1.3 m aboveground, while tree height was quantified using a haga altimeter from aboveground to the top crown. Moreover, the coordinate of trees was also recorded using a global positioning system (GPS).

Data Analysis

Three indicators were selected to describe vegetation diversity, i.e., richness, heterogeneity, and evenness. Vegetation richness was determined by Margalef Index (*R'*), while its heterogeneity was quantified using Shannon-Wiener Index (*H'*). On another side, the evenness of vegetation was assessed by Pielou Evenness Index (*E'*). Detail equations for calculating those indicators are expressed below (Nugroho et al. 2022):

$$R' = S\text{-}1/ln(N) \quad (1)$$

$$H' = -\sum (n_i/N)\ (ln\ n_i/N) \quad (2)$$

$$E' = H'/ln(S) \quad (3)$$

where *S* was the number of species observed, *N* represented the total tree population in each compartment, and n_i described the sum of trees for each species.

To determine the quantity of timber production, individual tree volume was calculated using the following equation:

$$V = 0.25\ \pi\ dbh^2\ h\ f \quad (4)$$

where *V* was tree volume (m^3), *dbh* indicated tree diameter (cm), *h* represented tree height (m), and *f* showed a constant of form factor (0.6) (Akossou et al. 2013). Then, the timber production degree was assumed to be the mean stand volume in hectare units. This value could be derived by dividing the total tree volume in a compartment by its area.

The quantification of carbon storage and CO_2 absorption were also calculated using a similar principle to timber production. However, we used biomass accumulation as a conversion to compute both parameters. In this context, the individual tree biomass was estimated using a generalized allometric model for secondary tropical rainforest as given (Krisnawati et al. 2012):

$$B = 0.047454 dbh^{2.078} \quad (4)$$

B was aboveground biomass (kg), and *dbh* indicated tree diameter (cm). Next, the carbon stock of each tree was computed by multiplying its biomass with a conversion factor of 0.46 (Latifah et al. 2018), while CO_2 absorption was estimated by multiplying carbon stock with a constant of 3.67 (Latifah & Sulistiyono 2013). Then, the result was converted into a hectare unit.

Descriptive analysis was selected to compare the value of vegetation diversity, timber production, and carbon storage among different compartments based on the trend of the histogram and the summarized information from the table. Meanwhile, the spatial distribution of three parameters was processed using QGIS. Finally, to evaluate the relationship between vegetation diversity and stand productivity, both in timber production and carbon storage, Pearson correlation analysis was applied with a significant level of 5%.

RESULTS AND DISCUSSION

Vegetation Diversity

Results found that vegetation diversity among compartments was substantially different (Table 1). The highest species abundance was recorded in the compartment of 18Y, while the lowest number of species was observed in the compartment of 20Y. Similar trends were also discovered in the richness, heterogeneity, and evenness, wherein the highest value of those indicators was noted in compartment 18Y. These findings directly confirmed our first hypothesis that assumed there was different vegetation diversity between compartments in the study site.

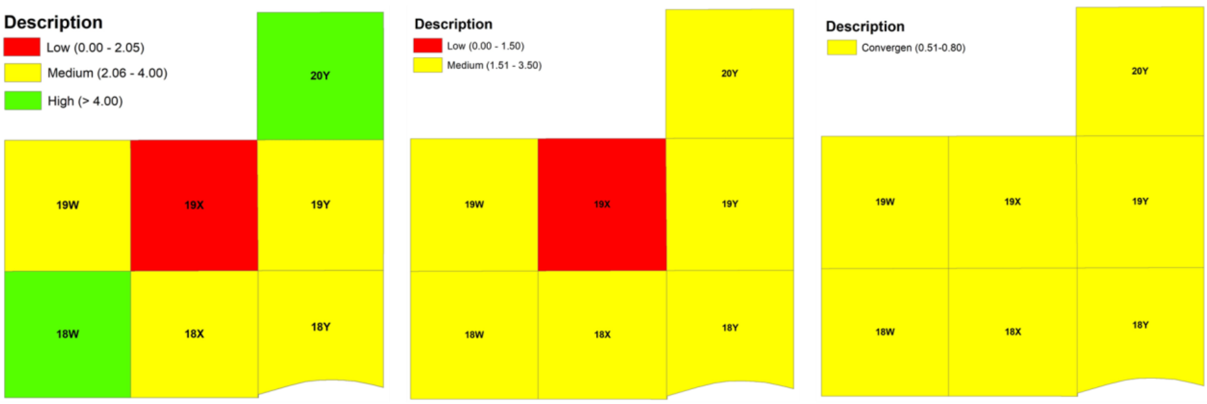
The diversity of vegetation in secondary tropical rainforests was generally caused by the interaction between vegetation and the environment. This process generated natural competition wherein trees compete with each other to obtain sufficient resources to support their survival (Wirabuana et al. 2022b). On another side, environmental variation also became a limiting factor for certain species; thus, it could inhibit several vegetation from growing well (Wang et al. 2019). Consequently, the regeneration capacity of each species in this ecosystem was highly dynamic depending on their adaptation to environmental conditions. Several previous studies also reported similar results wherein the natural regeneration in secondary tropical rainforests was exceptionally dynamics due to the impact of intraspecific and

interspecific competition between trees for obtaining light, water, nutrients, and space (Barabás et al. 2016, Adler et al. 2018, Yang et al. 2019).

Table 1. Comparison of species abundance, richness, heterogeneity, and evenness among compartments

Compartment	N species	Richness	Heterogeneity	Evenness
18W	32	4.01	1.91	0.55
18X	31	3.79	2.10	0.61
18Y	36	4.43	2.42	0.68
19W	32	3.99	1.96	0.57
19X	30	3.59	1.84	0.54
19Y	31	3.89	1.86	0.54
20Y	4	0.38	0.81	0.58

This study recorded that the heterogeneity of vegetation in the study location was dominated by medium classes with a range of 1.51−3.50 (Table 1) (Hidayat 2013). It was similar to previous studies that documented the secondary tropical rainforests commonly had medium vegetation biodiversity (Siregar and Undaharta 2018, Murdjoko et al. 2021, Tawer et al. 2021). This condition could happen because this site was managed using a selective cutting system; thus, only certain species were maintained to support the ecological function of the forest (Butarbutar 2014). In addition, most trees with a limit diameter of more than 50 cm and having commercial values were harvested to provide better-growing space for younger trees (Matangaran et al. 2019). Therefore, this scheme was expected to stabilize the regeneration capacity of secondary forests without sacrificing its economic benefits.



(a) Richness **(b) Heterogeneity** **(c) Evenness**

Figure 2. Spatial distribution of vegetation diversity in the study site

Our results also indicated that species distribution in the study site was not evenly distributed. It was shown by the evenness index value ranging from 0.54 to 0.68 (Table 1). These outcomes signified that most species in this location grew in groups (Hussain et al. 2012). It was not surprising since Dipterocarpaceae families dominated most species in secondary tropical rainforests. Many studies explained that these families naturally live in groups and have a specific preference for their habitat (Purwaningsih 2004, Hadi et al. 2019, Sari et al. 2019).

According to the results, it was seen that vegetation diversity in the study site was still maintained well. It also implied that the forest management activity in this area fulfills the principle of sustainability by minimizing the risk of biodiversity loss. However, the effort of enrichment planting is required to improve biodiversity in the compartment with low diversity level. This scheme will also facilitate the conservation of native species from the secondary tropical rainforests.

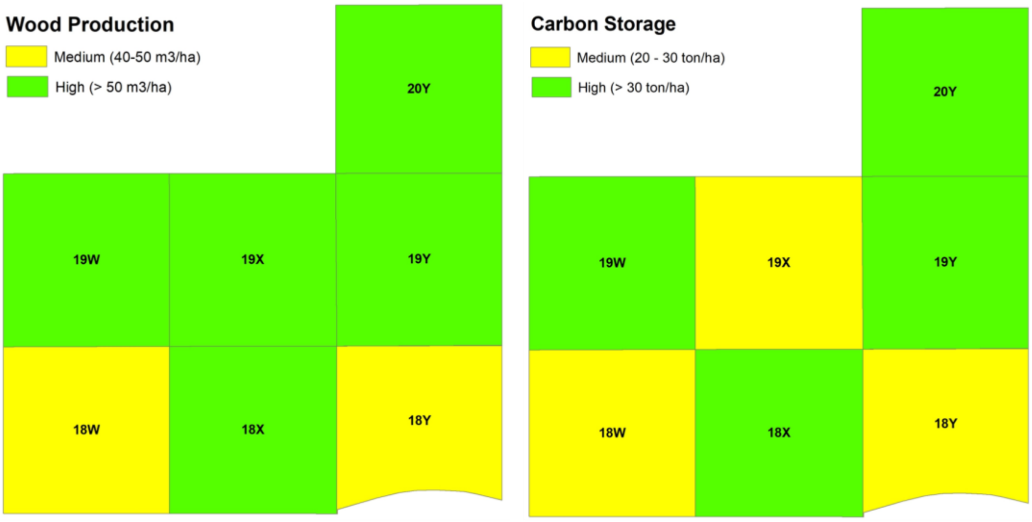
Timber Production

Summarized observation results documented that timber production in the study area ranged from 44.49±1.72 m^3 ha^{-1} to 68.32±2.69 m^3 ha^{-1} (Table 2). These values were substantially higher than the average productivity of Borneo's natural forests, ranging from 30 m^3 ha^{-1} (KLHK, 2019). Therefore, it indicated that the secondary tropical rainforest in this area had high productivity and could still support industry development. Moreover, this study recorded that the average timber production in each compartment was relatively different, wherein the most increased timber production was found in the compartment of 19Y. These findings also confirmed our first hypothesis that timber production was highly varied between compartments in secondary tropical rainforests.

Table 2. Comparison of timber production, biomass accumulation, carbon storage, and CO_2 absorption among compartments

Compartment	Timber production (m^3 ha^{-1})	Biomass accumulation (t ha^{-1})	Carbon stock (t ha^{-1})	CO_2 absorption (t ha^{-1})
18W	44.49±1.72	45.13±2.02	20.76±0.93	76.18±3.40
18X	56.05±2.05	68.35±2.85	31.44±1.31	115.38±4.81
18Y	54.3±2.43	69.25±3.74	31.86±1.73	116.92±6.32
19W	45.56±1.86	48.83±2.42	22.46±1.12	82.44±4.08
19X	54.96±1.55	67.11±2.44	30.87±1.12	113.29±4.11
19Y	68.32±2.69	84.22±3.89	38.74±1.79	142.17±6.56
20Y	50.57±2.30	46.37±2.36	21.33±1.09	78.29±3.98

Interestingly, the compartment of 18Y only occupied the fourth position of the most productivity compartments, even though it had the highest vegetation diversity (Table 2). Our study also did not find a significant correlation between vegetation diversity and timber production (Table 3). It was in contrast to previous studies that documented a substantial effect of vegetation diversity on stand productivity in tropical rainforest ecosystems (Cai et al. 2016, Gevaña et al. 2017, McNicol et al. 2018). These findings rejected our second hypothesis that higher vegetation diversity significantly increases timber production in the study site. However, several kinds of literature also found a similar outcome to ours wherein there was no significant relationship between vegetation diversity and forest productivity (Belote et al. 2011, Bravo-Oviedo et al. 2021). In this context, forest ecosystems may have diverse patterns regarding the connection between biodiversity and productivity.



(a) Timber Production **(b) Carbon Storage**

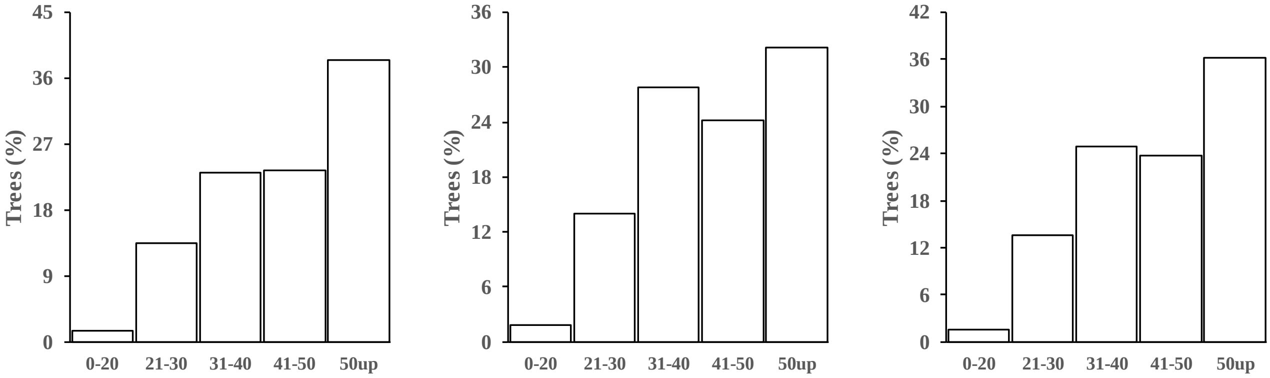
Figure 3. Spatial distribution of timber production and carbon storage in the study site

Table 3. Correlation between diversity indicators and stand productivity parameters

Diversity parameter	Productivity parameter	
	Timber production	Carbon Storage
Richness	0.123^{ns}	0.420^{ns}
Heterogeneity	0.116^{ns}	0.442^{ns}
Evenness	-0.056^{ns}	0.098^{ns}

ns: non-significant based on correlation test

Forest ecosystems in the study site had high productivity since their vegetation was dominated by trees with a diameter of more than 50 cm (Figure 4). On another side, the frequency of trees with a diameter lower than 20 cm was only around 2%. These indicated there was sufficient stock of timber production for selective cutting. Moreover, the relative contribution of non-commercial species to total timber production was considerably lower than commercial species (Figure 4). It demonstrated that the current standing stock had high economic value. These results confirmed our third hypothesis that commercial species' relative contribution to stand productivity was higher than non-commercial species. Although this site had increased productivity, forest managers should be careful to determine the quantity of annual allowable cutting (AAC) since the implementation of timber extraction can be impacted young trees' regeneration. Most importantly, the process of timber extraction should not harvest trees that generate seeds for maintaining natural regeneration.



(a) Commercial (b) Non Commercial (c) All Species

Figure 4. Diameter distribution of tree species in the study site

Carbon Storage

Carbon storage in each compartment varied, wherein the carbon stock in the study site ranged from 20.76±0.93 t ha^{-1} to 38.74±1.79 t ha^{-1} (Table 3). The highest CO_2 absorption was recorded in the compartment of 19Y by around 142.17±6.56 t ha^{-1}. In addition, the relative contribution of commercial species on carbons stock was considerably higher than species non-commercial (Figure 4). These findings directly verified our first and third hypotheses in this study. However, similarly to timber production, our study did not find a significant effect of vegetation diversity on carbon storage in this area (Table 3).

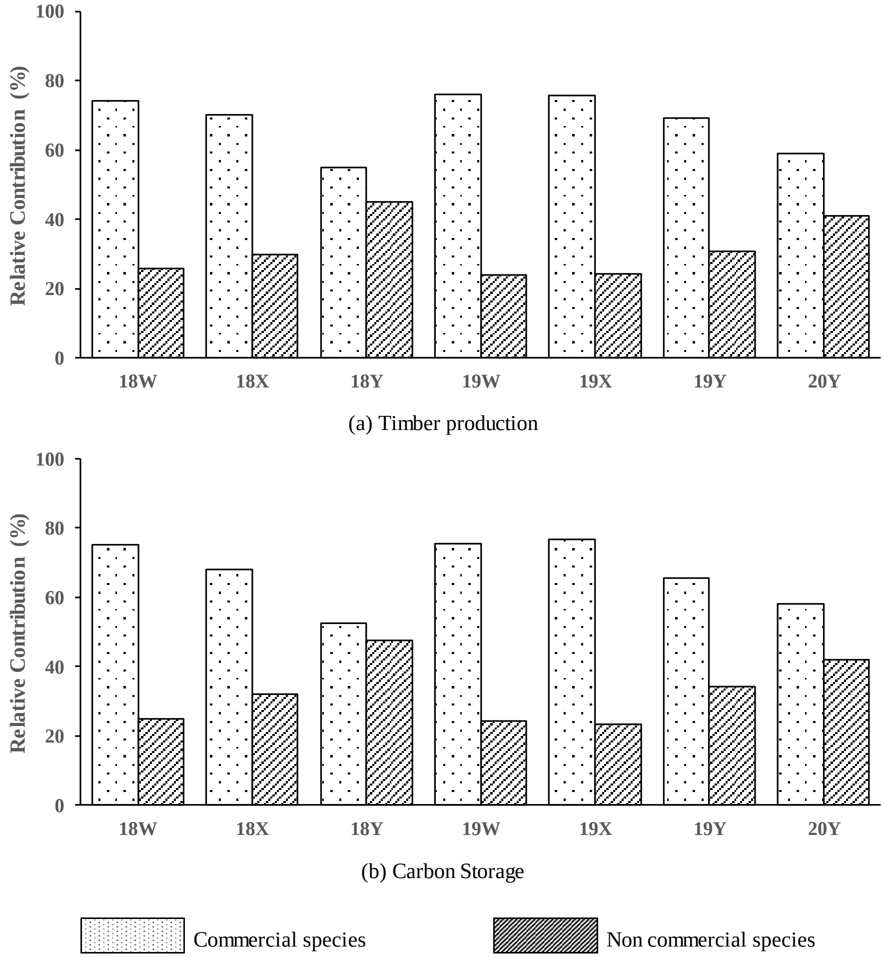


Figure 4. The relative contribution of commercial and non-commercial species on timber production and carbon storage

The accumulation of carbon storage in forest ecosystems has a positive relationship with stand productivity. Higher stand productivity increases carbon stock since it was generated from photosynthesis (Cai et al. 2016, Brancalion et al. 2019, Alam et al. 2022, Wirabuana et al. 2022a). A study reported the average carbon stock in tropical rainforest ecosystems was 51.18 t ha^{-1} (Butarbutar et al. 2019). This value is higher than carbon storage in the study site. However, this study's carbon stock measurement is still limited to the tree level. We still have not quantified the carbon stock in other life stages like poles, saplings, seedlings, and understorey. Thereby, the actual carbon storage in the study area may be higher than the current estimation. It is also essential for forest managers in the study location to consider the quantity of carbon stock as the additional value of sustainable natural resources management.

Implication Results

This study concluded that the secondary tropical rainforest ecosystems in the study site had good vegetation diversity, timber production, and carbon storage. Furthermore, it indicated that forest managers had applied sustainability principles in the context of operation scale. Nevertheless, some improvements are still required to increase the value of forest management on this site. Besides conducting enrichment planting in the compartment with low biodiversity levels, we also suggest forest managers determine the scheme of yield regulation to minimize forest disturbance due to the impact of harvesting operations. Furthermore, the cutting process has a high potential to decline regeneration capacity since the felled trees will override the younger plants like seedlings and saplings.

We also suggest forest managers identify the distribution of mother trees in their concession area for obtaining seed as plant material in artificial regeneration. The seed collection is also essential to maintain the genetic diversity in this area. On another side, it is also necessary to document the carbon dynamics during the rotation periods, including loss and increment, since it will provide comprehensive information about forest management's effectiveness in tackling the climate change mitigation issue. We also encourage forest managers in this area to share their knowledge with other natural resources managers who fail to manage the secondary tropical rainforest ecosystems. It is highly required since forest ecosystems play an essential role in economic development, climate change mitigation, and biodiversity conservation. They have a strategic position in hydrological cycles related to food security and natural disaster.

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UGM Mail

Pandu Yudha Adi Putra Wirabuana <pandu.yudha.a.p@ugm.ac.id>

[biodiv] Editor Decision

1 message

Nor Liza <smujo.id@gmail.com> Fri, Nov 11, 2022 at 9:09 AM
To: Pandu Wirabuana <pandu.yudha.a.p@ugm.ac.id>

Pandu Wirabuana:

We have reached a decision regarding your submission to Biodiversitas Journal of Biological Diversity, "Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Borneo".

Our decision is: Revisions Required

Reviewer A:

Dear Editor-in-Chief,

The article is an interesting and comprehensive analysis to link species diversity, timber production, and carbon stock. However, I suggest to the author make some revisions to make more clear on the materials and method section. Please find the comments in the attached file. Overall, the article should be considered to be published in this journal.

Best regards

Recommendation: Revisions Required

Reviewer J:

My comments on how the manuscript can be improved are in the word document. There are major information gaps in the manuscript, but more fundamentally I am not seeing how the sampling sites were selected. Are the samples representative of the landscape? If not, then the results are not meaningful for management.

Recommendation: Resubmit for Review

Biodiversitas Journal of Biological Diversity

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2 attachments

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Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Borneo

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Abstract. Sustainable management in secondary tropical rainforests requires basic information about stand characteristics, mainly related to productivity and biodiversity. This study aimed to quantify vegetation diversity, timber production, and carbon storage from various sites of secondary forests in South Borneo. Forest inventory was conducted using a census method at seven different natural forest management unit compartments. Four parameters were measured from each tree, including the type of species, commercial categories, tree diameter, and tree height. Individual tree volume and biomass were estimated using allometric equations, while carbon storage was determined using a conversion factor from biomass. Three indicators were used to evaluate vegetation diversity: richness, heterogeneity, and evenness. The analysis of correlations was applied to examine the relationship between vegetation diversity and stand productivity with a significant level of 5%. Results found that there were 41 tree species in the study site comprising 20 commercial and 21 non-commercial species. The highest richness (*R′*) was recorded in compartment 18X by approximately 4.0, while the most increased heterogeneity (*H′*) and evenness (*E′*) were observed in compartment 18Y by around 2.4 and 0.7, respectively. The accumulation of timber production varied in each site, with a range of 45.46−68.32 m^3 ha^{-1}. The highest carbon storage was noted in compartment 19Y (38.74±1.79t ha^{-1}), while the lowest was found in compartment 18W (20.76±0.93 t ha^{-1}). The relative contribution of commercial species to timber production and carbon storage was substantially higher than non-commercial species at all sites. However, there was not a significant correlation between vegetation diversity and stand productivity (*P>0.05*). Overall, our study concluded that the secondary tropical forest ecosystems in the site had good vegetation diversity, timber production, and carbon storage.

Commented [A1]: Timber production may or may not lead to long-term carbon storage.

Keywords: biodiversity, ecosystems, inventory, natural forest, productivity

Running title: Spatial distribution of vegetation diversity

INTRODUCTION

Biodiversity conservation, climate change mitigation, and economic development are essential issues in sustainable forest management, particularly in Indonesia. In this context, the management of forests is expected to stabilize wood supplies for commercial industries, support species conservation, and reduce carbon emissions in the atmosphere (Wirabuana et al. 2021b). To tackle these challenges, information about stand dynamics is required as baseline considerations to determine alternative forest management strategies (Pretzsch et al. 2014). It is related to timber production and includes vegetation diversity and carbon storage.

In general, the quantity of timber production will provide adequate information about the economic value of the forest and its capacity for supporting industry viability (Simmons et al. 2021). It also determines the maximum annual allowable cutting from the forest ecosystem (Asamoah et al., 2020). The number of timber production also describes the regeneration stock from different life stages of trees to maintain business sustainability (Zambiazi et al. 2021). Meanwhile, vegetation diversity information indicates the stability of environmental health and forest ecosystems (Pan et al. 2018). It also shows how many species live in the forest and their relative contribution to ecological functions (Matatula et al. 2021). The vegetation diversity can also be used to understand the natural competition in the ecosystems (Duan et al. 2021). On another side, the accumulation of carbon storage indicates the ability of the forest ecosystem to support climate change mitigation, primarily for reducing carbon emissions (Sadono et al. 2021a). Many studies explain forest vegetation generally absorbs CO_2 through the photosynthesis process. First, it converts it into biomass (Sasaki et al. 2016, Ma et al. 2017, Kocurek et al. 2020, Wirabuana et al. 2020, Sadono et al. 2021b, Setiahadi 2021). Then, the biomass will be distributed in components like roots, stems, branches, and foliage (Poorter et al. 2012, Yue et al. 2018, Altanzagas et al. 2019, Wirabuana et al. 2021a). Higher biomass indicates excellent carbon storage wherein the carbon absorption in forests will increase along with vegetation age (Arora et al. 2014). Another study report the critical role of vegetation on carbon absorption is also a part of the balance in biogeochemical cycles (Taillardat et al. 2018). To collect this information, forest

inventory is necessary to support forest managers in monitoring the stand dynamics in each forest ecosystem, including secondary tropical rainforest (STR).

Before the 1990s, STR played an essential role in economic development. It provided wood materials for forest industries like furniture, veneer, and plywood. STR also occupied the second position of important sectors contributing to country revenue. However, the occurrence of deforestation has declined its contribution significantly to the gross domestic product. Most STR currently have low productivity and high biodiversity loss (Gaveau et al. 2014). To anticipate this condition, the government has conducted the effort of reforestation to recover forest productivity and prevent vegetation extinction. However, this program is not easy to implement because STR commonly has high variation in land configuration with low accessibility (Wardhana et al. 2020).

Moreover, soil quality in these sites is also dominated by mature soil with low fertility, like oxisols and ultisols (Fujii et al. 2018). Therefore, it causes the low survival rate of vegetation generated from the reforestation program. Nevertheless, several concession areas of STR still exist and maintain their functions for economic development, biodiversity conservation, and climate change mitigation. One of them is a secondary tropical rainforest area managed by PT Aya Yayang Indonesia (AYI) located in South Borneo. Although it has been managed for over 30 years, the information about forest dynamics in this location is still limited, mainly related to vegetation diversity and carbon storage. Therefore, it is essential to provide more comprehensive details on stand dynamics in this area to support better forest management efforts.

This study aims to document vegetation diversity, timber production, and carbon storage from several compartments of secondary tropical rainforests managed by AYI. This information will help forest manager to determine the forest planning strategy, mainly related to yield regulation and harvesting schedules. Thus, even though it is managed as a production zone, forest regeneration is still maintained and minimizes the risk of biodiversity loss. We hypothesize that: Every compartment has a different value for vegetation diversity, timber production, and carbon storage (i). Higher vegetation diversity significantly increases timber production and carbon storage (ii). The contribution of non-commercial species on stand productivity is higher than commercial species (iii).

MATERIALS AND METHODS

Study area

Commented [A2]: What is the history of the site? How long ago was it last logged? Logged for how many times? How was it logged?

This study was conducted in the secondary tropical rainforest concession area managed by PT Aya Yayang Indonesia. It is situated in Tabalong District, approximately 270 km from Banjarmasin, the capital city of South Borneo province. The geographic coordinates of this area are located in S1°39'−1°40' and E115°29'−115°30'. Altitude ranges from 225 to 470 m above sea level. Land configuration is dominated by hills with a slope level of 15−40%. The average daily temperature is 27.6°C with a minimum of 25.7°C and a maximum of 30.3°C. The mean annual rainfall during the past ten years is 2,589 mm $year^{-1}$, with an average air humidity of 87.6%. The highest rainfall is recorded in November. Dry periods are relatively short, only around two months from July to August. Oxisols and ultisols dominate soil types with high acidity levels.

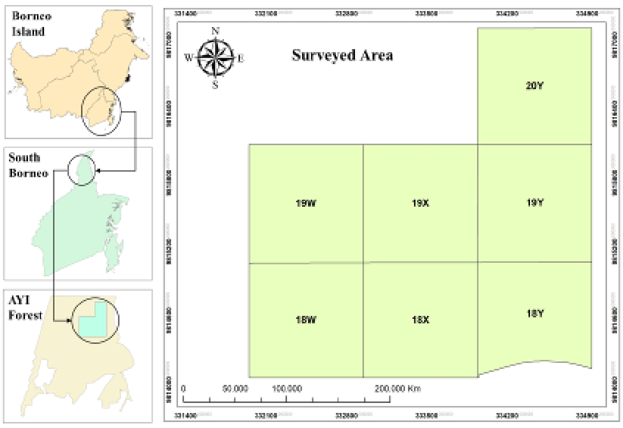

Figure 1. The study area of secondary tropical rainforest in South Borneo

Data collection

Forest inventory was conducted using a census method at seven compartments of the secondary tropical rainforest management unit, namely 18W, 18X, 18Y, 19W, 19X, 19Y, and 20Y. The total surveyed area reached 700 ha, with each site 100 ha. To facilitate the measurement process, the field survey was conducted step by step using sub-plots of 20 m x 20 m. These sub-plots were arranged systematically; all trees in compartments could be covered and measured correctly. Four parameters were measured from each tree, i.e., type of species, commercial categories, tree diameter, and tree height. The determination of commercial and non-commercial species was undertaken, referring to the guidance from the company. Tree diameter was measured using a phi band at 1.3 m aboveground, while tree height was quantified using a haga altimeter from aboveground to the top crown. Moreover, the coordinate of trees was also recorded using a global positioning system (GPS).

Commented [A3]: Why only these compartments? What are the operations happening in these compartments?

Commented [A4]: What is the minimum tree size measured?

Data analysis

Three indicators were selected to describe vegetation diversity, i.e., richness, heterogeneity, and evenness. Vegetation richness was determined by Margalef Index (*R′*), while its heterogeneity was quantified using Shannon-Wiener Index (*H′*). On another side, the evenness of vegetation was assessed by Pielou Evenness Index (*E′*). Detail equations for calculating those indicators are expressed below (Nugroho et al. 2022):

$$R' = S\text{-}1/ln(N) \quad (1)$$

$$H' = -\sum (n_i/N)\ (ln\ n_i/N) \quad (2)$$

$$E' = H'/ln(S) \quad (3)$$

where *S* was the number of species observed, *N* represented the total tree population in each compartment, and n_i described the sum of trees for each species.

To determine the quantity of timber production, individual tree volume was calculated using the following equation:

$$V = 0.25\ \pi\ dbh^2\ h\ f \quad (4)$$

where *V* was tree volume (m^3), *dbh* indicated tree diameter (cm), *h* represented tree height (m), and *f* showed a constant of form factor (0.6) (Akossou et al. 2013). Then, the timber production degree was assumed to be the mean stand volume in hectare units. This value could be derived by dividing the total tree volume in a compartment by its area.

The quantification of carbon storage and CO_2 absorption were also calculated using a similar principle to timber production. However, we used biomass accumulation as a conversion to compute both parameters. In this context, the individual tree biomass was estimated using a generalized allometric model for secondary tropical rainforest as given (Krisnawati et al. 2012):

$$B = 0.047454dbh^{2.078} \quad (4)$$

B was aboveground biomass (kg), and *dbh* indicated tree diameter (cm). Next, the carbon stock of each tree was computed by multiplying its biomass with a conversion factor of 0.46 (Latifah et al. 2018), while CO_2 absorption was estimated by multiplying carbon stock with a constant of 3.67 (Latifah & Sulistiyono 2013). Then, the result was converted into a hectare unit.

Descriptive analysis was selected to compare the value of vegetation diversity, timber production, and carbon storage among different compartments based on the trend of the histogram and the summarized information from the table. Meanwhile, the spatial distribution of three parameters was processed using QGIS. Finally, to evaluate the relationship between vegetation diversity and stand productivity, both in timber production and carbon storage, Pearson correlation analysis was applied with a significant level of 5%.

RESULTS AND DISCUSSION

Vegetation diversity

Commented [A5]: I would like to see the species list, density, and basal area contribution

Results found that vegetation diversity among compartments was substantially different (Table 1). The highest species abundance was recorded in the compartment of 18Y, while the lowest number of species was observed in the compartment of 20Y. Similar trends were also discovered in the richness, heterogeneity, and evenness, wherein the highest value of those indicators was noted in compartment 18Y. These findings directly confirmed our first hypothesis that assumed there was different vegetation diversity between compartments in the study site.

The diversity of vegetation in secondary tropical rainforests was generally caused by the interaction between vegetation and the environment. This process generated natural competition wherein trees compete with each other to obtain sufficient resources to support their survival (Wirabuana et al. 2022b). On another side, environmental variation also became a limiting factor for certain species; thus, it could inhibit several vegetation from growing well (Wang et al. 2019). Consequently, the regeneration capacity of each species in this ecosystem was highly dynamic depending on their adaptation to environmental conditions. Several previous studies also reported similar results wherein the natural regeneration in secondary tropical rainforests was exceptionally dynamics due to the impact of intraspecific and

interspecific competition between trees for obtaining light, water, nutrients, and space (Barabás et al. 2016, Adler et al. 2018, Yang et al. 2019).

Table 1. Comparison of species abundance, richness, heterogeneity, and evenness among compartments

Compartment	N species	Richness	Heterogeneity	Evenness
18W	32	4.01	1.91	0.55
18X	31	3.79	2.10	0.61
18Y	36	4.43	2.42	0.68
19W	32	3.99	1.96	0.57
19X	30	3.59	1.84	0.54
19Y	31	3.89	1.86	0.54
20Y	4	0.38	0.81	0.58

This study recorded that the heterogeneity of vegetation in the study location was dominated by medium classes with a range of 1.51−3.50 (Table 1) (Hidayat 2013). It was similar to previous studies that documented the secondary tropical rainforests commonly had medium vegetation biodiversity (Siregar and Undaharta 2018, Murdjoko et al. 2021, Tawer et al. 2021). This condition could happen because this site was managed using a selective cutting system; thus, only certain species were maintained to support the ecological function of the forest (Butarbutar 2014). In addition, most trees with a limit diameter of more than 50 cm and having commercial values were harvested to provide better-growing space for younger trees (Matangaran et al. 2019). Therefore, this scheme was expected to stabilize the regeneration capacity of secondary forests without sacrificing its economic benefits.

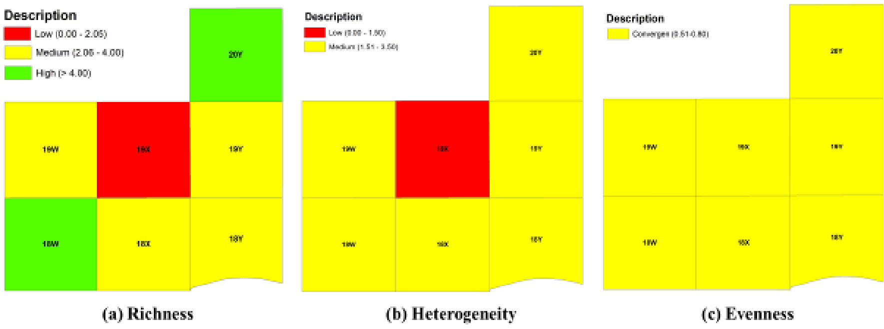

Figure 2. Spatial distribution of vegetation diversity in the study site

Our results also indicated that species distribution in the study site was not evenly distributed. It was shown by the evenness index value ranging from 0.54 to 0.68 (Table 1). These outcomes signified that most species in this location grew in groups (Hussain et al. 2012). It was not surprising since Dipterocarpaceae families dominated most species in secondary tropical rainforests. Many studies explained that these families naturally live in groups and have a specific preference for their habitat (Purwaningsih 2004, Hadi et al. 2019, Sari et al. 2019).

According to the results, it was seen that vegetation diversity in the study site was still maintained well. It also implied that the forest management activity in this area fulfills the principle of sustainability by minimizing the risk of biodiversity loss. However, the effort of enrichment planting is required to improve biodiversity in the compartment with low diversity level. This scheme will also facilitate the conservation of native species from the secondary tropical rainforests.

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Timber production

Summarized observation results documented that timber production in the study area ranged from 44.49±1.72 m^3 ha^{-1} to 68.32±2.69 m^3 ha^{-1} (Table 2). These values were substantially higher than the average productivity of Borneo's natural forests, ranging from 30 m^3 ha^{-1} (KLHK, 2019). Therefore, it indicated that the secondary tropical rainforest in this area had high productivity and could still support industry development. Moreover, this study recorded that the average timber production in each compartment was relatively different, wherein the most increased timber production was found in the compartment of 19Y. These findings also confirmed our first hypothesis that timber production was highly varied between compartments in secondary tropical rainforests.

Table 2. Comparison of timber production, biomass accumulation, carbon storage, and CO_2 absorption among compartments

Compartment	Timber production (m^3 ha^{-1})	Biomass accumulation (t ha^{-1})	Carbon stock (t ha^{-1})	CO_2 absorption (t ha^{-1})
18W	44.49±1.72	45.13±2.02	20.76±0.93	76.18±3.40
18X	56.05±2.05	68.35±2.85	31.44±1.31	115.38±4.81
18Y	54.3±2.43	69.25±3.74	31.86±1.73	116.92±6.32
19W	45.56±1.86	48.83±2.42	22.46±1.12	82.44±4.08
19X	54.96±1.55	67.11±2.44	30.87±1.12	113.29±4.11
19Y	68.32±2.69	84.22±3.89	38.74±1.79	142.17±6.56
20Y	50.57±2.30	46.37±2.36	21.33±1.09	78.29±3.98

Interestingly, the compartment of 18Y only occupied the fourth position of the most productivity compartments, even though it had the highest vegetation diversity (Table 2). Our study also did not find a significant correlation between vegetation diversity and timber production (Table 3). It was in contrast to previous studies that documented a substantial effect of vegetation diversity on stand productivity in tropical rainforest ecosystems (Cai et al. 2016, Gevaña et al. 2017, McNicol et al. 2018). These findings rejected our second hypothesis that higher vegetation diversity significantly increases timber production in the study site. However, several kinds of literature also found a similar outcome to ours wherein there was no significant relationship between vegetation diversity and forest productivity (Belote et al. 2011, Bravo-Oviedo et al. 2021). In this context, forest ecosystems may have diverse patterns regarding the connection between biodiversity and productivity.

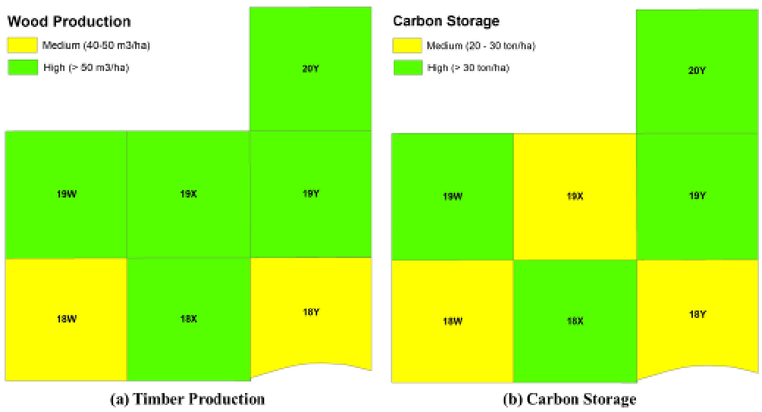

Figure 3. Spatial distribution of timber production and carbon storage in the study site

Table 3. Correlation between diversity indicators and stand productivity parameters

Diversity parameter	Productivity parameter	
	Timber production	Carbon Storage
Richness	0.123^{ns}	0.420^{ns}
Heterogeneity	0.116^{ns}	0.442^{ns}
Evenness	-0.056^{ns}	0.098^{ns}

ns: non-significant based on correlation test

Forest ecosystems in the study site had high productivity since their vegetation was dominated by trees with a diameter of more than 50 cm (Figure 4). On another side, the frequency of trees with a diameter lower than 20 cm was only around 2%. These indicated there was sufficient stock of timber production for selective cutting. Moreover, the relative contribution of non-commercial species to total timber production was considerably lower than commercial species (Figure 4). It demonstrated that the current standing stock had high economic value. These results confirmed our third hypothesis that commercial species' relative contribution to stand productivity was higher than non-commercial species. Although this site had increased productivity, forest managers should be careful to determine the quantity of annual allowable cutting (AAC) since the implementation of timber extraction can be impacted young trees' regeneration. Most importantly, the process of timber extraction should not harvest trees that generate seeds for maintaining natural regeneration.

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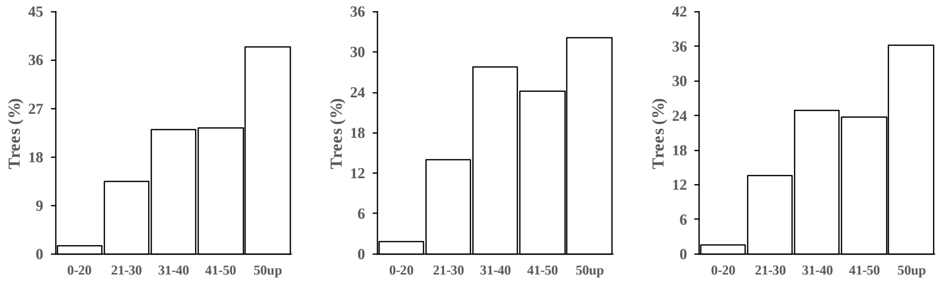

(a) Commercial (b) Non Commercial (c) All Species

Figure 4. Diameter distribution of tree species in the study site

Carbon storage

Carbon storage in each compartment varied, wherein the carbon stock in the study site ranged from 20.76±0.93 t ha^{-1} to 38.74±1.79 t ha^{-1} (Table 3). The highest CO_2 absorption was recorded in the compartment of 19Y by around 142.17±6.56 t ha^{-1}. In addition, the relative contribution of commercial species on carbons stock was considerably higher than species non-commercial (Figure 4). These findings directly verified our first and third hypotheses in this study. However, similarly to timber production, our study did not find a significant effect of vegetation diversity on carbon storage in this area (Table 3).

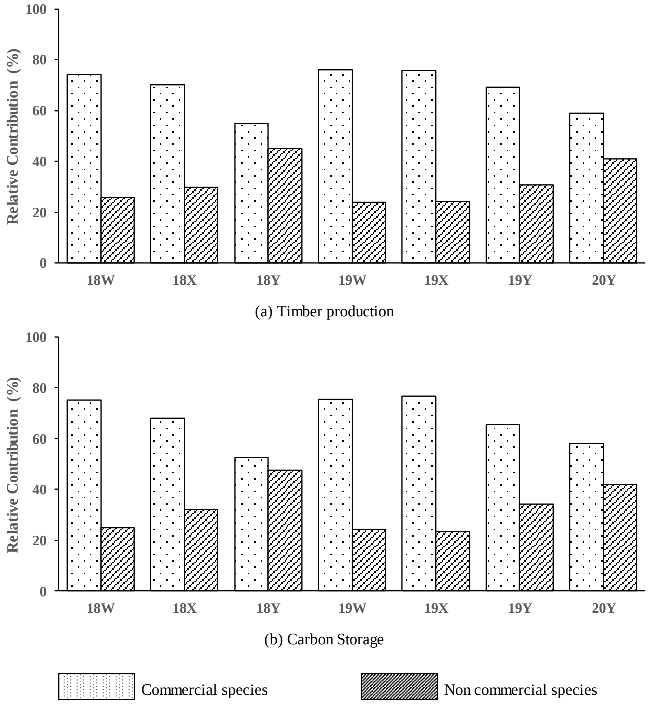

Figure 4. The relative contribution of commercial and non-commercial species on timber production and carbon storage

The accumulation of carbon storage in forest ecosystems has a positive relationship with stand productivity. Higher stand productivity increases carbon stock since it was generated from photosynthesis (Cai et al. 2016, Brancalion et al. 2019, Alam et al. 2022, Wirabuana et al. 2022a). A study reported the average carbon stock in tropical rainforest ecosystems was 51.18 t ha^{-1} (Butarbutar et al. 2019). This value is higher than carbon storage in the study site. However, this study's carbon stock measurement is still limited to the tree level. We still have not quantified the carbon stock in other life stages like poles, saplings, seedlings, and understorey. Thereby, the actual carbon storage in the study area may be higher than the current estimation. It is also essential for forest managers in the study location to consider the quantity of carbon stock as the additional value of sustainable natural resources management.

Implication results

This study concluded that the secondary tropical rainforest ecosystems in the study site had good vegetation diversity, timber production, and carbon storage. Furthermore, it indicated that forest managers had applied sustainability principles in the context of operation scale. Nevertheless, some improvements are still required to increase the value of forest management on this site. Besides conducting enrichment planting in the compartment with low biodiversity levels, we also suggest forest managers determine the scheme of yield regulation to minimize forest disturbance due to the impact of harvesting operations. Furthermore, the cutting process has a high potential to decline regeneration capacity since the felled trees will override the younger plants like seedlings and saplings.

We also suggest forest managers identify the distribution of mother trees in their concession area for obtaining seed as plant material in artificial regeneration. The seed collection is also essential to maintain the genetic diversity in this area. On another side, it is also necessary to document the carbon dynamics during the rotation periods, including loss and increment, since it will provide comprehensive information about forest management's effectiveness in tackling the climate change mitigation issue. We also encourage forest managers in this area to share their knowledge with other natural resources managers who fail to manage the secondary tropical rainforest ecosystems. It is highly required since forest ecosystems play an essential role in economic development, climate change mitigation, and biodiversity conservation. They have a strategic position in hydrological cycles related to food security and natural disaster.

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Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Borneo

Abstract. Sustainable management in secondary tropical rainforests requires basic information about stand characteristics, mainly related to productivity and biodiversity. This study aimed to quantify vegetation diversity, timber production, and carbon storage from various sites of secondary forests in South Borneo. Forest inventory was conducted using a census method at seven different natural forest management unit compartments. Four parameters were measured from each tree, including the type of species, commercial categories, tree diameter, and tree height. Individual tree volume and biomass were estimated using allometric equations, while carbon storage was determined using a conversion factor from biomass. Three indicators were used to evaluate vegetation diversity: richness, heterogeneity, and evenness. The analysis of correlations was applied to examine the relationship between vegetation diversity and stand productivity with a significant level of 5%. Results found that there were 41 tree species in the study site comprising 20 commercial and 21 non-commercial species. The highest richness (*R′*) was recorded in compartment 18X by approximately 4.0, while the most increased heterogeneity (*H′*) and evenness (*E′*) were observed in compartment 18Y by around 2.4 and 0.7, respectively. The accumulation of timber production varied in each site, with a range of 45.46−68.32 m^3 ha^{-1}. The highest carbon storage was noted in compartment 19Y (38.74±1.79t ha^{-1}), while the lowest was found in compartment 18W (20.76±0.93 t ha^{-1}). The relative contribution of commercial species to timber production and carbon storage was substantially higher than non-commercial species at all sites. However, there was not a significant correlation between vegetation diversity and stand productivity (*P>0.05*). Overall, our study concluded that the secondary tropical forest ecosystems in the site had good vegetation diversity, timber production, and carbon storage.

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Keywords: biodiversity, ecosystems, inventory, natural forest, productivity

Running title: Spatial distribution of vegetation diversity

INTRODUCTION

Biodiversity conservation, climate change mitigation, and economic development are essential issues in sustainable forest management, particularly in Indonesia. In this context, the management of forests is expected to stabilize wood supplies for commercial industries, support species conservation, and reduce carbon emissions in the atmosphere (Wirabuana et al. 2021b). To tackle these challenges, information about stand dynamics is required as baseline considerations to determine alternative forest management strategies (Pretzsch et al. 2014). It is related to timber production and includes vegetation diversity and carbon storage.

In general, the quantity of timber production will provide adequate information about the economic value of the forest and its capacity for supporting industry viability (Simmons et al. 2021). It also determines the maximum annual allowable cutting from the forest ecosystem (Asamoah et al., 2020). The number of timber production also describes the regeneration stock from different life stages of trees to maintain business sustainability (Zambiazi et al. 2021). Meanwhile, vegetation diversity information indicates the stability of environmental health and forest ecosystems (Pan et al. 2018). It also shows how many species live in the forest and their relative contribution to ecological functions (Matatula et al. 2021). The vegetation diversity can also be used to understand the natural competition in the ecosystems (Duan et al. 2021). On another side, the accumulation of carbon storage indicates the ability of the forest ecosystem to support climate change mitigation, primarily for reducing carbon emissions (Sadono et al. 2021a). Many studies explain forest vegetation generally absorbs CO_2 through the photosynthesis process. First, it converts it into biomass (Sasaki et al. 2016, Ma et al. 2017, Kocurek et al. 2020, Wirabuana et al. 2020, Sadono et al. 2021b, Setiahadi 2021). Then, the biomass will be distributed in components like roots, stems, branches, and foliage (Poorter et al. 2012, Yue et al. 2018, Altanzagas et al. 2019, Wirabuana et al. 2021a). Higher biomass indicates excellent carbon storage wherein the carbon absorption in forests will increase along with vegetation age (Arora et al. 2014). Another study report the critical role of vegetation on carbon absorption is also a part of the balance in biogeochemical cycles (Taillardat et al. 2018). To collect this information, forest

inventory is necessary to support forest managers in monitoring the stand dynamics in each forest ecosystem, including secondary tropical rainforest (STR).

Before the 1990s, STR played an essential role in economic development. It provided wood materials for forest industries like furniture, veneer, and plywood. STR also occupied the second position of important sectors contributing to country revenue. However, the occurrence of deforestation has declined its contribution significantly to the gross domestic product. Most STR currently have low productivity and high biodiversity loss (Gaveau et al. 2014). To anticipate this condition, the government has conducted the effort of reforestation to recover forest productivity and prevent vegetation extinction. However, this program is not easy to implement because STR commonly has high variation in land configuration with low accessibility (Wardhana et al. 2020).

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Moreover, soil quality in these sites is also dominated by mature soil with low fertility, like oxisols and ultisols (Fujii et al. 2018). Therefore, it causes the low survival rate of vegetation generated from the reforestation program. Nevertheless, several concession areas of STR still exist and maintain their functions for economic development, biodiversity conservation, and climate change mitigation. One of them is a secondary tropical rainforest area managed by PT Aya Yayang Indonesia (AYI) located in South Borneo. Although it has been managed for over 30 years, the information about forest dynamics in this location is still limited, mainly related to vegetation diversity and carbon storage. Therefore, it is essential to provide more comprehensive details on stand dynamics in this area to support better forest management efforts.

This study aims to document vegetation diversity, timber production, and carbon storage from several compartments of secondary tropical rainforests managed by AYI. This information will help forest manager to determine the forest planning strategy, mainly related to yield regulation and harvesting schedules. Thus, even though it is managed as a production zone, forest regeneration is still maintained and minimizes the risk of biodiversity loss. We hypothesize that: Every compartment has a different value for vegetation diversity, timber production, and carbon storage (i). Higher vegetation diversity significantly increases timber production and carbon storage (ii). The contribution of non-commercial species on stand productivity is higher than commercial species (iii).

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MATERIALS AND METHODS

Study area

This study was conducted in the secondary tropical rainforest concession area managed by PT Aya Yayang Indonesia. It is situated in Tabalong District, approximately 270 km from Banjarmasin, the capital city of South Borneo province. The geographic coordinates of this area are located in S1°39'−1°40' and E115°29'−115°30'. Altitude ranges from 225 to 470 m above sea level. Land configuration is dominated by hills with a slope level of 15−40%. The average daily temperature is 27.6°C with a minimum of 25.7°C and a maximum of 30.3°C. The mean annual rainfall during the past ten years is 2,589 mm year^{-1}, with an average air humidity of 87.6%. The highest rainfall is recorded in November. Dry periods are relatively short, only around two months from July to August. Oxisols and ultisols dominate soil types with high acidity levels.

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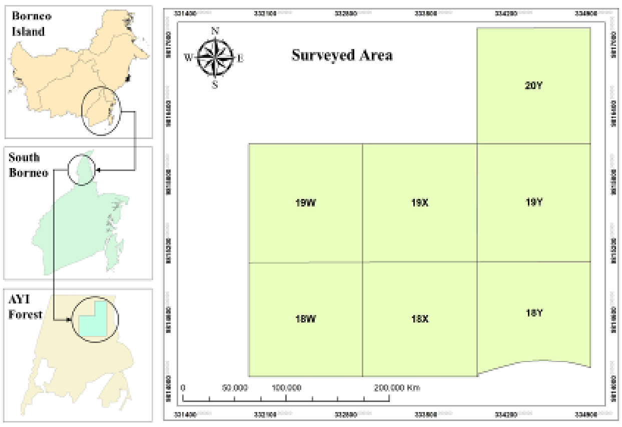

Figure 1. The study area of secondary tropical rainforest in South Borneo

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Data collection

Forest inventory was conducted using a census method at seven compartments of the secondary tropical rainforest management unit, namely 18W, 18X, 18Y, 19W, 19X, 19Y, and 20Y. The total surveyed area reached 700 ha, with each site 100 ha. To facilitate the measurement process, the field survey was conducted step by step using sub-plots of 20 m x 20 m. These sub-plots were arranged systematically; all trees in compartments could be covered and measured correctly. Four parameters were measured from each tree, i.e., type of species, commercial categories, tree diameter, and tree height. The determination of commercial and non-commercial species was undertaken, referring to the guidance from the company. Tree diameter was measured using a phi band at 1.3 m aboveground, while tree height was quantified using a haga altimeter from aboveground to the top crown. Moreover, the coordinate of trees was also recorded using a global positioning system (GPS).

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Data analysis

Three indicators were selected to describe vegetation diversity, i.e., richness, heterogeneity, and evenness. Vegetation richness was determined by Margalef Index (*R′*), while its heterogeneity was quantified using Shannon-Wiener Index (*H′*). On another side, the evenness of vegetation was assessed by Pielou Evenness Index (*E′*). Detail equations for calculating those indicators are expressed below (Nugroho et al. 2022):

$$R' = S\text{-}1/\ln(N) \quad (1)$$

$$H' = -\sum (n_i/N)(\ln n_i/N) \quad (2)$$

$$E' = H'/\ln(S) \quad (3)$$

where S was the number of species observed, N represented the total tree population in each compartment, and n_i described the sum of trees for each species.

To determine the quantity of timber production, individual tree volume was calculated using the following equation:

$$V = 0.25\,\pi\, dbh^2\, h\, f \quad (4)$$

where V was tree volume (m^3), *dbh* indicated tree diameter (cm), *h* represented tree height (m), and *f* showed a constant of form factor (0.6) (Akossou et al. 2013). Then, the timber production degree was assumed to be the mean stand volume in hectare units. This value could be derived by dividing the total tree volume in a compartment by its area.

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The quantification of carbon storage and CO_2 absorption were also calculated using a similar principle to timber production. However, we used biomass accumulation as a conversion to compute both parameters. In this context, the individual tree biomass was estimated using a generalized allometric model for secondary tropical rainforest as given (Krisnawati et al. 2012):

$$B = 0.047454 dbh^{2.078} \quad (4)$$

B was aboveground biomass (kg), and *dbh* indicated tree diameter (cm). Next, the carbon stock of each tree was computed by multiplying its biomass with a conversion factor of 0.46 (Latifah et al. 2018), while CO_2 absorption was estimated by multiplying carbon stock with a constant of 3.67 (Latifah & Sulistiyono 2013). Then, the result was converted into a hectare unit.

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Descriptive analysis was selected to compare the value of vegetation diversity, timber production, and carbon storage among different compartments based on the trend of the histogram and the summarized information from the table. Meanwhile, the spatial distribution of three parameters was processed using QGIS. Finally, to evaluate the relationship between vegetation diversity and stand productivity, both in timber production and carbon storage, Pearson correlation analysis was applied with a significant level of 5%.

RESULTS AND DISCUSSION

Vegetation diversity

Results found that vegetation diversity among compartments was substantially different (Table 1). The highest species abundance was recorded in the compartment of 18Y, while the lowest number of species was observed in the compartment of 20Y. Similar trends were also discovered in the richness, heterogeneity, and evenness, wherein the highest value of those indicators was noted in compartment 18Y. These findings directly confirmed our first hypothesis that assumed there was different vegetation diversity between compartments in the study site.

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The diversity of vegetation in secondary tropical rainforests was generally caused by the interaction between vegetation and the environment. This process generated natural competition wherein trees compete with each other to obtain sufficient resources to support their survival (Wirabuana et al. 2022b). On another side, environmental variation also became a limiting factor for certain species; thus, it could inhibit several vegetation from growing well (Wang et al. 2019). Consequently, the regeneration capacity of each species in this ecosystem was highly dynamic depending on their adaptation to environmental conditions. Several previous studies also reported similar results wherein the natural regeneration in secondary tropical rainforests was exceptionally dynamics due to the impact of intraspecific and

interspecific competition between trees for obtaining light, water, nutrients, and space (Barabás et al. 2016, Adler et al. 2018, Yang et al. 2019).

Table 1. Comparison of species abundance, richness, heterogeneity, and evenness among compartments

Compartment	N species	Richness	Heterogeneity	Evenness
18W	32	4.01	1.91	0.55
18X	31	3.79	2.10	0.61
18Y	36	4.43	2.42	0.68
19W	32	3.99	1.96	0.57
19X	30	3.59	1.84	0.54
19Y	31	3.89	1.86	0.54
20Y	4	0.38	0.81	0.58

This study recorded that the heterogeneity of vegetation in the study location was dominated by medium classes with a range of 1.51−3.50 (Table 1) (Hidayat 2013). It was similar to previous studies that documented the secondary tropical rainforests commonly had medium vegetation biodiversity (Siregar and Undaharta 2018, Murdjoko et al. 2021, Tawer et al. 2021). This condition could happen because this site was managed using a selective cutting system; thus, only certain species were maintained to support the ecological function of the forest (Butarbutar 2014). In addition, most trees with a limit diameter of more than 50 cm and having commercial values were harvested to provide better-growing space for younger trees (Matangaran et al. 2019). Therefore, this scheme was expected to stabilize the regeneration capacity of secondary forests without sacrificing its economic benefits.

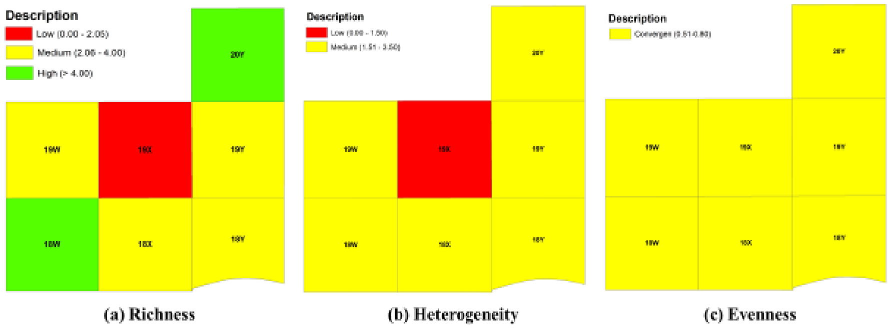

Figure 2. Spatial distribution of vegetation diversity in the study site

Our results also indicated that species distribution in the study site was not evenly distributed. It was shown by the evenness index value ranging from 0.54 to 0.68 (Table 1). These outcomes signified that most species in this location grew in groups (Hussain et al. 2012). It was not surprising since Dipterocarpaceae families dominated most species in secondary tropical rainforests. Many studies explained that these families naturally live in groups and have a specific preference for their habitat (Purwaningsih 2004, Hadi et al. 2019, Sari et al. 2019).

According to the results, it was seen that vegetation diversity in the study site was still maintained well. It also implied that the forest management activity in this area fulfills the principle of sustainability by minimizing the risk of biodiversity loss. However, the effort of enrichment planting is required to improve biodiversity in the compartment with low diversity level. This scheme will also facilitate the conservation of native species from the secondary tropical rainforests.

Timber production

Summarized observation results documented that timber production in the study area ranged from 44.49±1.72 m^3 ha^{-1} to 68.32±2.69 m^3 ha^{-1} (Table 2). These values were substantially higher than the average productivity of Borneo's natural forests, ranging from 30 m^3 ha^{-1} (KLHK, 2019). Therefore, it indicated that the secondary tropical rainforest in this area had high productivity and could still support industry development. Moreover, this study recorded that the average timber

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It also will useful to explain the figure 2. whree the authors have made classification also production in each compartment was relatively different, wherein the most increased timber production was found in the compartment of 19Y. These findings also confirmed our first hypothesis that timber production was highly varied between compartments in secondary tropical rainforests.

Table 2. Comparison of timber production, biomass accumulation, carbon storage, and CO_2 absorption among compartments

Compartment	Timber production (m^3 ha^{-1})	Biomass accumulation (t ha^{-1})	Carbon stock (t ha^{-1})	CO_2 absorption (t ha^{-1})
18W	44.49±1.72	45.13±2.02	20.76±0.93	76.18±3.40
18X	56.05±2.05	68.35±2.85	31.44±1.31	115.38±4.81
18Y	54.3±2.43	69.25±3.74	31.86±1.73	116.92±6.32
19W	45.56±1.86	48.83±2.42	22.46±1.12	82.44±4.08
19X	54.96±1.55	67.11±2.44	30.87±1.12	113.29±4.11
19Y	68.32±2.69	84.22±3.89	38.74±1.79	142.17±6.56
20Y	50.57±2.30	46.37±2.36	21.33±1.09	78.29±3.98

Interestingly, the compartment of 18Y only occupied the fourth position of the most productivity compartments, even though it had the highest vegetation diversity (Table 2). Our study also did not find a significant correlation between vegetation diversity and timber production (Table 3). It was in contrast to previous studies that documented a substantial effect of vegetation diversity on stand productivity in tropical rainforest ecosystems (Cai et al. 2016, Gevaña et al. 2017, McNicol et al. 2018). These findings rejected our second hypothesis that higher vegetation diversity significantly increases timber production in the study site. However, several kinds of literature also found a similar outcome to ours wherein there was no significant relationship between vegetation diversity and forest productivity (Belote et al. 2011, Bravo-Oviedo et al. 2021). In this context, forest ecosystems may have diverse patterns regarding the connection between biodiversity and productivity.

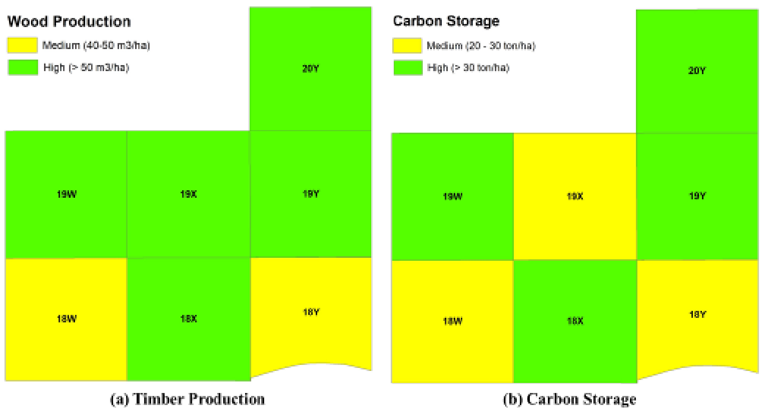

Figure 3. Spatial distribution of timber production and carbon storage in the study site

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Table 3. Correlation between diversity indicators and stand productivity parameters

Diversity parameter	Productivity parameter	
	Timber production	Carbon Storage
Richness	0.123^{ns}	0.420^{ns}
Heterogeneity	0.116^{ns}	0.442^{ns}
Evenness	-0.056^{ns}	0.098^{ns}

ns: non-significant based on correlation test

Forest ecosystems in the study site had high productivity since their vegetation was dominated by trees with a diameter of more than 50 cm (Figure 4). On another side, the frequency of trees with a diameter lower than 20 cm was only around 2%. These indicated there was sufficient stock of timber production for selective cutting. Moreover, the relative contribution of non-commercial species to total timber production was considerably lower than commercial species (Figure 4). It demonstrated that the current standing stock had high economic value. These results confirmed our third hypothesis that commercial species' relative contribution to stand productivity was higher than non-commercial species. Although this site had increased productivity, forest managers should be careful to determine the quantity of annual allowable cutting (AAC) since the implementation of timber extraction can be impacted young trees' regeneration. Most importantly, the process of timber extraction should not harvest trees that generate seeds for maintaining natural regeneration.

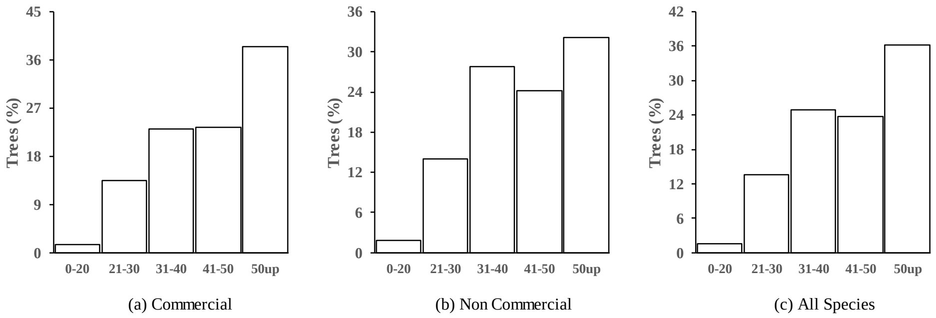

Figure 4. Diameter distribution of tree species in the study site

Carbon storage

Carbon storage in each compartment varied, wherein the carbon stock in the study site ranged from 20.76±0.93 t ha^{-1} to 38.74±1.79 t ha^{-1} (Table 3). The highest CO_2 absorption was recorded in the compartment of 19Y by around 142.17±6.56 t ha^{-1}. In addition, the relative contribution of commercial species on carbons stock was considerably higher than species non-commercial (Figure 4). These findings directly verified our first and third hypotheses in this study. However, similarly to timber production, our study did not find a significant effect of vegetation diversity on carbon storage in this area (Table 3).

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Table 3 is correlation between diversity indicators and stand productivity parameters.

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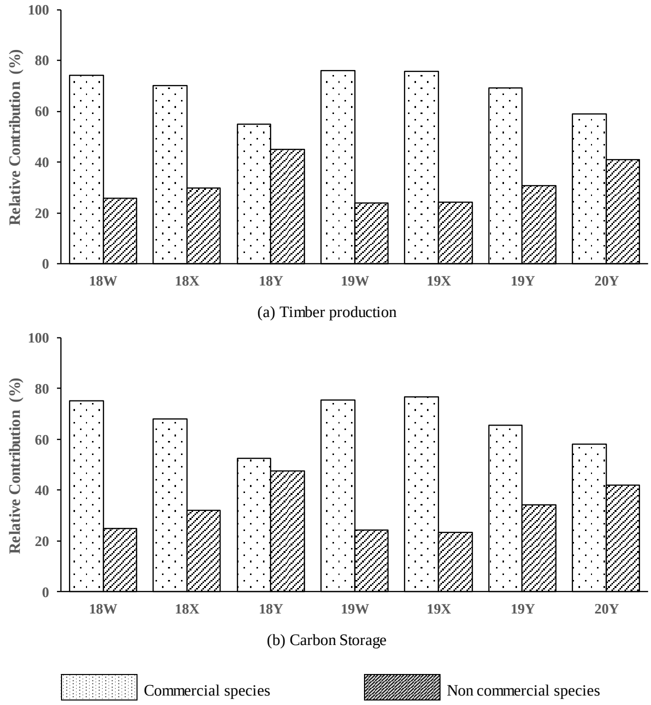

Figure 4. The relative contribution of commercial and non-commercial species on timber production and carbon storage

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The accumulation of carbon storage in forest ecosystems has a positive relationship with stand productivity. Higher stand productivity increases carbon stock since it was generated from photosynthesis (Cai et al. 2016, Brancalion et al. 2019, Alam et al. 2022, Wirabuana et al. 2022a). A study reported the average carbon stock in tropical rainforest ecosystems was 51.18 t ha^{-1} (Butarbutar et al. 2019). This value is higher than carbon storage in the study site. However, this study's carbon stock measurement is still limited to the tree level. We still have not quantified the carbon stock in other life stages like poles, saplings, seedlings, and understorey. Thereby, the actual carbon storage in the study area may be higher than the current estimation. It is also essential for forest managers in the study location to consider the quantity of carbon stock as the additional value of sustainable natural resources management.

Implication results

This study concluded that the secondary tropical rainforest ecosystems in the study site had good vegetation diversity, timber production, and carbon storage. Furthermore, it indicated that forest managers had applied sustainability principles in the context of operation scale. Nevertheless, some improvements are still required to increase the value of forest management on this site. Besides conducting enrichment planting in the compartment with low biodiversity levels, we also suggest forest managers determine the scheme of yield regulation to minimize forest disturbance due to the impact of harvesting operations. Furthermore, the cutting process has a high potential to decline regeneration capacity since the felled trees will override the younger plants like seedlings and saplings.

We also suggest forest managers identify the distribution of mother trees in their concession area for obtaining seed as plant material in artificial regeneration. The seed collection is also essential to maintain the genetic diversity in this area. On another side, it is also necessary to document the carbon dynamics during the rotation periods, including loss and increment, since it will provide comprehensive information about forest management's effectiveness in tackling the climate change mitigation issue. We also encourage forest managers in this area to share their knowledge with other natural resources managers who fail to manage the secondary tropical rainforest ecosystems. It is highly required since forest ecosystems play an essential role in economic development, climate change mitigation, and biodiversity conservation. They have a strategic position in hydrological cycles related to food security and natural disaster.

ACKNOWLEDGEMENTS

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November 26, 2022

Subject: Revision and re-submission of manuscript ID 12632

Dear Editor Biodiversitas,
Thank you for your decision e-mail and the opportunity to revise our manuscript entitled "**Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Borneo**". The suggestions offered by the reviewers have immensely helpful to improve our manuscript.

The revisions have been approved by all authors. The changes are demonstrated by green highlight in MS Word. Our response to reviewer's comments have been enclosed below.

We hope the revised manuscript will be better suit to Biodiversitas, but are pleased to consider further revisions. Thank you for your interest in our research.

Sincerely yours,
Pandu Yudha Adi Putra Wirabuana

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Response to Reviewer A

Part of Article	**Reviewer's Comments**	**Authors's Response**
Abtract	I suggest to use the unit for carbon storage is t C/ha. If you calculate the biomass, the unit is t/ha (Line 22)	The unit of carbon storage has been changed into t C ha^{-1} (Line 22)
Introduction	- Please add the citation (Line 54) - Authors should explain clearly in the materials and methods section on how to test these hypothesis (Line 70-73)	- The citation has been added (Line 54) - The hypothesis test not always uses inferential statistics to examine it. The descriptive test is also possible to apply. We use descriptive test to answer the first and last hypothesis while the analysis of pearson correlation is utilized to answer the second hypothesis. We have described a clear method how to test the hypothesis in the section of data analysis. Please see "Descriptive analysis was selected to compare the value of vegetation diversity, timber production….." (Line 117-118)..
Methods	- When was the data collection conducted? (Line 76) - Please use contras color to show the research site map (Line 86) - Census method but authors used sub-plots 20 m x 20 m. What the authors did, census method or sampling method? Or the authors used sampling method but in each sampling plot used census to measure all vegetation in the sampling plot? (Line 88) - I guess, the author have used the uniform systematic distribution sampling and measured the unit sample using census method. Please, state clearly on the data collection method (Line 91)	- Data collection was conducted from 2021 to 2022. Forest inventory was undertaken with the intensity sampling of 100% in 700 ha area - We think the color for site map is sufficient because it only uses to ilustrate the position of study area - Forest inventory was carried out using census method. We has clearly stated in the first statement. However, since the study area is too large, the process of tree measurement was done step by step with a subplot 20 m x 20 m. There is no distance between subplot. To avoid missunderstanding we have deleted the statement. (Line 90-91)

	- Is it total tree height or commercial height? (Line 105) - I suggest to use the terminology of percentage carbon content (PCC) than conversion factor. In general, the total carbon is dry-weight biomass multiply with percentage carbon content (Line 114)	- No, this research used a cencus method. We have deleted a confusing statement about forest inventory method (Line 90-91) - It is total tree height (Line 103) - We have changed into a percentage carbon content (Line 112)
Results and Discussion	- I suggest the authors to pay attention on compartment 20Y. Why the number of species is 4? While in other compartments the species more than 30 (Line 124-128) - Please state in the data analysis section on how authors classified biodiversity indices into low, medium, high. It also will useful to explain the figure 2. whree the authors have made classification also (Line 144-145) - How you classifying the wood production and carbon storage into medium and high? Please state your approach on data analysis section to classification the wood production and carbon storage (Line 194) - I suggest to add an explanation for figure 5 that relative contribution of commercial species on carbon storage higher than non-commercial species based on your finding on diameter distribution in the figure 4 (Line 215) - Please re-check, table 3 or table 2? Table 3 is correlation between diversity indicators	- Yes, we also still curious about this compartment. Further investigation will be planned to explore this information (Line 124-128) - We classify the value of biodiversity parameters referring to the literatures. This explanation has been added in the article (Line 118-121) - The classification of wood production and carbon storage was determined referring to the literatures. We also add the explanation in the method (Line 118-121) - We have add the explanation about the relative contribution of commercial and non commercial species based on the information from Figure 4 and Figure 4 (Line 221-222) - We have re-checked it and make a revision (Line 219) - We have re-checked it and make revision (Line 221) - We test the hypothesis based on the trend of value obtained from the descriptive test. The analysis of table 2 was calculated by dividing the productivity with the area of compartment. We did not use

	and stand productivity parameters. (Line 217) - Please check again. Figure 4 is diameter distribution of tree species in the study site. Figure 4 does not explain about relative contribution of commercial species on carbon stock (Line 219) - How author test the hypotheses 1? Refer to table 2, I can not see the difference on timber production and carbon storage for each compartment. How author analyze the table 2 to get the conclusion that your findings have been verified for the first hypotheses? (Line 219) - It should be figure 5 not figure 4 (Line 223)	an inferential statistic since our hypothesis did not state a significant different but only different value. - We have changed it for Figure 5 (Line 221)

Response to Reviewer J

Part of Article	**Reviewer's Comments**	**Authors's Response**
Abtract	Timber production may or may not lead to long-term carbon storage (Line 25)	Yes, it is also become a good question for the next research about stand dynamics. We have placed permanent sampling plots here to monitor the change of forest stand in long-term periods
Methods	- What is the history of the site? How long ago was it last logged? Logged for how many times? How was it logged? (Line 75) - Why only these compartments? What are the operations happening in these compartments? (Line 89) - What is the minimum tree size measured? (Line 94)	- We highly apologize there is not sufficient information about this question. We have tried to ask with forest manager but they also did not about it because there are many staff rotation since the company has been operating. - We only have a permission to survey in these compartments since it will be managed for 10 years based on the forest planning strategies from the company. - The most minimum tree size is 15 cm in diameter at breast

		height and 15 cm at total tree height
Results and Discussion	- I would like to see the species list, density, and basal area contribution (Line 123) - Without a baseline, without a reference to primary forest, it is hard to see if this statement is true (Line 164) - How does this translate into rotation cycles? (Line 206-207)	- We have used those data to write other manuscripts that still considered, so that it can not be added here. - It is also difficult to find the baseline since there is not sufficient information about the stand characteristics of primary forest in this area - Annual Allowable Cutting refers to the sum of stand volume that can be harvested in each year. Therefore, change this term to rotation cylces is not correct

Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Borneo

Abstract. Sustainable management in secondary tropical rainforests requires basic information about stand characteristics, mainly related to productivity and biodiversity. This study aimed to quantify vegetation diversity, timber production, and carbon storage from various sites of secondary forests in South Borneo. Forest inventory was conducted using a census method at seven different natural forest management unit compartments. Four parameters were measured from each tree, including the type of species, commercial categories, tree diameter, and tree height. Individual tree volume and biomass were estimated using allometric equations, while carbon storage was determined using a conversion factor from biomass. Three indicators were used to evaluate vegetation diversity: richness, heterogeneity, and evenness. The analysis of correlations was applied to examine the relationship between vegetation diversity and stand productivity with a significant level of 5%. Results found that there were 41 tree species in the study site comprising 20 commercial and 21 non-commercial species. The highest richness (*R′*) was recorded in compartment 18X by approximately 4.0, while the most increased heterogeneity (*H′*) and evenness (*E′*) were observed in compartment 18Y by around 2.4 and 0.7, respectively. The accumulation of timber production varied in each site, with a range of 45.46−68.32 m^3 ha^{-1}. The highest carbon storage was noted in compartment 19Y (38.74±1.79 t C ha^{-1}), while the lowest was found in compartment 18W (20.76±0.93 t C ha^{-1}). The relative contribution of commercial species to timber production and carbon storage was substantially higher than non-commercial species at all sites. However, there was not a significant correlation between vegetation diversity and stand productivity ($P>0.05$). Overall, our study concluded that the secondary tropical forest ecosystems in the site had good vegetation diversity, timber production, and carbon storage.

Keywords: biodiversity, ecosystems, inventory, natural forest, productivity

Running title: Spatial distribution of vegetation diversity

INTRODUCTION

Biodiversity conservation, climate change mitigation, and economic development are essential issues in sustainable forest management, particularly in Indonesia. In this context, the management of forests is expected to stabilize wood supplies for commercial industries, support species conservation, and reduce carbon emissions in the atmosphere (Wirabuana et al. 2021b). To tackle these challenges, information about stand dynamics is required as baseline considerations to determine alternative forest management strategies (Pretzsch et al. 2014). It is related to timber production and includes vegetation diversity and carbon storage.

In general, the quantity of timber production will provide adequate information about the economic value of the forest and its capacity for supporting industry viability (Simmons et al. 2021). It also determines the maximum annual allowable cutting from the forest ecosystem (Asamoah et al., 2020). The number of timber production also describes the regeneration stock from different life stages of trees to maintain business sustainability (Zambiazi et al. 2021). Meanwhile, vegetation diversity information indicates the stability of environmental health and forest ecosystems (Pan et al. 2018). It also shows how many species live in the forest and their relative contribution to ecological functions (Matatula et al. 2021). The vegetation diversity can also be used to understand the natural competition in the ecosystems (Duan et al. 2021). On another side, the accumulation of carbon storage indicates the ability of the forest ecosystem to support climate change mitigation, primarily for reducing carbon emissions (Sadono et al. 2021a). Many studies explain forest vegetation generally absorbs CO_2 through the photosynthesis process. First, it converts it into biomass (Sasaki et al. 2016, Ma et al. 2017, Kocurek et al. 2020, Wirabuana et al. 2020, Sadono et al. 2021b, Setiahadi 2021). Then, the biomass will be distributed in components like roots, stems, branches, and foliage (Poorter et al. 2012, Yue et al. 2018, Altanzagas et al. 2019, Wirabuana et al. 2021a). Higher biomass indicates excellent carbon storage wherein the carbon absorption in forests will increase along with vegetation age (Arora et al. 2014). Another study report the critical role of vegetation on carbon absorption is also a part of the balance in biogeochemical cycles (Taillardat et al. 2018). To collect this information, forest

inventory is necessary to support forest managers in monitoring the stand dynamics in each forest ecosystem, including secondary tropical rainforest (STR).

Before the 1990s, STR played an essential role in economic development. It provided wood materials for forest industries like furniture, veneer, and plywood. STR also occupied the second position of important sectors contributing to country revenue (KLHK, 2015). However, the occurrence of deforestation has declined its contribution significantly to the gross domestic product. Most STR currently have low productivity and high biodiversity loss (Gaveau et al. 2014). To anticipate this condition, the government has conducted the effort of reforestation to recover forest productivity and prevent vegetation extinction. However, this program is not easy to implement because STR commonly has high variation in land configuration with low accessibility (Wardhana et al. 2020).

Moreover, soil quality in these sites is also dominated by mature soil with low fertility, like oxisols and ultisols (Fujii et al. 2018). Therefore, it causes the low survival rate of vegetation generated from the reforestation program. Nevertheless, several concession areas of STR still exist and maintain their functions for economic development, biodiversity conservation, and climate change mitigation. One of them is a secondary tropical rainforest area managed by PT Aya Yayang Indonesia (AYI) located in South Borneo. Although it has been managed for over 30 years, the information about forest dynamics in this location is still limited, mainly related to vegetation diversity and carbon storage. Therefore, it is essential to provide more comprehensive details on stand dynamics in this area to support better forest management efforts.

This study aims to document vegetation diversity, timber production, and carbon storage from several compartments of secondary tropical rainforests managed by AYI. This information will help forest manager to determine the forest planning strategy, mainly related to yield regulation and harvesting schedules. Thus, even though it is managed as a production zone, forest regeneration is still maintained and minimizes the risk of biodiversity loss. We hypothesize that: Every compartment has a different value for vegetation diversity, timber production, and carbon storage (i). Higher vegetation diversity significantly increases timber production and carbon storage (ii). The contribution of non-commercial species on stand productivity is higher than commercial species (iii).

MATERIALS AND METHODS

Study area

This study was conducted in the secondary tropical rainforest concession area managed by PT Aya Yayang Indonesia. It is situated in Tabalong District, approximately 270 km from Banjarmasin, the capital city of South Borneo province. The geographic coordinates of this area are located in S1°39'−1°40' and E115°29'−115°30'. Altitude ranges from 225 to 470 m above sea level. Land configuration is dominated by hills with a slope level of 15−40%. The average daily temperature is 27.6°C with a minimum of 25.7°C and a maximum of 30.3°C. The mean annual rainfall during the past ten years is 2,589 mm year^{-1}, with an average air humidity of 87.6%. The highest rainfall is recorded in November. Dry periods are relatively short, only around two months from July to August. Oxisols and ultisols dominate soil types with high acidity levels.

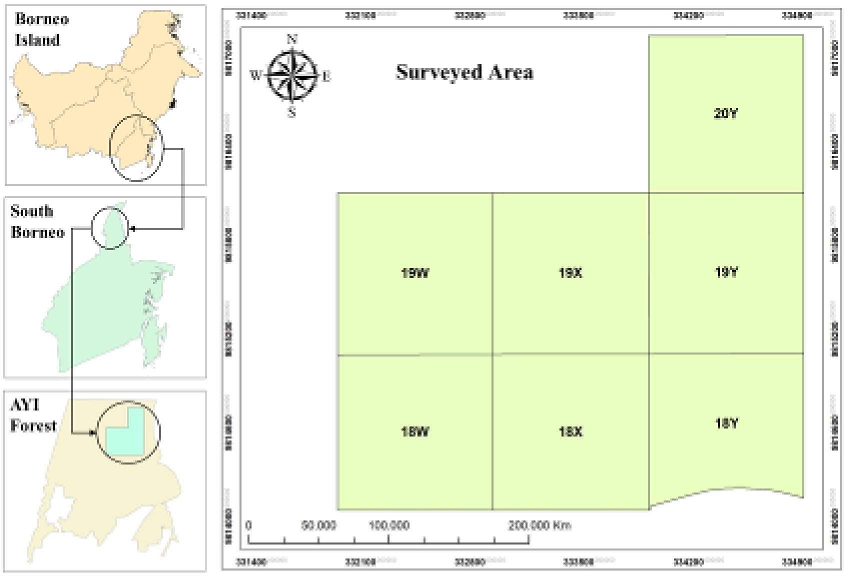


Figure 1. The study area of secondary tropical rainforest in South Borneo

Data collection

Forest inventory was conducted using a census method at seven compartments of the secondary tropical rainforest management unit, namely 18W, 18X, 18Y, 19W, 19X, 19Y, and 20Y. The total surveyed area reached 700 ha, with each site 100 ha. All trees in compartments could be covered and measured correctly. Four parameters were measured from each tree, i.e., type of species, commercial categories, tree diameter, and tree height. The determination of commercial and non-commercial species was undertaken, referring to the guidance from the company. Tree diameter was measured using a phi band at 1.3 m aboveground, while tree height was quantified using a haga altimeter from aboveground to the top crown. Moreover, the coordinate of trees was also recorded using a global positioning system (GPS).

Data analysis

Three indicators were selected to describe vegetation diversity, i.e., richness, heterogeneity, and evenness. Vegetation richness was determined by Margalef Index (*R′*), while its heterogeneity was quantified using Shannon-Wiener Index (*H′*). On another side, the evenness of vegetation was assessed by Pielou Evenness Index (*E′*). Detail equations for calculating those indicators are expressed below (Nugroho et al. 2022):

$$R' = S-1/ln(N) \quad (1)$$

$$H' = -\sum (n_i/N)\,(ln\ n_i/N) \quad (2)$$

$$E' = H'/ln(S) \quad (3)$$

where *S* was the number of species observed, *N* represented the total tree population in each compartment, and n_i described the sum of trees for each species.

To determine the quantity of timber production, individual tree volume was calculated using the following equation:

$$V = 0.25\ \pi\ dbh^2\ h\ f \quad (4)$$

where *V* was tree volume (m^3), *dbh* indicated tree diameter (cm), *h* represented total tree height (m), and *f* showed a constant of form factor (0.6) (Akossou et al. 2013). Then, the timber production degree was assumed to be the mean stand volume in hectare units. This value could be derived by dividing the total tree volume in a compartment by its area.

The quantification of carbon storage and CO_2 absorption were also calculated using a similar principle to timber production. However, we used biomass accumulation as a conversion to compute both parameters. In this context, the individual tree biomass was estimated using a generalized allometric model for secondary tropical rainforest as given (Krisnawati et al. 2012):

$$B = 0.047454dbh^{2.078} \quad (4)$$

B was aboveground biomass (kg), and *dbh* indicated tree diameter (cm). Next, the carbon stock of each tree was computed by multiplying its biomass with a percentage carbon content of 0.46 (Latifah et al. 2018), while CO_2 absorption was estimated by multiplying carbon stock with a constant of 3.67 (Latifah & Sulistiyono 2013). Then, the result was converted into a hectare unit.

Descriptive analysis was selected to compare the value of vegetation diversity, timber production, and carbon storage among different compartments based on the trend of the histogram and the summarized information from the table. Meanwhile, the spatial distribution of three parameters was processed using QGIS. The diversity of vegetation including richness, heteogeneity, and evenness was categorized referring to the classification of ecological indices by Hussain et al (2012). The quantity of timber production was classified into three categories, i.e. low (< 40 $m^3\ ha^{-1}$), medium (40-50 $m^3\ ha^{-1}$), and high (> 50 $m^3\ ha^{-1}$). We also stratified the carbon storage into three classes, namely low (< 20 t C ha^{-1}), medium (20-30 t C ha^{-1}), and high (> 30 t C ha^{-1}). Finally, to evaluate the relationship between vegetation diversity and stand productivity, both in timber production and carbon storage, Pearson correlation analysis was applied with a significant level of 5%.

RESULTS AND DISCUSSION

Vegetation diversity

Results found that vegetation diversity among compartments was substantially different (Table 1). The highest species abundance was recorded in the compartment of 18Y, while the lowest number of species was observed in the compartment of 20Y. Similar trends were also discovered in the richness, heterogeneity, and evenness, wherein the highest value of those indicators was noted in compartment 18Y. These findings directly confirmed our first hypothesis that assumed there was different vegetation diversity between compartments in the study site.

The diversity of vegetation in secondary tropical rainforests was generally caused by the interaction between vegetation and the environment. This process generated natural competition wherein trees compete with each other to obtain sufficient resources to support their survival (Wirabuana et al. 2022b). On another side, environmental variation also became a limiting factor for certain species; thus, it could inhibit several vegetation from growing well (Wang et al. 2019). Consequently, the regeneration capacity of each species in this ecosystem was highly dynamic depending on their adaptation to environmental conditions. Several previous studies also reported similar results wherein the natural regeneration in secondary tropical rainforests was exceptionally dynamics due to the impact of intraspecific and interspecific competition between trees for obtaining light, water, nutrients, and space (Barabás et al. 2016, Adler et al. 2018, Yang et al. 2019).

Table 1. Comparison of species abundance, richness, heterogeneity, and evenness among compartments

Compartment	N species	Richness	Heterogeneity	Evenness
18W	32	4.01	1.91	0.55
18X	31	3.79	2.10	0.61
18Y	36	4.43	2.42	0.68
19W	32	3.99	1.96	0.57
19X	30	3.59	1.84	0.54
19Y	31	3.89	1.86	0.54
20Y	4	0.38	0.81	0.58

This study recorded that the heterogeneity of vegetation in the study location was dominated by medium classes with a range of 1.51−3.50 (Table 1) (Hidayat 2013). It was similar to previous studies that documented the secondary tropical rainforests commonly had medium vegetation biodiversity (Siregar and Undaharta 2018, Murdjoko et al. 2021, Tawer et al. 2021). This condition could happen because this site was managed using a selective cutting system; thus, only certain species were maintained to support the ecological function of the forest (Butarbutar 2014). In addition, most trees with a limit diameter of more than 50 cm and having commercial values were harvested to provide better-growing space for younger trees (Matangaran et al. 2019). Therefore, this scheme was expected to stabilize the regeneration capacity of secondary forests without sacrificing its economic benefits.

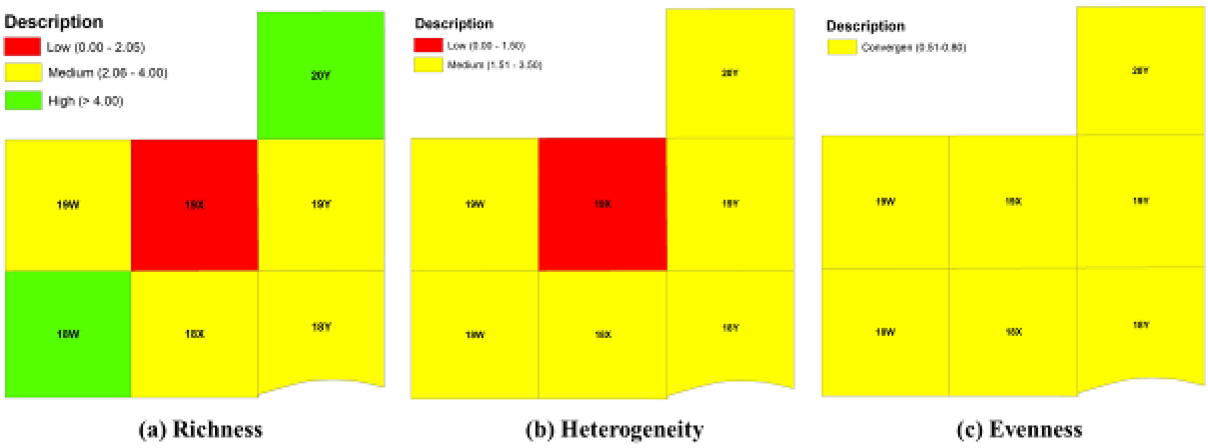


Figure 2. Spatial distribution of vegetation diversity in the study site

Our results also indicated that species distribution in the study site was not evenly distributed. It was shown by the evenness index value ranging from 0.54 to 0.68 (Table 1). These outcomes signified that most species in this location grew in groups (Hussain et al. 2012). It was not surprising since Dipterocarpaceae families dominated most species in secondary tropical rainforests. Many studies explained that these families naturally live in groups and have a specific preference for their habitat (Purwaningsih 2004, Hadi et al. 2019, Sari et al. 2019).

According to the results, it was seen that vegetation diversity in the study site was still maintained well. It also implied that the forest management activity in this area fulfills the principle of sustainability by minimizing the risk of biodiversity loss. However, the effort of enrichment planting is required to improve biodiversity in the compartment with low diversity level. This scheme will also facilitate the conservation of native species from the secondary tropical rainforests.

Timber production

Summarized observation results documented that timber production in the study area ranged from 44.49±1.72 m^3 ha^{-1} to 68.32±2.69 m^3 ha^{-1} (Table 2). These values were substantially higher than the average productivity of Borneo's natural forests, ranging from 30 m^3 ha^{-1} (KLHK, 2019). Therefore, it indicated that the secondary tropical rainforest in this area had high productivity and could still support industry development. Moreover, this study recorded that the average timber production in each compartment was relatively different, wherein the most increased timber production was found in the compartment of 19Y. These findings also confirmed our first hypothesis that timber production was highly varied between compartments in secondary tropical rainforests.

Table 2. Comparison of timber production, biomass accumulation, carbon storage, and CO_2 absorption among compartments

Compartment	Timber production (m^3 ha^{-1})	Biomass accumulation (t ha^{-1})	Carbon stock (t ha^{-1})	CO_2 absorption (t ha^{-1})
18W	44.49±1.72	45.13±2.02	20.76±0.93	76.18±3.40
18X	56.05±2.05	68.35±2.85	31.44±1.31	115.38±4.81
18Y	54.3±2.43	69.25±3.74	31.86±1.73	116.92±6.32
19W	45.56±1.86	48.83±2.42	22.46±1.12	82.44±4.08
19X	54.96±1.55	67.11±2.44	30.87±1.12	113.29±4.11
19Y	68.32±2.69	84.22±3.89	38.74±1.79	142.17±6.56
20Y	50.57±2.30	46.37±2.36	21.33±1.09	78.29±3.98

Interestingly, the compartment of 18Y only occupied the fourth position of the most productivity compartments, even though it had the highest vegetation diversity (Table 2). Our study also did not find a significant correlation between vegetation diversity and timber production (Table 3). It was in contrast to previous studies that documented a substantial effect of vegetation diversity on stand productivity in tropical rainforest ecosystems (Cai et al. 2016, Gevaña et al. 2017, McNicol et al. 2018). These findings rejected our second hypothesis that higher vegetation diversity significantly increases timber production in the study site. However, several kinds of literature also found a similar outcome to ours wherein there was no significant relationship between vegetation diversity and forest productivity (Belote et al. 2011, Bravo-Oviedo et al. 2021). In this context, forest ecosystems may have diverse patterns regarding the connection between biodiversity and productivity.

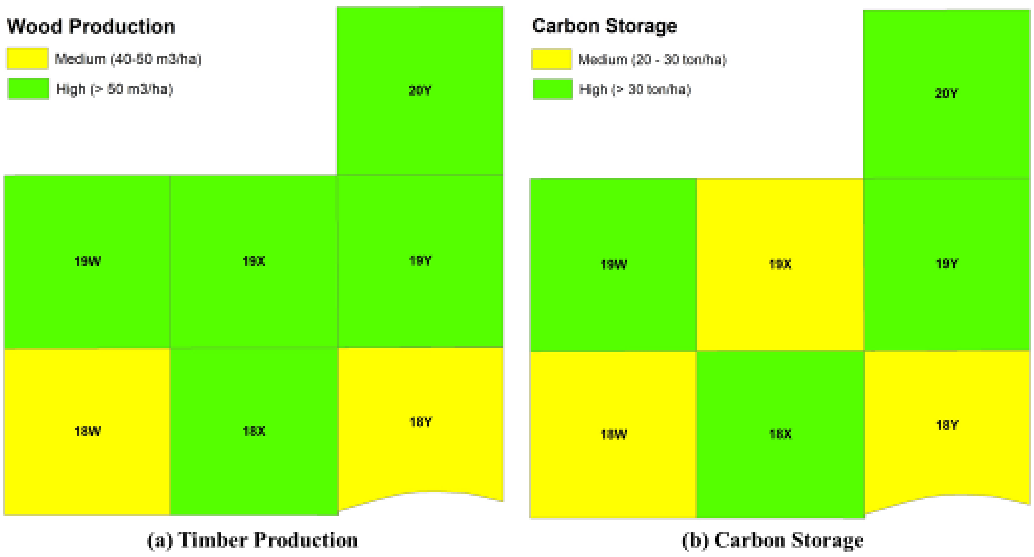


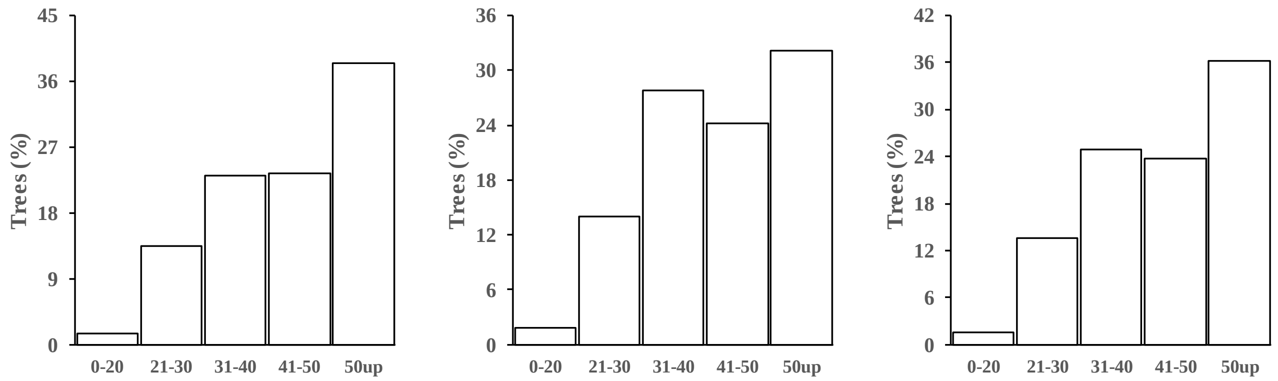
Figure 3. Spatial distribution of timber production and carbon storage in the study site

Table 3. Correlation between diversity indicators and stand productivity parameters

Diversity parameter	Productivity parameter	
	Timber production	Carbon Storage
Richness	0.123^{ns}	0.420^{ns}
Heterogeneity	0.116^{ns}	0.442^{ns}
Evenness	-0.056^{ns}	0.098^{ns}

ns: non-significant based on correlation test

Forest ecosystems in the study site had high productivity since their vegetation was dominated by trees with a diameter of more than 50 cm (Figure 4). On another side, the frequency of trees with a diameter lower than 20 cm was only around 2%. These indicated there was sufficient stock of timber production for selective cutting. Moreover, the relative contribution of non-commercial species to total timber production was considerably lower than commercial species (Figure 4). It demonstrated that the current standing stock had high economic value. These results confirmed our third hypothesis that commercial species' relative contribution to stand productivity was higher than non-commercial species. Although this site had increased productivity, forest managers should be careful to determine the quantity of annual allowable cutting (AAC) since the implementation of timber extraction can be impacted young trees' regeneration. Most importantly, the process of timber extraction should not harvest trees that generate seeds for maintaining natural regeneration.



(a) Commercial (b) Non Commercial (c) All Species

Figure 4. Diameter distribution of tree species in the study site

Carbon storage

Carbon storage in each compartment varied, wherein the carbon stock in the study site ranged from 20.76±0.93 t ha^{-1} to 38.74±1.79 t ha^{-1} (Table 2). The highest CO_2 absorption was recorded in the compartment of 19Y by around 142.17±6.56 t ha^{-1}. In addition, the relative contribution of commercial species on carbons stock was considerably higher than species non-commercial (Figure 5). It was possible since the percentage of trees with diameter more than 50 cm in commercial species higher than species non-commercial (Figure 4). These findings directly verified our first and third hypotheses in this study. However, similarly to timber production, our study did not find a significant effect of vegetation diversity on carbon storage in this area (Table 3).

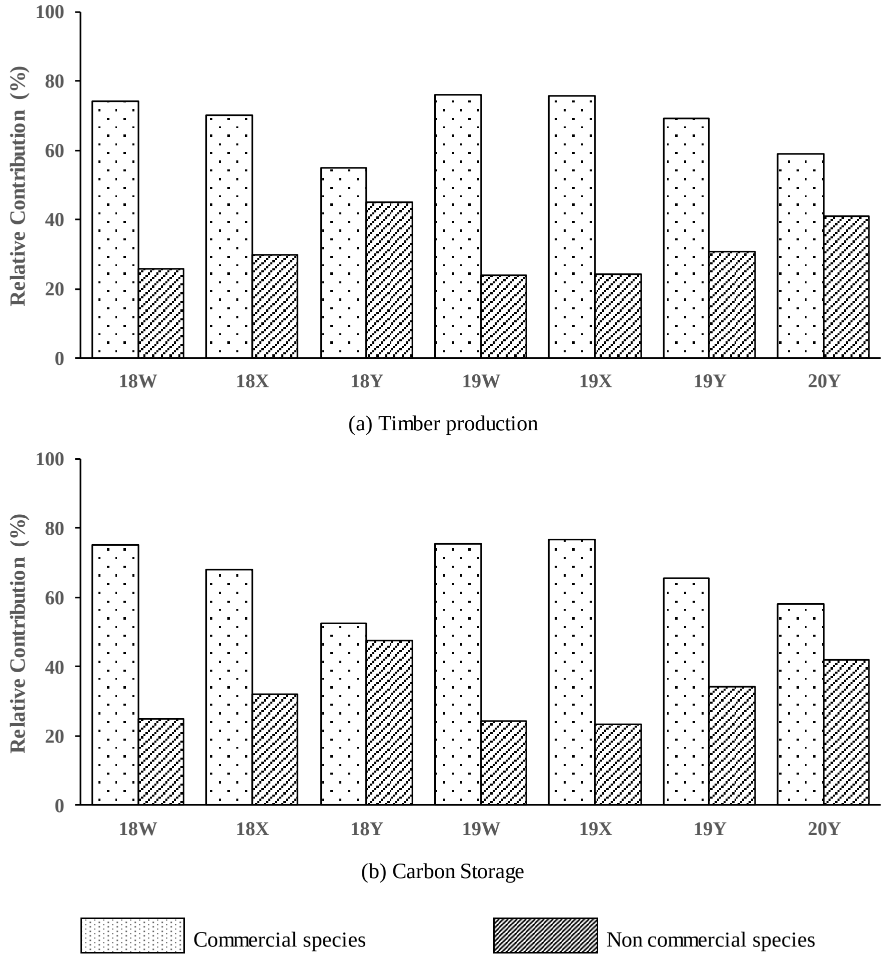


Figure 5. The relative contribution of commercial and non-commercial species on timber production and carbon storage

The accumulation of carbon storage in forest ecosystems has a positive relationship with stand productivity. Higher stand productivity increases carbon stock since it was generated from photosynthesis (Cai et al. 2016, Brancalion et al. 2019, Alam et al. 2022, Wirabuana et al. 2022a). A study reported the average carbon stock in tropical rainforest ecosystems was 51.18 t ha^{-1} (Butarbutar et al. 2019). This value is higher than carbon storage in the study site. However, this study's carbon stock measurement is still limited to the tree level. We still have not quantified the carbon stock in other life stages like poles, saplings, seedlings, and understorey. Thereby, the actual carbon storage in the study area may be higher than the current estimation. It is also essential for forest managers in the study location to consider the quantity of carbon stock as the additional value of sustainable natural resources management.

Implication results

This study concluded that the secondary tropical rainforest ecosystems in the study site had good vegetation diversity, timber production, and carbon storage. Furthermore, it indicated that forest managers had applied sustainability principles in the context of operation scale. Nevertheless, some improvements are still required to increase the value of forest management on this site. Besides conducting enrichment planting in the compartment with low biodiversity levels, we also suggest forest managers determine the scheme of yield regulation to minimize forest disturbance due to the impact of harvesting operations. Furthermore, the cutting process has a high potential to decline regeneration capacity since the felled trees will override the younger plants like seedlings and saplings.

We also suggest forest managers identify the distribution of mother trees in their concession area for obtaining seed as plant material in artificial regeneration. The seed collection is also essential to maintain the genetic diversity in this area. On another side, it is also necessary to document the carbon dynamics during the rotation periods, including loss and increment, since it will provide comprehensive information about forest management's effectiveness in tackling the climate change mitigation issue. We also encourage forest managers in this area to share their knowledge with other natural resources managers who fail to manage the secondary tropical rainforest ecosystems. It is highly required since forest ecosystems play an essential role in economic development, climate change mitigation, and biodiversity conservation. They have a strategic position in hydrological cycles related to food security and natural disaster.

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[biodiv] Editor Decision

1 message

Nor Liza <support@mail.smujo.id> Tue, Dec 6, 2022 at 12:37 PM
To: SUYANTO <author@smujo.id>, PANDU YUDHA ADI PUTRA WIRABUANA <pandu.yudha.a.p@ugm.ac.id>

SUYANTO, YUSANTO NUGROHO, MOEHAR MARAGHIY HARAHAP, LIA KUSUMANINGRUM, PANDU YUDHA ADI PUTRA WIRABUANA:

We have reached a decision regarding your submission to Biodiversitas Journal of Biological Diversity, "Spatial distribution of vegetation diversity, timber production, and carbon storage in secondary tropical rainforest at South Kalimantan, Indonesia".

Our decision is to: Accept Submission

Biodiversitas Journal of Biological Diversity