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The dynamics of soil carbon in revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia

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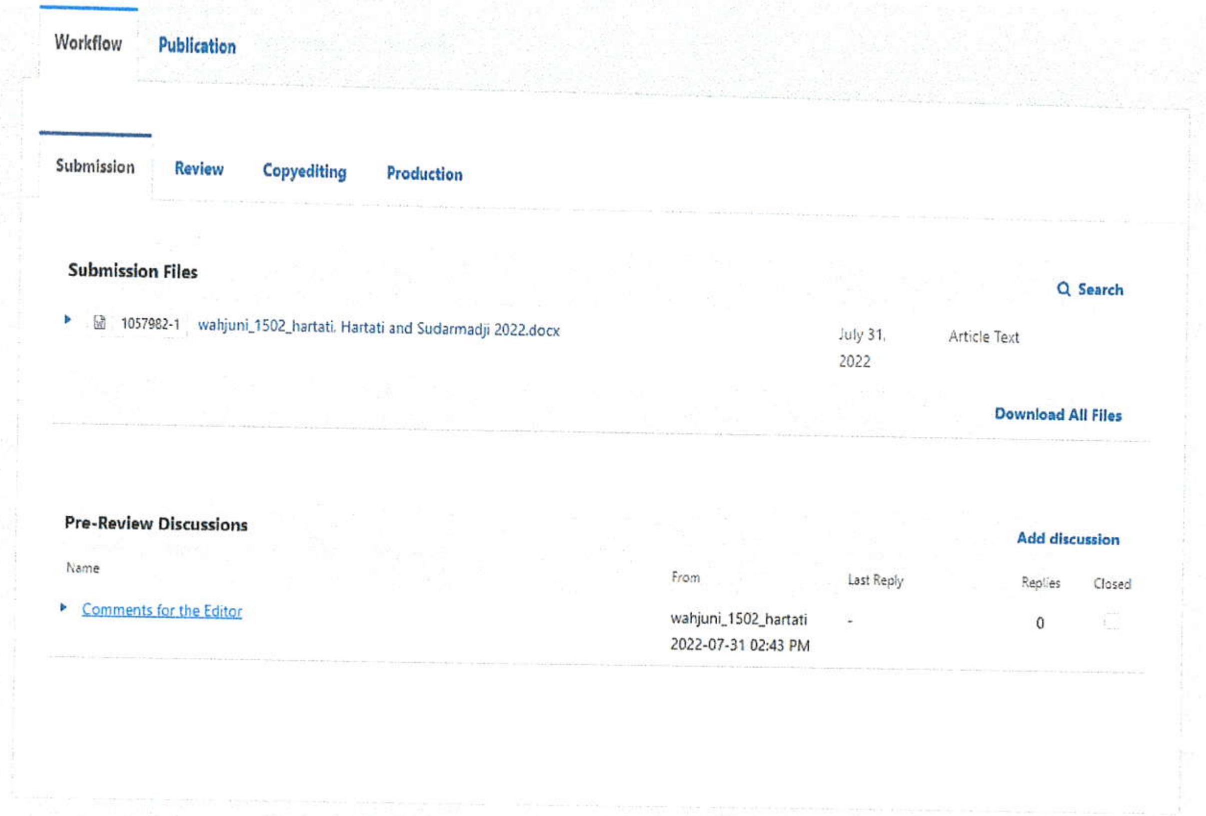

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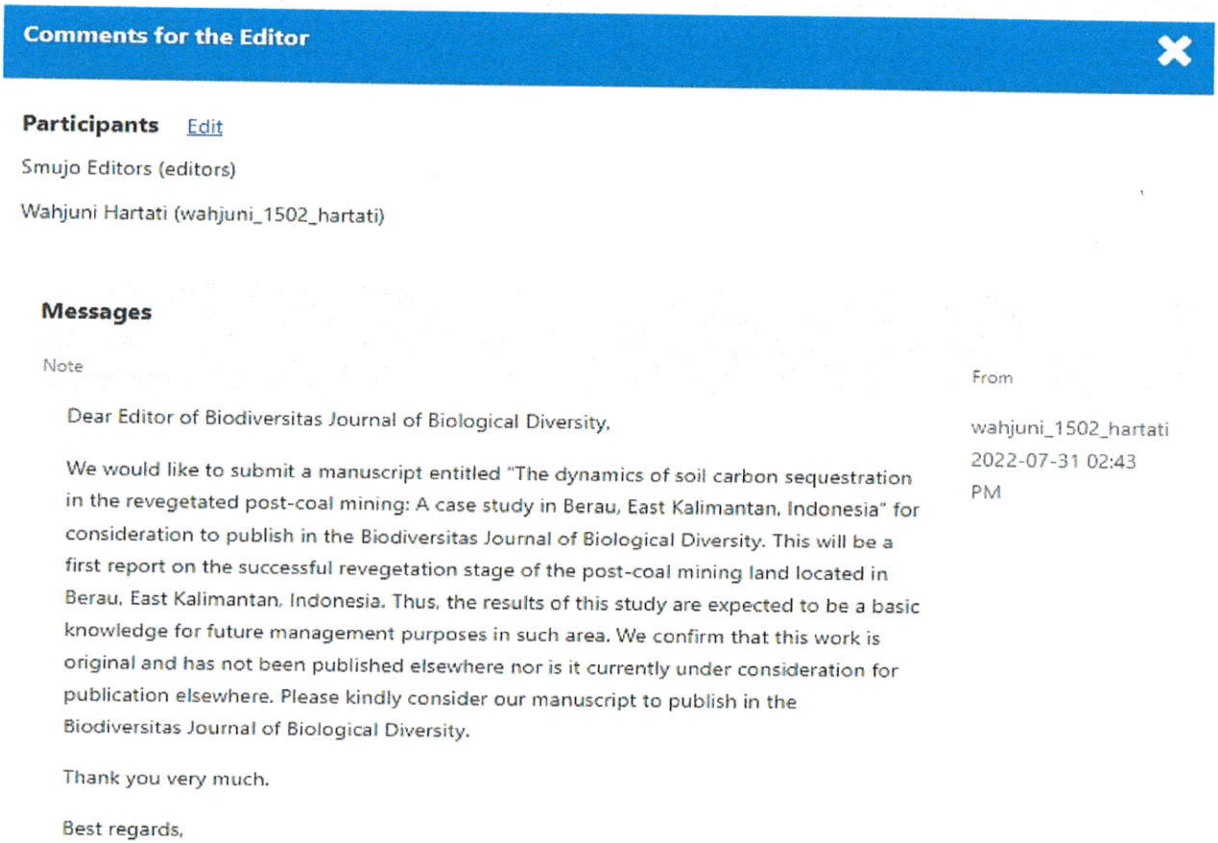

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Messages

Note	From
Dear Editor of Biodiversitas Journal of Biological Diversity, We would like to submit a manuscript entitled "The dynamics of soil carbon sequestration in the revegetated post-coal mining: A case study in Berau, East Kalimantan, Indonesia" for consideration to publish in the Biodiversitas Journal of Biological Diversity. This will be a first report on the successful revegetation stage of the post-coal mining land located in Berau, East Kalimantan, Indonesia. Thus, the results of this study are expected to be a basic knowledge for future management purposes in such area. We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere. Please kindly consider our manuscript to publish in the Biodiversitas Journal of Biological Diversity. Thank you very much. Best regards,	wahjuni_1502_hartati 2022-07-31 02:43 PM

REVIEW (4 ROUND) - 7 SEPTEMBER 2022

The dynamics of soil carbon ~~sequestration~~ in ~~the~~ revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia

Abstract. O~~The forest land clearing is an initial o~~pen pit mining practices cause the loss of vegetation cover as well as soil degradation. Post-mining land reclamation and revegetation are therefore enforced to recover the vegetation and soil quality. While several studies have revealed the vegetation succession following post-mining revegetation, on limited studies have focused on carbon dynamics of the soil. ~~in the coal mining system. This practice contributes to the elimination of land cover, which contains abundance in vegetation and soil material. Thus, its function as a carbon storage facility is no longer available. A rehabilitation stage is needed to restore this essential function. Since the available carbon (C) content above the ground has an important contribution to absorbing CO₂ in the air for plant photosynthesis purposes, its determination is required in order to successfully enhance the rehabilition of the post-coal mining land and also to predict its emission reduction.~~ This study aimed to investigate~~estimate~~ the dynamics of soil carbon stock~~the content of C in the soil after~~ due to mining operation and how it changed following revegetation. ~~rehabilitation of post-mining land.~~ The research was carried out in the concession ~~working~~ area of a coal mining company in ~~PT Berau Coal,~~ Berau, East Kalimantan which were divided into three sites: Sambarata Mining Operation (SMO) Site, Binungan Mining Operation (BMO) Site, and Lati Mining Operation (LMO) Site. At ~~E~~each site, eight sampling plots were established ~~possesses eight plots~~ representing land with varying vegetational conditions, namely original land and post mined lands with varying ~~and coal post-mining~~ revegetation stages ~~land,~~ from open land to 12-year-old vegetation. The percentage of C content was calculated from 288 disturbed soil samples, while bulk density was analyzed from 144 whole soil samples using the Walkey & Black and gravimetric methods. We found that the C stock at the initial state after mining operation was very low. Coal mining activities caused a loss of C in soil with an average value of 21.29%, or equal to 5.65 tons/ha. The biggest loss occurred at the SMO site (44.97%, or 13.04 tons/ha), while the smallest was found at the LMO site (2.24%, or 0.40 tons/ha). The carbon stock improved after revegetation, particularly in the SMO and LMO sites, and the rate of carbon stock enhancement in the soil differed across sites. ~~The C in the soil of the coal post-mining revegetation area of 10–30 cm was greater than that of the 0–10 cm layer. It ranged from very low (VL) to low (L). Coal mining activities caused a loss of C in soil with an average value of 21.29%, or equal to 5.65 tons/ha. The biggest loss occurred at the SMO site (44.97%, or 13.04 tons/ha), while the smallest was found at the LMO site (2.24%, or 0.40 tons/ha).~~ The results also showed that soil carbon in the post-mining area of 10–30 cm was greater than that of the 0–10 cm layer.~~In general, this study demonstrates the current status of soil organic carbon (SOC) in the successful rehabilitation of post-mining land in the area studied for future land use management purposes.~~ Along with the increasing age of plants, the vertical distribution of C stock shifted from the lower layer to the upper layer.

Commented [AR1]: The Abstract is difficult to understand with too much introductory background information and very few results presented. I would suggest to re-arrange the wordings as well as to reduce the amount of background and enrich the results.

Key words: Carbon sequestration, coal, land rehabilitation, post-mining, revegetation

Running title: Carbon sequestration in the revegetated post-coal mining

INTRODUCTION

Commented [AR2]: The Introduction is considerably short to provide sufficient background information. Thus, I would suggest to add two or three more paragraphs to expand the Introduction. Suggested ideas are provided below.

The mining sector is considered one of the most essential sectors for Indonesia's economic development. It contributes to approximately 10% of the national total gross domestic product (GDP) (Lestari et al. 2019). In the last decades~~Nowadays~~, accelerated growth has been seen in the coal mining sector ~~-~~(Chandrarin et al. 2022), with Indonesia being the most important country in Southeast Asia in terms of coal producers, alongside Vietnam and the Philippines (Clark et al. 2020). At national context of Indonesia, ~~C~~coal has a significant role in fulfilling energy supply for~~for~~ domestic purposes which is used~~applied~~ in electricity generation with 33 GW of coal-fired power plant facilities (Ordonez et al. 2022). ~~In 2013,~~ At global context, in 2013 Indonesia supplied 38% of global coal demand and half of total exports in Asia

(Friederich and Leeuwen 2017). This contribution is increasing from year to year, making Indonesia ~~, as it can be observed from the obtained status of this country as~~ as the second greatest coal exporter in the world since 2018 (Baskoro et al. 2021) with ~~. T~~the five biggest coal importers are China, Japan, India, Korea, and Chinese Taipei (Dutu 2016). It has been forecasted that global coal usage will continue to increase from 171 to 208 GJ by 2040 (Aguirre-Villegas and Benson 2017). ~~The British Petroleum (2019) has reported that~~ Indonesia is estimated to have around 3.5% of the ~~overall~~ global coal reserves (The British Petroleum, 2019) with total of 140.48 billion tons ~~discovered in Indonesia. According to the data obtained from (Indonesia's~~ Ministry of Energy and Mineral Resources ~~(~~2018)~~, the entire coal resources in this country are estimated to reach 140.48 billion tons~~. Such reserves are mostly located in three provinces, i.e. ~~The most abundance among all province is found in~~ East Kalimantan, South Kalimantan, and South Sumatra (Pratiwi et al. 2021).

Although it plays important role in energy provision and economic development~~offers various advantages~~, coal mining generates inevitable adverse environmental impacts during its extraction. In particular, open-cut mining, which is the most commonly used technique in Indonesia, causes irreversible damage to the landscapes of natural ecosystems (Sudarmadji and Hartati 2016; Yuan et al. 2016; Bucka et al. 2021; Pudełko et al. 2021; Wang et al. 2022). ~~Furthermore, it strongly~~ removes vegetation~~biomass~~, topsoil, and subsoil ~~cover~~, which are the major sinks of carbon (C) (Ahirwal and Maiti 2017). Since the majority of coal reserves are~~Mostly~~ located in the forested area, the coal mining operation ~~process significantly influences~~causes ~~up-scale~~ deforestation (Mukhopadhyay and Masto 2022). Soil, also known as C reservoirs, contains three times more C than any combination of biomass and atmosphere (Hüblova and Frouz 2021). As a consequence, there is evidence that soil degradation caused by mining ~~those degraded lands will lead~~contributes to an increased global warming risk by releasing CO_2 into the atmosphere (Yan et al. 2020). It will take a very long time to naturally recover the biological and physical qualities of the soil in post-~~coal~~ mined site ~~soil~~ (Singh et al. 2015). Common conditions of the post-mined soil, including high temperature, poor moisture, poor soil organic carbon (SOC), ~~and~~ low nutrient and high acidity~~ce~~, could be barriers that inhibit successful natural succession (Singh et al. 2022).

Reclamation and revegetation are enforced to recover the vegetation and ecological functions of post-mining site. These activities improve the above-ground biomass, biodiversity, soil qualities and microclimate conditions (Trimanto et al, 2021). ~~Therefore, rehabilitation stage is fundamental importance.~~ In term of enhancement of soil qualities, Rereclamation and revegetation ~~forestation~~in post-mining site also haves the potential to make a significant contribution to provide a sink of CO_2 by improving SOC through the plant litter, root and above-ground biomass (Das and Maiti 2016).

The studies ~~describing~~ investigating the dynamics of carbon stock~~C sequestration~~ in post-mining areas in Indonesia~~'s post-mining areas~~ have been previously reported by several authors, such as in Kutai Kartangera, East Kalimantan (Yunanto et al. 2022) and Kolaka, Southeast Sulawesi (Purnomo et al. 2022). In this study, we evaluated the changes in the C content in the soil after mining and rehabilitation of post-coal mining land in ~~the coal mining company, PT. Berau Coal, which is located~~ in Berau, East Kalimantan. In doing, we focused on ~~T~~two layers of soil at each point of collection (0–10 cm and > 10–30 cm) ~~were investigated~~. We expected this study might enrich the existing knowledge on soil ecology of post-mining site, particularly in the contexts of coal mining and Kalimantan region.

Commented [AR3]: This point can be developed into a separate paragraph by elaborating efforts on reclamation and revegetation in post-mining site. Please add some sentences to provide a deeper understanding regarding reclamation and revegetation in post-mining site.

Commented [AR4]: Trimanto, T., Hapsari, L. & Budiharta, S. (2021) Integrating indicators of natural regeneration, enrichment planting, above-ground carbon stock, micro-climate and soil to asses vegetation succession in postmining reclamation in tropical forest. *Turkish Journal of Botany*, **45**, 457-467.

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MATERIALS AND METHODS

Study area

The research was carried out in the concession ~~working~~ area of a coal mining company~~, PT Berau Coal, which is~~ located in Berau District, East Kalimantan, Indonesia. The research location was divided into three sites~~sections~~: Sambarata Mining Operation (SMO) Site; Binungan Mining Operation (BMO) Site; and Lati Mining Operation (LMO) Site. Geographically, SMO is located at the coordinates of 01 ° 52'26.74 "-02 ° 25'09.78" N~~L~~ and 117 ° 07'44.54 "-117 ° 38'26.46" E~~L~~, BMO is located between the coordinates of 03 ° 53'35 "-03 ° 55'37" N~~L~~ and 117 ° 35'02"-117 ° 37'07" E~~L~~, while LMO is located at the coordinates of 02 ° 12'18"-02 ° 17'52" N~~L~~ and 117 ° 33'32"-117 ° 36'32" E~~L~~. The detailed research sites can be seen in Figure 1.

~~Climate condition~~

Rainfall in the research sites occurs throughout the year. The highest intensity occurs in December, while the lowest intensity occurs in August. The hottest temperature generally occurs in June, whereas the coldest temperature occurs in January. The annual average of air humidity is 86.3% with a maximum value of 98% and a minimum value of 60%, and the average sunlight was 47.4% (Sudarmadji and Hartati, 2016). The research sites of Sambarata and Lati have type A climate of Schmidt and Ferguson (1951) classification with quotient (Q) indicators of 6.1% and 3.9%, respectively. On the other hand, the Binungan site is classified under type B with a Q value of 22.0% due to its wet condition with a richness in vegetation of tropical rain forest. Based on Koppen (1931) climate classification, all areas studied is classified as wet tropical type (Af).

~~Land physiography~~

Generally, there are river plains and hills in the research location with altitudes ranging from 1 to 90 m above sea level. River plains consist of floodplains, levee plains, back swamps, and river terraces. The river plains have slope variations of

0–8% while those of the slope hills vary from 8 to 35%. The floodplains are periodically waterlogged and are affected by tidal conditions. The back swamp is a permanent puddle or at least saturated with water at an irregular time. The rocks in this area include the composition of tertiary sediments, sandstone, layers of clay, loam rocks (claystone), slate rock (shale) and rock dust (siltstone). Geomorphologically, the coal mining area is considered a syncline area (valley). The physiography of the river plain is located at an altitude of 1–10 m above sea level, while the physiography of the hills is located at an altitude of 1–90 m above sea level (Hartati and Sudarmadji 2016).

~~Soil and geology~~

The types of soil in the river plains are fluvisols (FAO) or entisols (USDA). The type of soil in the area is dominated by luvisols and cambisols (FAO) or ultisols-inceptisols (USDA). The soil fertility is categorized as~~characterized~~ low, ~~calculated~~indicated by acidic soil ~~reaction~~ (pH 4.5-6.2), total nitrogen content (<0.5%), organic matter content (8.8–9.6%), and effective cation exchange capacity (<16 meq/100g). The potential cation exchange capacity of less than 35 meq/100 g of soil indicates relatively moderate base saturation. The availability of phosphorus (P) and potassium (K) elements is sufficient. The soil structure ~~found~~ in hilly areas is lumpy, while the valley plains have partially ustructured soil. The soil texture overall is ~~characterized~~classified as moderate to small (dusty clay to sandy clay). The classes of soil texture in the hillsides are generally consistent from the surface layer to the deep layer, but gravel-forming strata are occasionally found. The soil texture in the area of the vertical plains is unstable, in which gravel rocks are dominantly found along the profile.

~~Vegetations~~

~~According the field observation combined with some information obtained from the PT Berau Coal, t~~The vegetations ~~grown~~ in the study ~~this~~ area prior to mining activities were~~are~~ mangrove (*Rhizophora* sp.), nipah (*Nypa fruticans*), rumbia (*Metroxilon sagu*), grasses, meranti (*Shorea* sp.), ulin (*Eusideroxylon zwagerii*), keruing (*Dipterocarpus* sp.), rattan (*Calamus* sp.), rubber (*Hevea brasiliensis*), coconut (*Cocos nucifera*), jackfruit (*Artocarpus heterophyllus*), rambutan (*Nephelium lappaceum*), durian (*Durio zibethinus*), petai (*Parkia speciosa*), cempedak (*Artocarpus integer*) and oil palm (*Elaeis guineensis*). The local communities close to the area also planted various agricultural crops. The company has planted various plants as post-mining rehabilitation efforts, including sengon (*Falcataria mollucana*), sengon buto (*Enterolobium cylocarpum*), *Acacia mangium*, jabon (*Antocephalus* sp), angsana (*Pterocarpus indicus*), ~~g~~*Gmelina arborea*, *Eucalyptus pellita*, johar (*Senna siamea*), trembesi (*Albizia saman*) and *Centrosema pubescens*. They also grow various types of inserted plants, such as kamper~~lime~~ (*Dryobalanops aromatica*), meranti (*Shorea* sp), ulin (*Eusideroxylon zwageri*), jackfruit (*Artocarpus heterophyllus*), oranges (*Citrus sinensis*), starfruit (*Averrhoa carambola*), and soursop (*Annona muricata*).

Commented [AR6]: I would suggest to move the description regarding the study area in the Methods so that readers have initial understanding about the ecological context of the study.

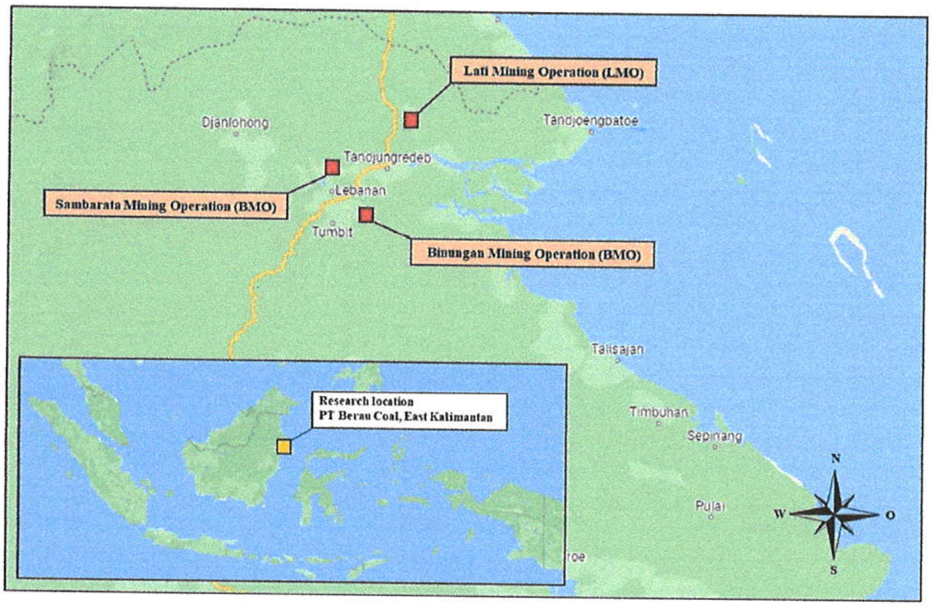

Figure 1. Map of R~~r~~esearch location in a ~~the~~ mining concession area ~~of PT Berau Coal,~~in Berau, East Kalimantan, Indonesia

Sampling method

The estimation of soil C sequestration was determined using eight research measurement plots (RMP). One of the RMPs was treated~~noted~~ as the representative of original land (OL), namely forested land outside the mining operation~~e sequence~~. The other RMPs represented coal post-mining revegetation land (PMRL) with a variety of stand age classes, starting from open coal post-mining land (after soil spreading-ASS) to 10-12 years old with a 2 year interval. The size of each RMP was 10 m × 25 m. Then, for the purposes of soil sampling, the RMP was divided into 10 sub-RMPs (Figure 2). The soil samples for C sequestration estimation were taken to a depth of 30 cm (Manuri et al. 2011). In this study, soil samples were taken from two (two) layers of soil at each point of collection, i.e., 0–10 cm and >10-30 cm.

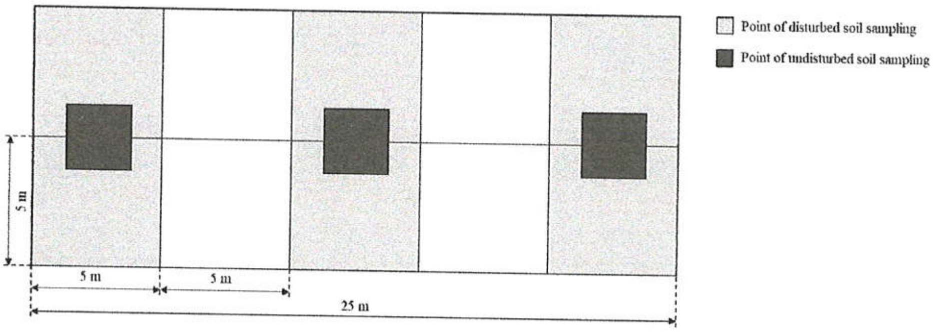

Figure 2. Detail of the research measurement plots (RMPs) used in this study

Two types of soil samples were collected in this study. The disturbed soil samples were used for C analysis, while the undisturbed soil samples were used for b~~B~~ulk d~~D~~ensity analysis. Each type of sample was collected for each layer of the sampling point. Each plot represented 6 points of ~~sampling~~ disturbed soil sampling and 3 points of ~~sampling~~ undisturbed soil sampling, as displayed in Figure 2. Among the collected soil samples, 288 samples were taken for C analysis and 144 samples were taken for bulk density analysis. The Walkey and Black method as previously reported by Enang et al. (2018) was used for C analysis (%). In this study, we used gravimetric method for determination of bulk density. Furthermore, estimation of C soil sequestration to the top 30 cm depth was calculated based on the sum of C content per hectare for 0–10 cm soil layer and > 10–30 cm as~~. Its calculation used~~ the following equation:

$$Ct = (Kd \; x \; \rho \; x \; C) \; x \; f \qquad (1)$$

Where Ct is the soil carbon content (g/cm^2), Kd is the depth of soil samples (cm), ρ is the bulk density (g/cm^3), C is the percentage of C content measured from laboratory analysis (%), and f is the unit of conversion factor from kg/cm^2 to ton/ha (100).

Data analysis

The changes in soil C sequestration in coal post-mining land were observed by comparing the value of the average C content at 30 cm of the upper soil layer on open post-mining land before revegetation activities, revegetated land, and original land both overall and at each site. The potential of coal post-mining land to store C was determined based on criteria developed by the Soil Research Center and the comparison of the C-soil sequestration in several places representing land cover types, as previously described in our report (Hartati and Sudarmadji 2016).

RESULTS AND DISCUSSION

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~~Climate condition~~

~~The distribution of rainfall in the research sites, PT Berau Coal, was evenly spread throughout the year. The highest intensity occurs in December, while the lowest intensity occurs in August. The hottest temperature generally occurs in June, whereas the coldest temperature occurs in January. Their annual average of air humidity has been reported at 86.3%, with a maximum value of 98% and a minimum value of 60%, and the average sunlight was 47.4% (Sudarmadji and Hartati, 2016). According to the classification of climate introduced by Schmidt and Ferguson (1951), sites in Sambarata~~

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~~Vegetations~~

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Dynamics of soil carbon ~~sequestration~~ content

The biosphere ~~is defined as the part of the earth that~~ stores more carbon than the atmosphere. In the biosphere, ~~It is seen from the fact that~~ more than 1.550 Gt of carbon is~~was~~ stored in the soil, while approximately 560 Gt of carbon ~~was~~is available in other ~~reservoirs~~sinks, such as living organisms (Ledo et al. 2020). Therefore, ~~is condition brings opportunities for~~ the biosphere plays an essential role to store carbon especially in the form of ~~to be a great~~ soil organic carbon (SOC) pool. On the other hand, the largest proportion ~~Most of the amount~~ of carbon stored in living organisms is in the form of forest biomass ~~from forest resources~~. Thus, ~~W~~when the living organisms on the forest are decomposed, the carbon will be accumulated in the forest soil. Since deforestation is increasing due to changes in land uses, including coal mining activities (Woodbury et al. 2020), it could potentially move carbon from the biosphere into the atmosphere. ~~Thus, this phenomenon~~ It will significantly~~exponentially~~ contribute to the ~~negative ecological impact due to~~ increase in~~d~~ greenhouse gas emission. ~~Therefore, the~~R~~r~~ehabilitation of degraded lands, including on post-mined sites, is ~~step with a goal of reforested land is an~~ important ~~activity~~ to recover the degraded area. One indicator for ~~T~~the successful rehabilitation could be observed from the improvement of carbon in the soil, particularly after the revegetation~~forestation step~~activity.

The percentage of SOC in the soil commonly ranges from 2.01% to 3.00%, while its bulk density (BD) varies from 1.0 to 1.7 kg/dm^3 (Hardjowigeno 2010). As the age of vegetation increases, ~~T~~the soil bulk density is declining while ~~e in the BD is usually found when the enhanced plant ages. However, in this situation,~~ the amount of organic matter ~~will~~is increasing~~e~~, especially in the top soil. Therefore, the C level in the topsoil is generally higher than in other layers, such as subsoil, which commonly has a higher bulk density. The result of our study shows that ~~According to the data presented in Table 1,~~ the C level ~~detected from~~of all soil depths ~~ranged from~~of 0–30 cm at open-post mining land (ASS) had~~showed~~ an average value of 0.56% (Table 1). This value is ~~demonstrated that it was~~ classified as very low ~~fertility~~. ~~Furthermore,~~On the other hand, all the revegetated post-mining areas at any ages and the original land (OL) were also classified as very low to low, in which their average values of C level were 0.88% and 1.22%, respectively. It was clearly observed that almost all the revegetated post-mining area and the OL had a C level in the layer of 0-10 cm higher than those of 10-30 cm, except the ASS in the BMO site, which had a C level for the upper and lower layer with similar value (0.66%). In general, the results of this study~~is work~~ was ~~inline~~in line with the previous study reported by Kunlanit et al. (2019).

Table 1. S~~Percentage of s~~oil organic carbon (%) ~~at different research~~across observation sites, soil depths and stand age classes

Site	Soil depth (cm)	ASS	Stand age class							OL
			< 2	2-4	4-6	6-8	8-10	10-12	Average	
SMO	0 – 10	0.33	0.64	0.54	1.24	2.06	1.24	1.67	1.23	1.88
	10 – 30	0.47	1.14	0.37	0.74	1.34	0.50	0.78	0.81	0.77
BMO	0 – 10	0.66	0.45	0.36	0.34	0.92	0.57	1.49	0.69	2.23
	10 – 30	0.66	0.61	0.46	0.29	0.37	0.17	0.51	0.40	0.55
LMO	0 – 10	0.65	0.36	0.68	0.76	1.66	1.87	1.98	1.22	1.18
	10 – 30	0.57	0.34	0.45	0.59	1.86	1.29	0.90	0.91	0.73
Average	0 – 30	0.56	0.59	0.48	0.66	1.37	0.94	1.22	0.88	1.22

Note: ASS = ~~is~~ after soil spreading; ~~and~~ OL = ~~is~~ original land;

Commented [AR8]: Please also provide notes for SMO, BMO and LMO. At first when reading it, it was not evidently clear what are these.

As the result of revegetation, there was an increase in the soil C levels, especially in the SMO and LMO sites in all layers investigated (Table 1). At the SMO site, the C level in the revegetated land reached a peak at a stand age of 6–8 years which exceeded that at the original land, but then it decreased. At the LMO site, the similar situation in which there was higher C level than that at the OL occurred from the age of 6–12 years old. On the other hand, at the BMO site, the C enhancement was slight in which there was an increase in C levels at 6–8 years old, but its maximum value was still lower than that of the C level of OL. The increase in C level was only observed in the 0–10 cm layer, despite the fact that the initial C level (ASS) in this site was similar to the LMO site and higher than the ASS in the SMO site. The soil at the BMO site was dominated by clay fraction, making it as the site with the roughest texture among all sites (Hartati and Sudarmadji 2016).

The results of C level were then used to estimate the C stock in an area (ton/ha) calculated from combination of the C concentration (%) and the soil BD (kg/dm^3). It could be observed from Table 2 that the C stock of the top 30 cm soil layer in the ASS, revegetated post-mining land, and the OL was 17.23-28.41 tons/ha, 10.32-66.47 tons/ha, and 26.55-41.31 ton/ha, respectively. The result presented in Table 2 suggests that the revegetation activity in the studied area is successful in enhancing carbon stock since the average value was enhanced from 23.78 tons/ha at the ASS site to 32.47 tons/ha at the revegetation sites, although it was still slightly lower than that in OL with 33.34 tons/ha. The carbon stock obtained a maximum value at the stand age of 6-8 years at the SMO site and 8-10 years old at the LMO site. In contrast, at the BMO site had lower carbon stock than that of ASS at any stand ages.

Table 2. Soil carbon stock~~equestration~~ (ton/ha) across observation sites, soil depths and stand age classes~~at different research site, soil depth and stand age class~~

Site	Soil depth (cm)	ASS	Stand age class							OL
			< 2	2-4	4-6	6-8	8-10	10-12	Average	
SMO	0 – 10	4.72	9.51	7.91	15.53	24.12	15.38	17.39	14.97	16.06
	10 – 30	12.51	34.47	10.82	17.69	37.07	13.65	18.88	22.10	16.10
BMO	0 – 10	9.25	6.65	5.21	4.66	10.65	6.49	15.17	8.23	27.50
	10 – 30	19.16	18.47	13.87	7.80	7.75	3.83	13.25	10.83	13.81
LMO	0 – 10	9.38	5.12	10.49	10.93	19.27	28.83	24.97	16.60	10.65
	10 – 30	16.33	9.83	13.50	18.53	44.41	37.64	24.23	24.69	15.90
Average	0 – 30	23.78	28.02	20.60	25.05	47.76	35.27	38.14	32.47	33.34

Note: ASS ~~is~~= after soil spreading; ~~and~~ OL ~~is~~= original land

Commented [AR9]: As per comment above, please also provide notes for SMO, BMO and LMO.

~~Along with the revegetation approach, there was an increase in the soil C levels, especially in the SMO and LMO sites in all layers investigated. At the BMO site, the C enhancement was slight. It was only observed in the 0–10 cm layer, despite the fact that the initial C level (ASS) in this site was similar to the LMO site and higher than the ASS in the SMO site. The C level at the BMO site was dominated by the high level of the clay fraction, with the roughest texture among all sites (Hartati and Sudarmadji 2016). The C level in the revegetated land at the SMO Site has exceeded the original land, but it has decreased at a stand age of 6–8 years old. At the site of LMO, this condition occurred from the age of 6–12 years old. The revegetation activity in the BMO site caused an increase in C levels at 6–8 years old, but its maximum value was still lower than that of the C level of OL.~~

~~Further estimated C content was C sequestration (ton/ha). This value had been calculated from combination result of the C concentration (%) and the soil BD (kg/dm^3). It could be orserved from Table 2 that the C sequestration of the top 30 cm soil layer in the AAS, revegetated post-mining land, and the OL was 17.23-28.41 tons/ha, 10.32-66.47 tons/ha, and 26.55-41.31 ton/ha, respectively. The successful revegetation was found in this study since the value was enhanced from 23.78 tons/ha to 32.47 tons/ha. Nevertheless, the OL was still the highest with a value of 33.34 tons/ha. The sequestration obtained a maximum value when the stand age reached 6-8 years (SMO) and 8-10 years old (LMO). In contract, BMO site~~

~~even from the beginning age until 12 years old, the value was still lower than that of ASS. This situation was never reached as far. The sequestration of C at this site was also lower than the OL.~~

More than 65% of the soil C stock~~-soil sequestration of~~at the ASS site was found in layers of 10–30 cm (Figure 3). Conversely, at the OL site showed~~ its high~~ that the proportion of C ~~sequestration~~ stock was higher ~~in~~at the layer of 0–10 cm than that at the 10–30 cm layer. Along with the increasing age of plants, the vertical distribution of C ~~sequestration~~ stock ~~distribution of C~~ shifted from the lower layer to the upper layer. At the sites of SMO and B~~L~~MO, C ~~sequestration~~ stock obtained a maximum percentage in the layer of 0–10 when the stand age was 8–10 years old, while at the LMO site it was occurred at 10–12 years old. ~~The value also indicated equal value with the OL.~~ While all sites had similar trends regarding the relationship between the vertical distribution of C stock and the stand age, ~~T~~the ~~distribution of~~proportion of C ~~sequestration~~ stock significantly differed among all three sites evaluated. The soils in the SMO and LMO sites with finer textures kept the C in the upper layer earlier at the time when the stand age was 2-4 years old which ~~. It~~ was different from the rough texture found at the BMO site.

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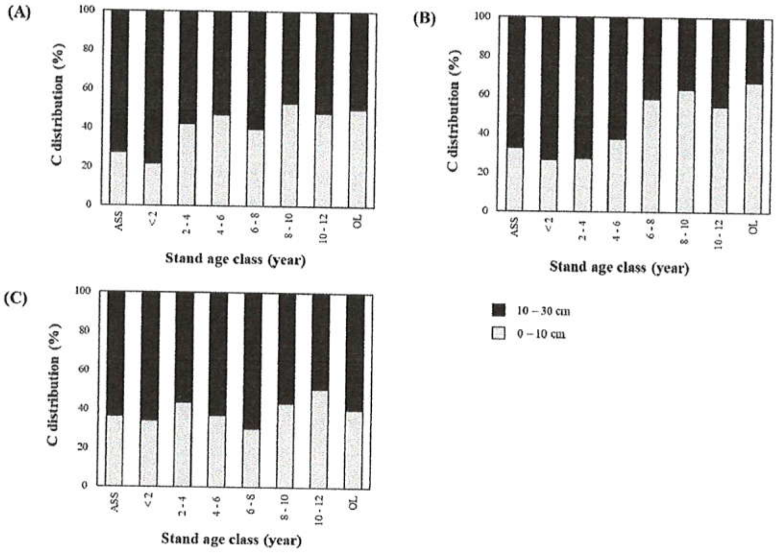
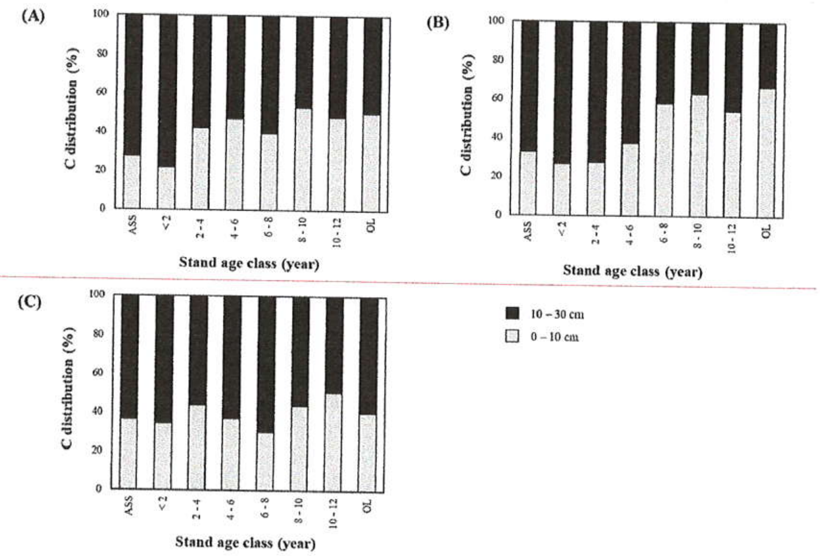


Figure 3. Vertical distribution of C stock of top soil (0-10 cm) and sub soil (10-30 cm): A) Sambarata Mining Operation (SMO) Site; B) Binungan Mining Operation (BMO) Site; and C) Lati Mining Operation (LMO) Site. Notes: ASS = after soil spreading and OL = original land.

Our findings demonstrated the impact of mining activities and the revegetation of the post-mining land. Based on the C soil content in the three sites~~areas~~, it was suspected that the reduction in C content in the soil was caused by coal mining activities. The content of C soil at the SMO site was 24.14 tons/ha, but after the conversion into mining areas, there was a ~~change in this C soil content. A~~ decrease of 13.04 tons/ha, or 54.03%, caused by land clearing was detected. The average C content of the revegetated land was 27.50 tons/ha. This value was higher by 16.40 tons/ha than the ASS. When compared to the OL, this area showed an increased value of 13.93%, or 3.36 tons/ha. At OL of the BMO Site, the C content was 22.36 tons/ha. A reduction in C content was also observed after the area was converted into a mining area. The average C soil content on the vegetated land of the BMO site was 13.63 tons/ha. This was 5.22 tons/ha (27.70%) lower than ASS. When compared to OL, the BMO site lost 39.03% of its C content, or 8.73 tons/ha. This phenomenon might be due to erosion that occurred at the land surface in the ASS and on vegetated post-mining land. The soil texture at the BMO site, which was dominated by the sand fraction, caused the soil to become easily eroded. In addition, the site's annual rainfall was also quite high (2,439 mm), so the C-organic soil is potentially washed along with erosion.



~~Figure 3. C Sequestration distribution of top soil (0-10 cm) and bottom (> 10-30 cm) at Sambarata Mining Operation Site (A), Binungan Operation Site (B), and Lati Operation Site (C). ASS is after soil spreading and OL is original land.~~

After the implementation of coal mining activities, there was a loss of C content of around 2.24%, or 0.40 tons/ha, from the OL to the ASS. The OL of the LMO site had a C content of 17.92 tons/ha, in which the ASS contained 15.52 tons/ha. The existence of revegetation at the ASS of LMO site increased the C content in the soil by 39.97% (11.67 tons/ha). This could be seen from the increasing value of the ASS to the vegetated land. When compared to OL, the vegetated land had an increase in C content of around 38.59%, or 11.26 tons/ha. When observed from the three sites studied, there was a loss of C due to coal mining activities. The loss of the amount of soil C ranged from 2.24% to 54.03%, or equal to 0.40 to 13.04 tons/ha. The biggest reduction occurred at the SMO site, while a small part occurred at the LMO site. The revegetation of land contributed to increasing the C content in the soil after mining activities. This was evidenced by the increase in the amount of land C at the SMO and LMO sites. A similar situation did not occur at the BMO site because the texture on this site was dominated by the sand fraction, which resulted in erodible soil and washed young C-organic. Thus, the C-organic content on the BMO site tended to decrease.

Commented [AR11]: Reading the text in these two paragraphs is confusing since it is not clear which results are referred to. The numbers mentioned in the text is inconsistent with any data presented in the tables and figures. For example, which tables or figures that presented the content of C soil at the SMO site was 24.14 tons/ha. Please check the consistency and accuracy of the numbers you mentioned in the text and data presented in tables and figures.

Potential of soil carbon ~~sequestration~~ stock

The potential of soil carbon ~~content~~ stock in all collected soil samples was assessed by classification according to soil fertility levels measured at a soil thickness of 30 cm. The information summarized in Table 3 showed the potential of~~for~~ C ~~content~~stock in the revegetated land, which was classified as very low to low with~~. T~~the average value indicated was very low. Only a few of them were characterized as low, including < 2 years and 6–8 years at the SMO site; OL at the BMO site; and 6–8 years, 8–10 years, and 10–12 years at the LMO site. The highest C content in the OL was found at the BMO site, while the highest C stock potential among all revegetated lands was found at the LMO site.

Table 3. Potential of soil carbon stock in the studied area ~~studied~~ and its classification based on soil fertility classes

Site	Soil depth (cm)	ASS	Stand age class						OL
			< 2	2-4	4-6	6-8	8-10	10-12	
SMO	0 – 30	17.23	43.98	18.73	33.22	61.19	29.03	36.27	32.16
	Classification	VL	L	VL	VL	L	VL	VL	VL
BMO	0 – 30	28.41	25.12	19.08	12.46	18.40	10.32	28.96	41,31
	Classification	VL	VL	VL	VL	VL	VL	VL	L
LMO	0 –~~-~~30	25.71	14.95	23.99	29.46	63.68	66.47	49.20	26.~~,~~56
	Classification	VL	VL	VL	VL	L	L	L	VL

Note: ASS ~~is~~= after soil spreading; OL ~~is~~= original land; L ~~is~~= low; VL ~~is~~= very low

We compared the soil carbon stock in the area studied to other sites in Indonesia under various land covers (Table 4). In this study, the average value of soil carbon stock of all revegetated sites was 31.49 tons/ha. This value is higher than the soil carbon stock in an agricultural land in North Lombok, West Nusa Tenggara, which has a carbon stock of 10.30 tons/ha (Kusumo et al. 2018). Surprisingly, although located in the same province, soil carbon stock in this study area is higher than that of various land cover types in Samboja, East Kalimantan, such as primary forest (21.15 tons/ha), secondary forest (18.70), and burned forest (16.51 tons/ha) (Van der Kamp et al. 2009). Nevertheless, the C stock in the study area is lower than that in several places. For instance, a forest plantation belonging to PT Finnantara Intiga in West Kalimantan Province showed a soil carbon stock of 40.59 tons/ha. The carbon stock in the peatland forest of North Kayong, West Kalimantan, was 111.56 tons/ha, while the value in the mangrove forest of Karimun Java Island, Central Java, reached 158.37 tons/ha. Furthermore, grassland and bush forest in Aceh Besar District, Aceh have been reported to have C potential of around 124.48 tons/ha and 131.61 tons/ha, respectively.

Table 4. Comparison of soil carbon stock~~content in the soil~~ of various land cover types in Indonesia

Location	Carbon stock (ton/ha)	Land cover	Source
PT Berau Coal (SMO), East Kalimantan	33.98	Post-coal mining	This study
PT Berau Coal (BMO), East Kalimantan	23.01	Post-coal mining	This study
PT Berau Coal (LMO), East Kalimantan	37.50	Post-coal mining	This study
Aceh Besar District, Aceh	124.48	Grassland	Abdullah et al. 2022
Aceh Besar District, Aceh	131.61	Bush forest	Abdullah et al. 2022
North Lombok, West Nusa Tenggara	10.30	Agriculture	Kusumo et al. 2018
North Kayong, West Kalimantan	111.56	Peatland forest	Astiani et al. 2017
Karimun Java Island, Central Java	158.37	Mangrove forest	Nehren and Wicaksono 2018
Sungai Wain, Samboja, East Kalimantan	21.15	Primary forest	Van der Kamp et al. 2009
Sungai Wain, Samboja, East Kalimantan	18.70	Secondary forest	Van der Kamp et al. 2009
Sungai Wain, Samboja, East Kalimantan	16.51	Burned forest	Van der Kamp et al. 2009
PT Finnantara Intiga, West Kalimantan	40.59	Plantation forest	Widhanarto et al. 2016

~~We also compared the condition of C potential in the area studied, PT Berau Coal, to other soil conditions in Indonesia under various land covers (Table 4). In this study, the average value of calculated C among all revegetated sites was 31.49 tons/ha. This value was superior compared to the agricultural land in North Lombok, West Nusa Tenggara, which has a carbon stock of 10.30 tons/ha. Surprisingly, although located in the same province (East Kalimantan), it could be observed that its carbon content was still higher than that of various types of land, such as primary forest (21.15 tons/ha), secondary forest (18.70), and burned forest (16.51 tons/ha). However, the C content in the PT Berau Coal consession was lower than in other places. For instance, a forest plantation belonging to PT Finnantara Intiga in West Kalimantan Province showed a C content of 40.59 tons/ha. The carbon stock in the peatland forest of North Kayong, West Kalimantan, was 111.56 tons/ha, while the value in the mangrove forest of Karimun Java Island, Central Java, reached 158.37 tons/ha. Furthermore, grassland and bush forest in Aceh Besar District, Aceh have been reported to have C potential of around 124.48 tons/ha and 131.61 tons/ha, respectively.~~

~~Finally, t~~This study reported ~~the current condition of~~ soil ~~organic~~ carbon ~~sequestration~~ at a revegetated~~the~~ post-coal mining area ~~of PT Berau Coal which is located~~ in Berau District, East Kalimantan, Indonesia. The C ~~sequestration~~ stock of~~from the~~ varying land conditions (i.e. original land, after soil spreading, ~~until the~~ revegetation site with varying stages from < 2 years to 10–12 years) has been comprehensively summarized. We concluded that the C ~~content~~stock ~~when~~at the initial soil spreading was characterized as very low fertility. The carbon stock~~C content has~~ improved after revegetation, particularly in the SMO and LMO sites, suggesting the rate of carbon stock enhancement in the soil differed across sites. Compared to other sites across Indonesia, ~~. The~~ soil fertility in the study area is classified as low due to the ~~East Kalimantan might differ from other provinces since it also had different characteristics, such as~~ lower C content. Hence, the results obtained from this study could enrich existing knowledge of soil ecology in the context of mining activities and

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revegetation of post-mining.~~be used as basic knowledge to manage the revegated area in East Kalimantan, especially in PT Berau Coal itself.~~

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The dynamics of soil carbon in revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia

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Abstract. *Hartati W, Sudarmadji T. 2022. The dynamics of soil carbon in revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia. Biodiversitas 23:* xxxx. Open pit mining practices cause the loss of vegetation cover as well as soil degradation. Post-mining land reclamation and revegetation are therefore enforced to recover the vegetation and soil quality. While several studies have revealed the vegetation succession following post-mining revegetation, limited studies have focused on carbon dynamics of the soil. This study aimed to investigate the dynamics of soil carbon stock due to mining operation and how it changed following revegetation. The research was carried out in the concession area of a coal mining company in Berau, East Kalimantan which were divided into three sites: Sambarata Mining Operation (SMO) Site, Binungan Mining Operation (BMO) Site, and Lati Mining Operation (LMO) Site. At each site, eight sampling plots were established representing land with varying vegetational conditions, namely original land and post mined lands with varying revegetation stages from open land to 12-year-old vegetation. The percentage of C content was calculated from 288 disturbed soil samples, while bulk density was analyzed from 144 whole soil samples using the Walkey & Black and gravimetric methods. We found that the C stock at the initial state after mining operation was very low. Coal mining activities caused a loss of C in soil with an average value of 21.29%, or equal to 5.65 tons/ha. The biggest loss occurred at the SMO site (44.97%, or 13.04 tons/ha), while the smallest loss was found at the LMO site (2.24%, or 0.40 tons/ha). The carbon stock improved after revegetation, particularly in the SMO and LMO sites, and the rate of carbon stock enhancement in the soil differed across sites. The results also showed that soil carbon in the post-mining area of 10–30 cm was greater than that of the 0–10 cm layer. Along with the increasing age of plants, the vertical distribution of C stock shifted from the lower layer to the upper layer.

Keywords: Carbon sequestration, coal, land rehabilitation, post-mining, revegetation

INTRODUCTION

The mining sector is considered one of the most essential sectors for Indonesia's economic development. It contributes to approximately 10% of the national total gross domestic product (GDP) (Lestari et al. 2019). In the last decades, accelerated growth has been seen in the coal mining sector (Chandrarin et al. 2022). It has been forecasted that global coal usage will continue to increase from 171 to 208 GJ by 2040 (Aguirre-Villegas and Benson 2017). In the context of Southeast Asia region, Indonesia is the most important country in terms of coal producers, alongside Vietnam and the Philippines (Clark et al. 2020). At global context, in 2013 Indonesia supplied 38% of global coal demand and half of total exports in Asia (Friederich and Leeuwen 2017). This contribution is increasing from year to year, making Indonesia as the second greatest coal exporter in the world since 2018 (Baskoro et al. 2021) with the five biggest coal importers are China, Japan, India, Korea, and Chinese Taipei (Dutu 2016). Indonesia is estimated to have around 3.5% of the global coal reserves (The British Petroleum, 2019) with total of 140.48 billion tons (Ministry of Energy and Mineral Resources 2018). Such reserves are mostly located in three provinces, i.e. East Kalimantan, South Kalimantan, and South Sumatra (Pratiwi et al. 2021). At national context of Indonesia, coal has a significant role in fulfilling energy supply for domestic use which is used in electricity generation with 33 GW of coal-fired power plant facilities (Ordonez et al. 2022).

Although it plays important role in energy provision and economic development, coal mining generates inevitable adverse environmental impacts during its extraction. In particular, open-cut mining, which is the most commonly used technique in Indonesia, causes irreversible damage to the landscapes of natural ecosystems (Sudarmadji and Hartati 2016; Yuan et al. 2016; Bucka et al. 2021; Pudełko et al. 2021; Wang et al. 2022). It removes vegetation, topsoil, and subsoil, which are the major sinks of carbon (C) (Ahirwal and Maiti 2017). Since the majority of coal reserves are located in the forested area, the coal mining operation causes deforestation (Mukhopadhyay and Masto 2022). Soil, also known as C reservoirs, contains three times more C than any combination of biomass and atmosphere (Hüblova and Frouz 2021). As a consequence, there is evidence that soil degradation caused by mining contributes to an increased global warming risk by releasing CO_2 into the atmosphere (Yan et al. 2020). It will take a very long time to naturally recover the biological and physical qualities of the soil in post-mined site (Singh et al.

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The dynamics of soil carbon in revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia

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