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

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BIODIVERSITAS
Volume 23, Number 10, October 2022
Pages: 4984-4991

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d231004

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

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Manuscript received: 31 July 2022. Revision accepted: 22 September 2022.

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 vegetation succession following post-mining revegetation, limited studies have focused on the carbon dynamics of the soil. This study aimed to investigate the dynamics of soil carbon stock due to mining operations 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 was divided into three sites: Sambarata Mining Operation (SMO) Site, Binungan Mining Operation (BMO) Site, and Lati Mining Operation (LMO) Site. At each site, eight research measurement plots (RMP) 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 the 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 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 the Southeast Asia region, Indonesia is the most important country in terms of coal producers, alongside Vietnam and the Philippines (Clark et al. 2020). In the global context, in 2013 Indonesia supplied 38% of global coal demand and half of the total exports in Asia (Friederich and Leeuwen 2017). This contribution is increasing from year to year, making Indonesia 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 a 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 an 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 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 (Hüblová 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 sites (Singh et al. 2015). Common conditions of the post-mined soil, including high temperature, poor moisture, poor soil organic carbon (SOC), low nutrient and high acidity, could be barriers that inhibit successful natural succession (Singh et al. 2022).

East Kalimantan has been reported as the province having the majority of coal reserves in Indonesia (Toumbourou et al. 2020). To overcome the adverse effects of the post-coal mining site, the governor signed Regulation No. 8 of 2013 related to the improvement of ecological function through reclamation and revegetation. These activities improve the above-ground biomass, biodiversity, soil qualities, and microclimate conditions (Trimanto et al. 2021). In terms of enhancement of soil qualities, reclamation and revegetation in post-mining sites also have the potential to make a significant contribution to providing a sink for CO_2 by improving SOC through plant litter, root biomass, and above-ground biomass (Das and Maiti 2016). Furthermore, the revegetation should utilize plant species which is fast-growing and has high adaptation to the local climate (Iskandar et al. 2022).

The physical, chemical, and biological components of the soil can be enhanced by the improvement of the SOC (Singh et al. 2022). Since the SOC is fundamental to achieving a successful rehabilitation step, its presence could be accelerated by the implementation of the revegetation. It was earlier reported that vegetation could accumulate organic matter, which could be decomposed by soil microorganisms to improve soil fertility (Dignac et al. 2017). This interaction will act as a catalyst to promote ecosystem restoration (Feng et al. 2019).

The studies investigating the dynamics of carbon stock in post-mining areas in Indonesia 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 the mining and rehabilitation of post-coal mining land in Berau, East Kalimantan. In doing, we focused on two layers of soil at each point of collection (0-10 cm and > 10-30 cm). We expected this study might enrich the existing knowledge on soil ecology of the post-mining site, particularly in the contexts of coal mining and Kalimantan region.

MATERIALS AND METHODS

Study area

The research was carried out in the concession area of a coal mining company located in Berau District, East Kalimantan, Indonesia. The research location was divided into three sites: 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 and 117° 07'44.54 "-117° 38'26.46" E, BMO is located between the coordinates of 03° 53'35 "-03° 55'37" N and 117° 35'02"-117° 37'07" E, while LMO is located at the coordinates of 02° 12'18"-02° 17'52" N and 117° 33'32"-117° 36'32" E. The detailed research sites can be seen in Figure 1.

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 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 the vegetation of tropical rain forests. Based on Koppen (1931) climate classification, all areas studied are classified as wet tropical type (Af).

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).

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 low, indicated by acidic soil (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 in hilly areas is lumpy, while the valley plains have ustructured soil partially. The soil texture overall is 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.

The vegetations in the study area prior to mining activities were 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 in post-mining rehabilitation efforts, including sengon (*Falcataria mollucana*), sengon buto (*Enterolobium cylocarpum*), *Acacia mangium*, jabon (*Antocephalus* sp), angsana (*Pterocarpus indicus*), *Gmelina arborea*, *Eucalyptus pellita*, johar (*Senna siamea*), trembesi (*Albizia saman*) and *Centrosema pubescens*. They also grow various types of inserted plants, such as kamper (*Dryobalanops aromatica*), meranti (*Shorea* sp), ulin (*Eusideroxylon zwageri*), jackfruit (*Artocarpus heterophyllus*), oranges (*Citrus sinensis*), starfruit (*Averrhoa carambola*), and soursop (*Annona muricata*).

Sampling method

The estimation of soil C sequestration was determined using eight research measurement plots (RMP). One of the RMPs was treated as the representative of original land (OL), namely forested land outside the mining operation. 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.

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 bulk density analysis. Each type of sample was collected for each layer of the sampling point. Each plot represented 6 points of disturbed soil sampling and 3 points of 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 the gravimetric method for the 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 the following equation:

$$Ct = (Kd \times \rho \times C) \times f$$

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).

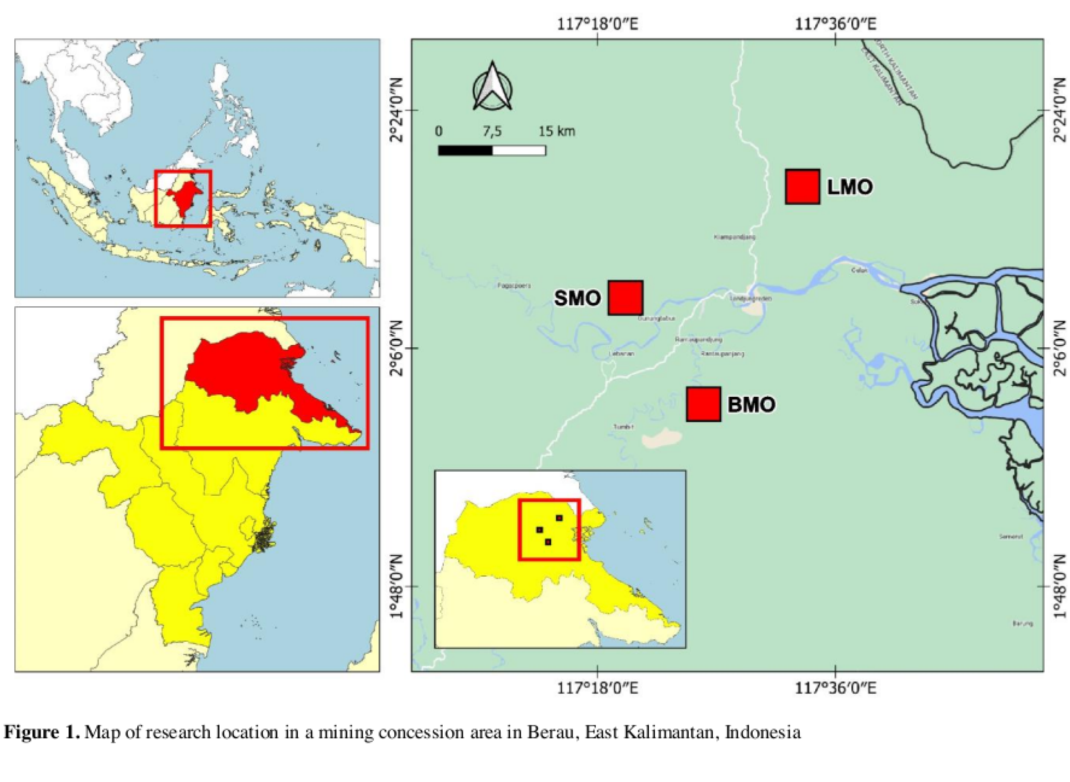

Figure 1. Map of research location in a mining concession area in Berau, East Kalimantan, Indonesia

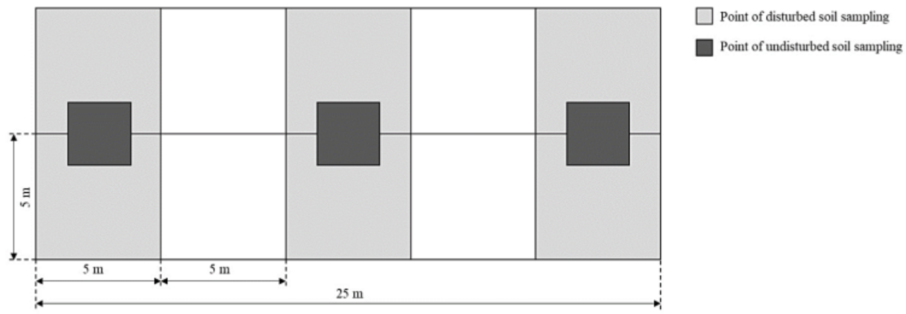

Figure 2. Detail of the research measurement plots (RMPs) used in this study

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 soil organic carbon (%) and its stock (ton/ha) observed from the sites were presented by mean value ± standard deviation. Furthermore, one-way analysis of variance (ANOVA) continued by Duncan's multiple range test (DMRT) was applied to compare any significant difference among the mean values at the level of $p < 0.05$ using IBM SPSS Statistic 22 (IBM Corp., Armonk, NY). 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

Dynamics of soil carbon content

The biosphere stores more carbon than the atmosphere. In the biosphere, more than 1.550 Gt of carbon is stored in the soil, while approximately 560 Gt of carbon is available in other sinks, such as living organisms (Ledo et al. 2020). Therefore, the biosphere plays an essential role in storing carbon, especially in the form of soil organic carbon (SOC) pool. On the other hand, the largest proportion of carbon stored in living organisms is in the form of forest biomass. Thus, when the living organisms in 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. It will significantly contribute to the increase in greenhouse gas emissions. Rehabilitation of degraded lands, including post-mined sites, is important to recover the degraded area. One indicator of successful rehabilitation could be observed from the improvement of carbon in the soil, particularly after the revegetation 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, the soil bulk density declines while the amount of organic matter increases, especially in the topsoil. 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 showed that the C level of all soil depths of 0-30 cm at open-post mining land (ASS) had an average value of 0.56% (Table 1). This value is classified as very low. On the other hand, all the revegetated post-mining areas at any age 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 were in line with the previous study reported by Kunlanit et al. (2019).

As a result of revegetation, there was an increase in the soil C levels, especially in the SMO and LMO sites in all layers investigated (Table 2). 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, a similar situation in which there was a 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 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 a combination of the C concentration (%) and the soil BD (kg/dm^3). It could be observed from Table 3 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 4 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, the BMO site had lower carbon stock than that of ASS at any stand age.

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, it was suspected that the reduction in C content in the soil was caused by coal mining activities. The average value of C soil content at the SMO site was 16.06 tons/ha, but after the conversion into mining areas, there was a decrease of 7.31 tons/ha, or 45.52%, caused by land clearing was detected. The average C content of the revegetated land was 18.69 tons/ha. This value was higher by 9.94 tons/ha than the ASS. When compared to the OL, the revegetated areas showed an increased value of 16.40%, or 2.63 tons/ha. At OL of the BMO Site, the C content was 21.10 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 9.51 tons/ha. This was 4.77 tons/ha lower than ASS. When compared to OL, the BMO site lost 54.92% of its C content, or 11.59 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. The successful C soil enhancement was also observed from the LMO site, in which its revegetated land was higher than that of ASS and OL.

More than 65% of the soil C stock at the ASS site was found in layers of 10-30 cm (Figure 3). Conversely, at the OL of the BMO site showed that the proportion of C stock was higher 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 stock shifted from the lower layer to the upper layer. At the sites of SMO and LMO, C stock obtained a maximum percentage in the layer of 10-30 when the stand age was 6-8 years old, while at the BMO site was occurred at less than 2 years old. While all sites had similar trends regarding the relationship between the vertical distribution of C stock and the stand age, the proportion of C 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 was different from the rough texture found at the BMO site.

Table 1. Soil organic carbon (%) at observation sites after soil spreading and original land

Site	Soil depth (cm)	ASS	OL
SMO	0-10	0.33 ± 0.06^{c}	1.88 ± 0.51^{ab}
	10-30	0.47 ± 0.22^{bc}	0.77 ± 0.35^{c}
BMO	0-10	0.66 ± 0.13^{a}	2.23 ± 1.52^{a}
	10-30	0.66 ± 0.13^{a}	0.55 ± 0.10^{c}
LMO	0-10	0.65 ± 0.12^{a}	1.18 ± 0.39^{bc}
	10-30	0.57 ± 0.13^{ab}	0.73 ± 0.70^{c}
Average	0-30	0.56 ± 0.13	1.22 ± 0.69

Note: SMO: Sambarata Mining Operation; BMO: Binungan Mining Operation; LMO: Lati Mining Operation; ASS: after soil spreading; OL: original land. Different superscript letter in the same column represents its significant difference among others at $p < 0.05$ in DMRT

Table 3. Soil carbon stock (ton/ha) at observation sites after soil spreading and original land

Site	Soil depth (cm)	ASS	OL
SMO	0-10	4.71 ± 0.86^{d}	16.17 ± 6.10^{ab}
	10-30	12.78 ± 6.66^{bc}	15.94 ± 6.60^{ab}
BMO	0-10	9.14 ± 1.30^{cd}	28.48±23.75^{a}
	10-30	19.42 ± 5.56^{a}	13.72 ± 3.30^{b}
LMO	0-10	9.37 ± 1.72^{cd}	11.78 ± 4.42^{b}
	10-30	16.30 ± 3.63^{ab}	12.29 ± 9.67^{b}
Average	0-30	11.95 ± 5.34	16.40 ± 6.19

Note: SMO: Sambarata Mining Operation; BMO: Binungan Mining Operation; LMO: Lati Mining Operation; ASS: after soil spreading; OL: original land. Different superscript letter in the same column represents its significant difference among others at $p < 0.05$ in DMRT

Table 2. Soil organic carbon (%) at revegetated post-mining sites

Site	Soil depth (cm)	Stand age class (year)					
		< 2	2-4	4-6	6-8	8-10	10-12
SMO	0-10	0.64 ± 0.17^{ab}	0.54 ± 0.10^{ab}	1.24 ± 0.55^{a}	2.06 ± 0.88^{a}	1.24 ± 0.49^{b}	1.67 ± 0.42^{ab}
	10-30	1.14 ± 0.46^{a}	0.37 ± 0.09^{b}	0.74 ± 0.67^{ab}	1.34 ± 0.61^{ab}	0.50 ± 0.26^{c}	0.78 ± 0.38^{bc}
BMO	0-10	0.45 ± 0.51^{b}	0.36 ± 0.16^{b}	0.34 ± 0.10^{b}	0.92 ± 0.17^{bc}	0.57 ± 0.23^{c}	1.49 ± 0.42^{ab}
	10-30	0.61 ± 0.75^{b}	0.46 ± 0.37^{ab}	0.29 ± 0.11^{b}	0.37 ± 0.23^{c}	0.17 ± 0.09^{c}	0.51 ± 0.08^{c}
LMO	0-10	0.36 ± 0.12^{b}	0.68 ± 0.20^{a}	0.76 ± 0.43^{ab}	1.66 ± 0.53^{ab}	1.87 ± 0.71^{a}	1.98 ± 1.24^{a}
	10-30	0.34 ± 0.14^{b}	0.45 ± 0.13^{ab}	0.59 ± 0.22^{b}	1.86 ± 1.16^{a}	1.29 ± 0.81^{ab}	0.90 ± 1.09^{bc}
Average	0-30	0.59 ± 0.30	0.48 ± 0.12	0.66 ± 0.35	1.37 ± 0.63	0.94 ± 0.63	1.22 ± 0.57

Note: SMO: Sambarata Mining Operation; BMO: Binungan Mining Operation; LMO: Lati Mining Operation. Different superscript letter in the same column represents its significant difference among others at $p < 0.05$ in DMRT

Table 4. Soil carbon stock (ton/ha) at revegetated post-mining sites

Site	Soil depth (cm)	Stand age class (year) < 2	2-4	4-6	6-8	8-10	10-12
SMO	0-10	9.56 ± 2.89^{b}	7.88 ± 1.33^{ab}	15.62 ± 7.10^{ab}	24.40 ± 11.85^{bc}	15.31 ± 5.78^{bc}	17.80 ± 7.09^{ns}
	10-30	34.31 ± 13.97^{a}	10.80 ± 2.62^{ab}	17.47 ± 15.57^{ab}	37.50 ± 18.17^{ab}	13.82 ± 7.62^{c}	19.76 ± 11.93^{ns}
BMO	0-10	6.72 ± 7.78^{b}	5.14 ± 2.05^{b}	4.69 ± 1.53^{c}	10.74 ± 2.52^{c}	6.42 ± 2.64^{c}	15.74 ± 4.48^{ns}
	10-30	18.37 ± 22.58^{b}	13.90 ± 10.84^{a}	7.81 ± 2.87^{bc}	7.54 ± 4.16^{c}	3.79 ± 1.82^{c}	13.26 ± 2.21^{ns}
LMO	0-10	5.13 ± 1.82^{b}	10.50 ± 3.12^{ab}	11.04 ± 6.54^{a-c}	19.32 ± 6.47^{bc}	28.88 ± 11.25^{ab}	25.04 ± 16.06^{ns}
	10-30	9.85 ± 4.41^{b}	13.51 ± 4.18^{a}	18.55 ± 7.01^{a}	44.48 ± 28.02^{a}	38.28 ± 25.28^{a}	25.78 ± 31.00^{ns}
Average	0-30	13.99 ± 10.96	10.29 ± 3.35	12.53 ± 5.59	24.00 ± 14.63	17.75 ± 13.34	19.56 ± 5.02

Note: SMO: Sambarata Mining Operation; BMO: Binungan Mining Operation; LMO: Lati Mining Operation. Different superscript letter in the same column represents its significant difference among others at $p < 0.05$ in DMRT; ns: not significant

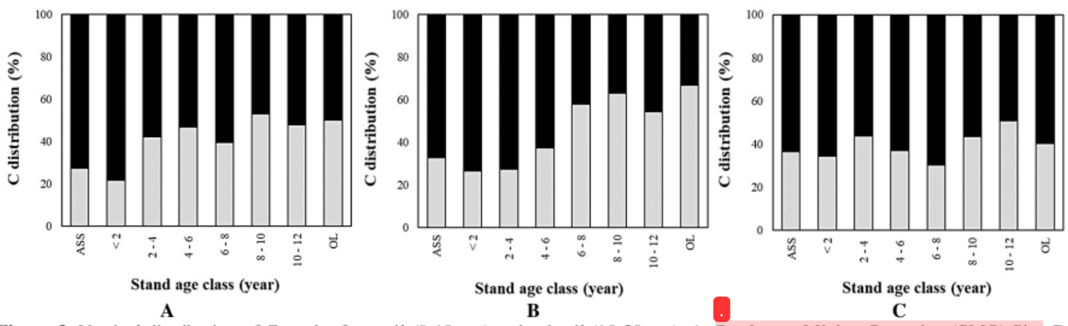

Figure 3. Vertical distribution of C stock of topsoil (0-10 cm) and subsoil (10-30 cm): A. Sambarata Mining Operation (SMO) Site; B. Binungan Mining Operation (BMO) Site; and C. Lati Mining Operation (LMO) Site. Notes: ASS: after soil spreading and OL: original land

Potential of soil carbon stock

The potential of soil carbon 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 5 showed the potential of C stock in the revegetated land, which was classified as very low to low with the average value indicated as 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.

We compared the soil carbon stock in the area studied to other sites in Indonesia under various land covers (Table 6). 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 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 5. Potential of soil carbon stock in the studied area and its classification based on soil fertility classes

Site	Soil depth (cm)	ASS	Stand age class < 2	2-4	4-6	6-8	8-10	10-12	OL
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: SMO: Sambarata Mining Operation; BMO: Binungan Mining Operation; LMO: Lati Mining Operation.; ASS: after soil spreading; OL: original land; L: low; VL: very low

Table 6. Comparison of soil carbon stock 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

This study reported soil carbon in a revegetated post-coal mining area in Berau District, East Kalimantan, Indonesia. The C stock of varying land conditions (i.e. original land, after soil spreading, the revegetation site with varying stages from < 2 years to 10-12 years) has been comprehensively summarized. We concluded that the C stock at the initial soil spreading was characterized as very low fertility. The carbon stock 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, soil fertility in the study area is classified as low due to the lower C content. Hence, the results obtained from this study could enrich existing knowledge of soil ecology in the context of mining activities and revegetation post-mining.

ACKNOWLEDGEMENTS

This study was financially supported by the Faculty of Forestry, Mulawarman University, Indonesia, under the research funding for lecturers and students 2022. The authors are grateful to PT. Berau Coal for facilitating this research from soil sample collection to laboratory test completion.

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