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Development of Secondary Forest Succession Based on Estimation of Forest Carbon Stocks Ten Years Post-Merapi Volcano Eruption

Inggita Utami[1,2*], Anjar Dimara Sakti[3,4,5], Febriant Isabella Yusuf[2], Fahmiatul Husna[2], Denni Susanto[6]

[1]Laboratory of Ecology and Systematics, Universitas Ahmad Dahlan, Bantul, Yogyakarta 55191, Indonesia
[2]Biology Department, Faculty of Applied Science and Technology, Universitas Ahmad Dahlan, Bantul, Yogyakarta 55191, Indonesia
[3]Remote Sensing and Geographic Information Science Research Group, Faculty of Earth Science and Technology, Institut Teknologi Bandung, Bandung 40132, Indonesia
[4]Center for Remote Sensing, Institut Teknologi Bandung, Bandung 40132, Indonesia
[5]Center of Sustainable Development Goals, Institut Teknologi Bandung, Bandung 40132, Indonesia
[6]Department of Bioresources Technology and Veterinary, Vocational College, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

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ABSTRACT

The eruption of the most active volcano in Indonesia, Mount Merapi, has resulted in a very dynamic landscape as a form of ecosystem succession. This study aimed to analyze the carbon stock and vegetation composition in the secondary forest with variations in the level of disturbance after the 2010 eruption of Mount Merapi. Data collection was carried out in January 2020, in which biomass, necromass, and soil organic carbon data were taken in plot transect and Geographic Information Systems carbon stock products compared field data. The results showed that secondary forests at stations A and B with low and medium disturbance levels had carbon stocks in the high category. In contrast, station C at Cangkringan Resort, with high disturbance levels, still had carbon stock with a low category. Furthermore, the comparison of 2020 field data with GIS carbon stock products concluded a similar pattern between carbon stock from aboveground biomass WHRC 2010 and belowground biomass NASA 2010. This research concludes that the disturbance affected forest carbon stocks ten years after the 2010 Merapi eruption. Therefore, monitoring the vegetation community needs to be carried out annually through a combination of spatial and direct checks in the field.

1. Introduction

A volcanic eruption is a non-anthropogenic event that is the source of stored carbon released from the Earth to the atmosphere (Brune *et al.* 2017; Fischer *et al.* 2019). The ring of fire in the tropical rain forest is the most vulnerable area to release carbon up to 31±22 × 1012 g CO_2 year^{-1} through materials exposure and forest fires that occur afterward (Johnson *et al.* 2020; Williamns *et al.* 1992; Zhang *et al.* 2019). Mount Merapi is the most active volcano in the tropical area of Indonesia (Gunawan *et al.* 2013), even one of the most active in the world (Voight *et al.* 2000). Mount Merapi produced a large explosive eruption on the Volcanic Explosivity Index (VEI) in 2010 (Jenkins *et al.* 2016) with a hot cloud range of up to 13 km (Surono *et al.* 2012) and damaged tropical rain forests in Mount Merapi National Park (MMNP) (Gunawan *et al.* 2013; Marhaento and Kurnia 2015) located in Central Java Province and Yogyakarta Province (KLHK 2018). According to Sutono *et al.* (2017), hot clouds heading west and south caused severe disturbances to the MMNP forest in the Cangkringan Resort and Srumbung Resort area with volcanic ash as high as 15 cm. Volcanic ash that comes out during an eruption is a source of accumulation of soil organic carbon (SOC) (Fiantis *et al.* 2019; Hunziker *et al.* 2019) and a source of macro and micronutrients in the soil (Mulyaningsih *et al.* 2012). Residents in 30 buffer villages (Garjita *et al.* 2013) utilize the soil fertility around Mount Merapi for agriculture and building raw materials (Sutono *et al.* 2017). In the first five years after the 2010 major eruption, vegetation succession has occurred, characterized by increased biomass and vegetation diversity (Afrianto *et al.* 2016; Sutomo and Fardilla 2013; Wardani and van Leeuwen 2014). According to Soraya *et al.* (2016), there was an increase in vegetation cover of 28.2% from the open land using remote

* Corresponding Author
E-mail Address: inggitautami@bio.uad.ac.id

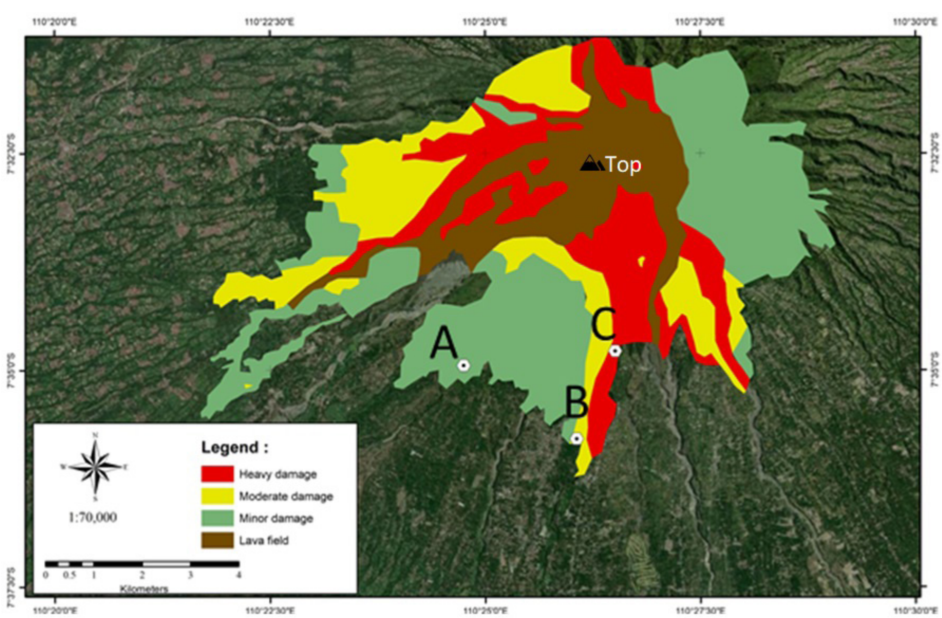
sensing and Geographic Information Systems (GIS) from 2011 to 2015.

Disturbed forests will experience a decrease in carbon stocks, but productivity will increase again as succession continues (Krisnawati *et al.* 2011; Molles 2013; Utami *et al.* 2021a). The magnitude of the disturbance, the size of the disturbed area, the distance from the source of life, and the continuity of the disturbance that occurs will affect the course of succession (Indriyanto 2006; Sutomo 2019; Sakti *et al.* 2020; Utami *et al.* 2021b). Soil organic carbon will dominate approximately in the first 100 years after the eruption, depending on the height of the volcanic ash (Zehetner 2010). The volcanic ash layer, which was initially dominated by inorganic carbon, will react with water (H_20), liberate Fe, and begin to accumulate organic carbon (OC) to form an algae mat layer that is dominated by cyanobacteria (Fiantis *et al.* 2016). This algae mat will become a substrate for pioneer mosses and vascular undergrowth such as grass and shrubs until the accumulation of forest carbon increases after that (Fiantis *et al.* 2016). The carbon sequestration process in plants will be stored in biomass and necromass (Hairiah *et al.* 2011). Remote sensing products have been widely published in modeling biomass and spatially carbon density in the world's terrestrial ecosystems (Spawn *et al.* 2020). However, direct measurements in the field have more accuracy value to validate the GIS product. Towards ten years after the 2010 Merapi eruption, it is necessary to conduct periodic vegetation analysis research to monitor Mount Merapi National Park's succession development directly in the field. This study aimed to analyze the carbon stock and composition of vegetation in the MMNP area of the Special Region of Yogyakarta in secondary forests with different levels of forest damage after the 2010 Merapi eruption. The novelty and contribution of this research is to provide an overview of the differences in succession processes that occur in the same area and time, especially in dynamic areas such as Mount Merapi National Park. This forest carbon data can validate various biomass and carbon stock products from GIS processing developed so far. Research on processing spatial data and field data, which often stands alone, needs to collaborate to improve the accuracy of information.

2. Materials and Methods

2.1. Study Area

Data was collected in January 2020 in the secondary forest of the Mount Merapi National Park (MMNP) in Yogyakarta Province. The sampling location in the MMNP forest was determined based on the disturbance level map after the 2010 eruption issued by the Mount Merapi National Park Agency (BTNGM 2011) (Figure 1). Locations with low and moderate disturbances are represented by Stations A and B at Resort Pakem-Turi.



Stations	Resort	Coordinate point	Distance to the top (km)
A	Pakem-Turi	S 07°34.991' E 110°24.970'	5.66
B	Pakem-Turi	S 07˚35.830' E 110˚26.124'	6.11
C	Cangkringan	S 07˚34.675' E 110˚26.546'	3.20

Figure 1. Sampling location and coordinate sampling station

Low disturbances are assumed to be where the forest is not damaged, only covered with thin volcanic ash. In contrast, the moderate disturbance is described by sixty percent of the forest area traversed by hot clouds and burning, leaving many dead trees. Locations with hard disturbances (hot clouds cover the entire area, and the forest is destroyed) are represented by Station C at Cangkringan Resort (Gunawan *et al.* 2013; Marhaento and Kurnia 2015).

2.2. Data Collection

Carbon stock data at each station was obtained by making the main square plot measuring 20 × 100 m, 5 × 40 m, and 1 × 1 m (Hairiah and Rahayu 2007). The 20 × 100 m plot collected biomass data for large trees with DBH ≥ 35 cm. A subplot measuring 5 × 40 m was created for measuring the biomass of small trees with DBH < 35 cm and woody necromass (dead trees). Data on understorey biomass, litter necromass, and soil organic carbon was carried out destructively on eight plots of 1 × 1 m subplots. The total biomass per sampling area is obtained by adding the aboveground biomass (AGB) and belowground biomass (BGB) (Hairiah *et al.* 2011). Data on tree biomass, understorey biomass, woody necromass, and leaf litter are part of AGB, while soil organic carbon is part of BGB. Total (forest) carbon stock is obtained from forty-six percent of the aboveground and belowground biomass (Figure 2). Forty-six percent is the default number describing the carbon content (C) in each component carried out by the International Center for Research in Agroforestry (Hairiah *et al.* 2001; Hairiah and Rahayu 2007). Light intensity, wind speed, air temperature, air humidity, soil temperature, soil pH, soil humidity, elevation, and land slope were measured to see the correlation between abiotic with carbon stock.

This study will also compare estimates of successional developments from 2010 to early 2020 based on carbon stock values between GIS products and field data. The estimated carbon value in 2010 will use two biomass carbon stock products issued by the Woods Hole Research Center (WHRC) and the National Aeronautics and Space Administration (NASA) biomass carbon density (Figure 3). This WHRC data

Forest carbon stock = (t C ha^{-1}) **(Above-ground biomass + below-ground biomass) x 46%**

Above-ground biomass:

Tree Biomass (Bt) + Understorey Biomass (Bu) + Woody necromass biomass (Bk) + Litter Biomass (Bl)

$$Bt = 0.118 \times DBH^{2.53}$$

Note:
Bt = tree biomass (t C ha^{-1})
DBH = Diameter at Breast Height (cm)
(Hairiah *et al.* 2001)

$$Bu,l = \frac{\text{BK sub sample (g)}}{\text{BB sub sample (g)}}\ x\ \text{Total BBc (g)}$$

Note:
Bu,l = understorey biomass/ leaf litter biomass
BK sub sample = Dry weight sub sample
BB sub sample = Wet weight sub sample
BBc = Total wet weight
(Hairiah and Rahayu 2007)

$$Bk = \frac{\pi\rho H D^2}{40} \quad \text{(Hairiah and Rahayu 2007)}$$

Note:
BK = woody necromass biomass (kg $necromas^{-1}$)
ρ = density of necromas (0.4 g cm^{-3})
H = length / height of necromas (m)
D = diameter of necromas (cm)

Below-ground biomass:

SOC = Ct x 100 (Hairiah and Rahayu 2007)
Ct = Kd x ρ x % C organic

Note:
SOC = Soil Organic Carbon
Ct = soil carbon content (g cm^{-2})
100= conversion factor from g cm^{-2} to ton ha^{-1}
Kd = depth of soil sample (cm)
ρ = bulk density (g m^{-3})
%C organic = percentage of organic carbon (Analysis in the laboratory)

Figure 2. Calculation of total carbon stock per sampling station

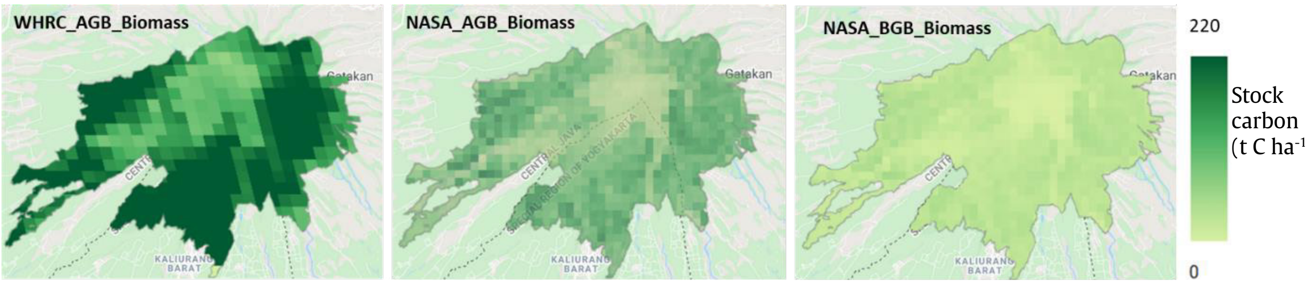


Figure 3. GIS carbon stock products from AGB and BGB from WHRC and NASA (maps are modified from Baccini *et al.* 2012 and Spawn *et al.* 2020)

product provides a national-level map of aboveground biomass density for tropical countries with a spatial resolution of 500 m (Baccini *et al.* 2012). This data product was collected from field measurements, LiDAR observations, and MODIS images. The following product is the NASA global aboveground and belowground biomass carbon density maps. The 2010 NASA data on above and belowground biomass carbon density data has a spatial resolution of 300 m (Spawn *et al.* 2020). NASA's above and belowground maps are integrated using additional tree cover maps, land cover percentages, and rule-based decision trees.

2.3. Data Analysis

Forest carbon stock data were analyzed descriptively to compare the stock carbon values between the three stations. Carbon stock data will be analyzed inferentially to see the correlation with abiotic parameters. Parametric and non-parametric correlation tests will be determined after prerequisites for the normality and homogeneity tests. The GIS analysis products published on the Google Earth engine are used to compare changes in carbon stock value from 2010 until 2019 in the field.

3. Results

Towards ten years after the major eruption of Mount Merapi, the total carbon stock of station A with the lowest level of damage, is 216.09 t C ha^{-1}, while station C has the lowest carbon stock value of 40.76 t C ha^{-1} (Table 1). Based on the inferential analysis, the carbon stock data differed significantly in the three stations. This result is indicated by the significance value (α) of the ANOVA test results below 0.05 (0.0376). Carbon stock sourced from AGB at stations A and B dominates in the range of 81-88%, while at station C, it is still deficient, with a percentage of 48% of the total carbon stock at that location. The high carbon stock from AGB at both stations was dominated by tree biomass (Table 1). The tree biomass at station A was most dominantly contributed from *Pinus merkusii* Jungh and de Vriese (large tree) and *Cestrum nocturnum* L. (small tree). In contrast, *Albizia chinensis* (Osbeck) Merr contributed the high tree biomass at station B. (large tree) and *Mallotus peltatus* (Geiseler) Müll.Arg. (small tree). On the other hand, station C, with a low level of disturbance, is still dominated by soil organic carbon (SOC) from BGB with a percentage of up to 52%, in contrast to stations A and B, which only contributed 12-19% (Table 1).

Vegetation composition carried out in three research locations resulted in discovery of 74 species of trees and understorey plants from 59 families. According to Table 2, the highest tree species, tree density, and total tree diameter at station A made the tree biomass value at that location the highest compared to other locations. On the other hand, it can be seen in Table 3 that the highest undergrowth density at station C was still unable to make the undergrowth biomass the highest at station C. On the other hand, the percentage of understorey biomass at stations A and B is almost equivalent to station C (Table 1), dominated by the Poaceae and Cyperaceae families. Both families require high light intensity for their growth to describe the condition of the forest that is still quite open in all locations. The highest tree and understorey diversity level was seen at station B (Table 2 and 3). However, this diversity does not directly affect biomass and carbon stocks.

Based on the Spearman correlation test results, abiotic parameters such as air temperature, air humidity, soil pH, soil humidity, and elevation correlate with carbon stock from aboveground biomass. Based on the correlation coefficient score in Table 4, it can be concluded that the higher the air temperature, soil pH, and elevation values, the

Table 1. Value of carbon stock (t C ha^{-1}) for each carbon source

Location (disturbance level)	Source of carbon stock						Total carbon stock
	Biomass (tree)	Biomass (understorey)	Necromass (Woody)	Necromass (Littler)	Aboveground biomass	Soil crganic carbon (belowground)	
Station A (low)	172.06 (80%)	9.38 (4%)	0.00 (0%)	8.15 (4%)	189.59 (88%)	26.50 (12%)	216.09
Station B (medium)	81.55 (48%)	9.57 (6%)	37.88 (22%)	8.12 (5%)	137.12 (81%)	32.44 (19%)	169.56
Station C (hard)	4.08 (10%)	9.28 (23%)	6.21 (15%)	0.00 (0%)	19.57 (48%)	21.19 (52%)	40.76

Table 2. Vegetation parameters on tree life forms

Location (disturbance level)	Tree species	Tree density (ind ha^{-1})	Tree DBH (cm)	Tree biomass (t C ha^{-1})	H' Shannon wiener
Station A (low)	22	6240	1285.19	374.04	1.96
Station B (medium)	16	3920	499.26	177.28	2.68
Station C (hard)	2	455	69.01	8.87	0.00

Table 3. Vegetation parameters on understorey life forms

Location (disturbance level)	Understorey species	Understorey density (ind ha^{-1})	Understorey dominance (% ha^{-1})	Understorey biomass (t C ha^{-1})	H' Shannon wiener
Station A (low)	11	93.00	43.13	17.17	1.97
Station B (medium)	14	189.50	60.13	17.71	2.15
Station C (hard)	9	255.50	45.25	17.37	1.74

Table 4. Correlation between abiotic parameters with AGB and BGB

Spearman's rho		Light intensity	Air temperature	Air humidity	Wind speed	Soil pH	Soil humidity	Soil temperature	Land slope	Elevation
ABG	Correlation coefficient	.189	-.415**	.534**	-.201	-.335*	.457**	-.051	-.300	-.332*
	Sig (2-tailed)	.248	.009	.000	.219	.037	.003	.758	.064	.039
BGB	Correlation coefficient	-.109	-.135	.087	-.219	-.121	-.271	.056	.075	.043
	Sig (2-tailed)	.611	.528	.686	.303	.572	.198	.797	.728	.842

lower the forest carbon stock value. Stations A and B, with higher carbon stock than station C, are in the range of elevation of 1,034 m asl with an average temperature of around 25.7°C and an average soil pH of 6.32. On the other hand, station C with the lowest carbon stock category, is at an altitude of 1,205 m asl with an average temperature of around 27.6°C and an average soil pH of 7.8. Positively correlated abiotic parameters such as air humidity and soil humidity (Table 4) are estimated to support the increase in forest carbon stocks at stations A and B.

On the other hand, there is no abiotic correlation with carbon stocks from belowground biomass. Abiotic parameters forming microclimate generally affect the formation of vegetation biomass. In addition, belowground biomass formed from soil organic carbon is easily influenced by materials from the volcanic eruption process.

Issues related to carbon stocks have become a global concern. As a result, several institutions have developed carbon stock from biomass products globally. Estimated AGB carbon stock at stations A and B points between the 2020 field data and WHRC and NASA products has a different pattern. Based on Table 5, the 2010 WHRC AGB product has a similar pattern to the field data in 2020 and is estimated to be analyzed before Mount Merapi erupted in November 2010. Station A had the highest carbon stock values in 2010 and 2020, reflecting that the location is not disturbed. Station B experienced a relatively rapid increase in tree biomass in 2020 after experiencing moderate disturbances in 2010, and can be seen from the comparison between the WHRC and AGB 2020. There is a significant decrease in carbon stock at locations with hard disturbances due to destroying all biomass sources significantly above

Table 5. Comparison of 2010 GIS estimated carbon stock and 2020 field data

Location (disturbance level)	Stock carbon estimation in 2010 (t C ha^{-1})			Stock carbon (t C ha^{-1})	
	WHRC AGB	NASA AGB	NASA BGB	2020 AGB	2020 BGB
Station A (low)	200.00	55.41	14.07	189.59	26.50
Station B (medium)	176.00	80.92	19.82	137.12	32.44
Station C (hard)	123.00	89.36	21.56	19.57	21.19

ground level. A similar trend is also seen between NASA's 2010 BGB estimate and 2020 field data (Table 5). Comparing carbon stock values between GIS products and field data is only used to estimate the pattern of succession development at locations with different levels of disturbance in tropical volcanic.

4. Discussion

Based on the criteria for forest carbon stock values issued by Reducing Emissions from Deforestation and Forest Degradation or REDD+, stations A and B have a high carbon stock category, while station C is still low. REDD+ issued three criteria for the categories of forest carbon stocks, namely low carbon stock (<35 t C ha^{-1}), medium carbon stock (35–100 t C ha^{-1}), and high carbon stock (>100 t C ha^{-1}) (REDD 2010). According to Rochmayanto *et al.* (2014), the value of secondary forest carbon stocks in Java should have a minimum value of 48.43 t C ha^{-1}. The carbon stock value at the site of low and moderate eruption disturbances (station A and station B) follows the Intergovernmental Panel on Climate Change (IPCC) recommendations for secondary forests in Southeast Asia with values above 138 t C ha^{-1} (IPCC 2006). The ICRAF Southeast Asia research results show that forests from various ecological areas in Indonesia have carbon stock values of 20-250 t C ha^{-1}, where the low carbon stock value at station C (40.76 t C ha^{-1}) is equivalent to the condition of the former forest low-density logging (Rahayu and Harja 2013). Adinugroho *et al.* (2006) stated that carbon storage is influenced by individual density, stem diameter, and diversity of plant species. Chairul *et al.* (2016) added that biomass and carbon storage are also influenced by forest, vegetation, climate, rainfall, and topography. Abiotic factors are also thought to influence the succession process and the forest carbon stocks (Raevel *et al.* 2012).

In this case, it is not only variations in the level of initial community that can affect carbon stocks and vegetation diversity but also interventions from human rehabilitation programs (Indriyanto 2006; Rinanti 2017). Human intervention in tree planting was carried out at station C in particular. At the location of station C, a high level of eruption disturbance destroyed all the plants that live above the soil surface. According to the research results of Afrianto *et al.* (2016), the invasive alien species *Acacia decurrens* from the Fabaceae dominates sites affected by hot clouds in the red and yellow zones (Figure 1), especially in valleys or steep ravines. However, the sampling location at station C, which is flat, is dominated by a local species from the Javan mountains, namely *Schima walichii* from Theaceae (Gunawan *et al.* 2013). These plants were deliberately planted, marked with wooden supports on each plant, as part of the MMNP area rehabilitation program. Schima walichii dominated at station C up to 400 individuals ha-1 and attempted to break the chain of the dominance of *Acacia decurrens*. *Acacia decurrens* also dominate the hilly location of station B. In addition, because the station is located in the utilization zone, it is not surprising to find introduced species such as Garden Croton (*Codiaeum variegatum*) as an ornamental plant.

Referring to the classification on Shannon-Wiener Index, it is known that the diversity of understorey from all research sites has a moderate diversity category, followed by the diversity value of small trees at station locations A and B, which also have a moderate diversity category. This result differs from the low diversity of large trees in the three locations. The moderate category of diversity in the understorey and small trees indicates that the succession of young secondary forests is ongoing, marked by the diversity of pioneer plants such as mosses, herbs, soil ferns, and small trees (Syachroni *et al.* 2018).

The carbon stock values for both ABG and BGB for almost ten years after the 2010 eruption of Mount Merapi can describe the succession developments in the MMNP forest area. The succession at station C can be classified as primary succession because hot clouds covered the location and destroyed it. After almost ten years of succession, volcanic soil began to form with a soil organic carbon (SOC) value of 21.19 t C ha^{-1} or 52% of the total carbon stock of the location (Table 2). Volcanic soils (andosols), the most productive soils globally, store soil organic carbon pools of up to 254 t C ha^{-1} at a depth of 100 m from the soil surface (Batjes 1996; Zehetner 2010). According to Hunziker *et al.* (2019) and Zehetner (2010), the potential for accumulation of SOC in volcanic areas will be high in the first 50 years with a minimum value of 20 t C ha^{-1}. Based on 86 years of primary succession on Mount Anak Krakatau in Indonesia, SOC values reached 49 t C ha^{-1} on soils at 25 cm altitude (Schlesinger *et al.* 1998). The first inorganic carbon released from volcanic eruptions will react with water or calcium (Ca) molecules to form organic compounds such as carbonic acid or calcium carbonate (Dahlgren *et al.* 2004) and increase the concentration of plant nutrients in the soil (Fiantis *et al.* 2019). In addition, soils rich in organic matter pump protons to the top layer and trap alkali for CO_2 (Ugolini and Dahlgren 2002).

Ash thickness strongly influenced this primary succession with a 6-12 months pedogenic time for ash < 20 cm thick (Fiantis *et al.* 2009). According to Rahayu *et al.* (2014), the height of volcanic ash due to the 2010 eruption of Mount Merapi reached 10 cm. Volcanic layers or tephra can store moisture and provide a source of life (water and CO_2) for pioneer plants such as cyanobacteria to form algal mats as a habitat for further pioneers such as mosses and undergrowth (Basile-Doelsch *et al.* 2005). Sutomo and Fardila (2013) reported that 72 pioneer plant species from 36 families had been present one year after the eruption in areas affected by hard disturbance. Pioneer species in the early life of primary succession can enrich N and P with their ability to symbiotically with nitrogen-fixing bacteria. At station C, the presence of understorey dominated by Poaceae and Fabaceae could store carbon 9.28 t C ha^{-1} or 23% of the total carbon stock (Table 1). The presence of volcanic soil has a high capacity to capture CO_2 from the atmosphere through plants (Fiantis *et al.* 2019). Stabilization and accumulation of SOC in volcanic soils can offset carbon dioxide emissions from volcanic activity (Zehetner 2010).

The low disturbance level at station A resulted in very high tree biomass, reaching 80% of the total carbon stock in the area (Table 1). Heavy disturbance at station C was indicated by almost no dead trees or woody necromass (0%). This situation contrasts with station B (moderate disturbance), which has carbon stocks from woody necromass up to 37.88 t C ha^{-1} (22%). The measurement of biomass describes the amount of CO_2 absorbed by plants, while the measurement of carbon in necromass describes the CO2 not released through combustion (Hairiah and Rahayu 2007). Regeneration of large and small trees at station B (modSerate disturbance) indicates that the location has a substrate that is already rich in nutrients and ready to grow higher plants. Over time, necromass will decompose, releasing carbon into the soil and stored as organic carbon. As a result, the soil carbon stock at station B is the highest compared to other locations, namely 32.44 t C ha^{-1}.

Carbon sequestration and storage in MMNP conservation forest areas is part of environmental service products based on the Regulation of the Minister of Forestry of the Republic of Indonesia number P.20/Menhut-II/2021 concerning the implementation of forest carbon (JDIH KLHK 2021). Conservation forest management, including monitoring the measurement of forest carbon stocks, is part of forest carbon activities. Direct measurement of carbon storage in the field in disaster-prone areas such as in the MMNP forest needs to be a routine step forward. The method must also be combined with sustainable GIS products to monitor the entire MMNP area for succession dynamics.

The results of carbon stock measurements using the transect method almost ten years after the 2010 Merapi eruption showed that the highest value was at the low eruption disturbances area, followed by the moderate disturbance area. Both locations have been included in the category of high carbon stocks, according to REDD+. In contrast, the locations with hard eruption disturbances are still in the low category. The dominance of BGB from soil organic carbon (SOC) at hard disturbance areas illustrates the early stages of primary succession that are still taking place there. The dominance of the SOC will be replaced by biomass from understorey vegetation and trees that begin to grow naturally until it is assisted by the rehabilitation program from the government in this area. It is hoped that the carbon stock of the highly dynamic MMNP area will continue to be measured continuously along with the dynamic frequency of eruptions occurring in this area. Abiotics at the sampling location support the succession process from the secondary forest area in MMNP. Efforts to plant native MMNP plants in the Cangkringan area (*Schima walichii*) are expected to help accelerate the regeneration process from the secondary forest. The vegetation community needs to be monitored annually through a combination of spatial and direct checks in the field.

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