



Pedological Approach for Soil Carbon Stock Estimating in Gayo Highland Coffee Plantations, Aceh-Indonesia

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ABSTRACT

Background: Soil carbon stocks (SCS) play a key role in regulating soil fertility and global climate. Determining the amount of SCS through a pedological approach is still limited, while the amount of SCS in highland areas based on elevation is still debated, also the role of elevation-slope combinations on SCS is not well known. This research aims to determine the amount of SCS in each soil horizon, elevation, slope position and also the effect of elevation and slope position on SCS.

Methods: A total of 46 undisturbed and disturbed soil samples were collected in each pedogenic horizon from 12 soil profiles at four elevation levels ie 700-715; 1000-1060; 1300-1351; 1600-1616 meter above sea level (m.a.s.l.) and three slope positions (foot, middle, and upper of slope) in Gayo highland Arabica coffee plantation fields.

Result: The results showed that SCS of soil horizons in Arabica coffee plantations in the Gayo highlands varied from 5.97 to 84.56 MgC.ha⁻¹, with SCS of the upper horizons being higher than those of the lower horizons. The amount of solum SCS from the soil profile also varied from 73.91 to 218.25 MgC.ha⁻¹. Based on the elevation, the highest mean amount of SCS of the solum was 157.35 MgC.ha⁻¹ which was found at the elevation of 1600-1616 m.a.s.l, whereas the mean amount of solum according to the slope position was 167.34 MgC.ha⁻¹ which was found on the foot of slope. Elevation and slope position significantly increased the SCS with the highest value found in the combination of 1000-1060 m.a.s.l, and foot of slope.

Key words: Elevation, Coffee arabica plantation, Organic carbon, Slope, Soil horizon, Soil properties.

INTRODUCTION

Soil carbon stocks (SCS) play an important role in controlling soil quality and global climate dynamics (Elbasiouny *et al.*, 2022). In the calculation of SCS content, the organic carbon (OC), bulk density (BD) and soil thickness/depth variables are used (FAO, 2019). However, the soil thicknesses that are often used are those that are made according to what the researcher wants, such as 10, 20, or 30 cm, including what was done by Urgessa and Ferede (2023) and Khusrizal *et al.* (2023). Meanwhile, calculating SCS using the desired soil horizon thickness pedogenetically has not been widely performed. On the other hand, information on the effect of the interaction between elevation and slope position on SCS in highland coffee plantation is also very limited and the level of SCS content at various elevations is still debated.

Soil thickness/depth as one of the variables in determining SCS that is prevalent and commonly practiced so far is based on the thickness/depth of certain soil layers (FAO, 2019; Tadiello *et al.*, 2022) and not referring to the thickness of the horizon as a pedogenic horizon formed and developed by pedogenesis (horizon). Determining the depth of a soil layer with a certain specified size is something that is considered to poorly describe the characteristics of the soil in each intended layer (Phillips, 2017). However, within a single layer of a certain size, soil properties tend to vary, while within a single pedogenic horizon, soil properties are considered more homogeneous (Hartemink *et al.*, 2020). Similarly, regarding the OC content

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and BD value of a layer used as variables, the amount of soil SCS content results is considered to be less descriptive for the layer. These two soil parameters in a horizon can be determined by other soil properties, especially those that become criteria or references as well as when drawing horizon boundaries (Jiang *et al.*, 2021). Organic matter (OM) content, for instance, can also be used to determine horizon boundaries as it can morphologically affect the soil color. The same applies to BD values as it can be affected by the fineness or coarseness of the soil fraction which is also used to determine the horizon boundaries (Reshi *et al.*, 2022). The determination of soil depth based

on pedogenic horizon thickness to calculate SCS content can accurately describe each soil horizon. Thus, the amount of SCS in the upper horizon and below may be the same or different. By determining the amount of SCS in each horizon, the amount of SCS in a soil solum will also be obtained, where many have only informed the amount of SCS at a certain soil depth. Information on the amount of SCS in the solum will be interesting data considering that the solum is more related to soil quality which is the medium where plants grow.

Elevation and slope position are topographic components associated with soil properties (Yuan *et al.*, 2019), as well as in the Gayo highland region where the land is used as an Arabica coffee plantation area that has various elevations and slope positions. Both elevation and slope position can affect the amount of SCS (Zhang *et al.*, 2021). Regarding the relationship between elevation and SCS, several studies reported different results, which is still a matter of a debate. One study suggests that SCS decrease as elevation increases (Kobler *et al.*, 2019; Seifu *et al.*, 2021). Other studies suggest the opposite where SCS increase along with the elevation (Wan *et al.*, 2019; Massaccesi *et al.*, 2020). Pragasan (2022) and Sheikh *et al.* (2020) also stated that SCS are positively correlated with elevation, while Bargali and Bargali (2020) and Chauhan *et al.* (2020) reported that SCS initially increased at low to medium elevations and then decreased at high elevations. The inconsistency in the magnitude of SCS at certain elevation positions is strongly related to the properties of the soil and its environment, which can have a direct or indirect effect, especially with the distribution of BD, OC values and soil fractions found in the soil (Merabtene *et al.*, 2021; Zhang *et al.*, 2021), where BD and OC are used as components to determine SCS, which are not homogeneous in one layer or horizon.

In addition to varying elevations, the Gayo highlands also have different slope positions: foot of slope, middle slope and upper slope. Soil pH, humus content, particle size and soil moisture may differ between these slope positions (Magdić *et al.*, 2022), as well as soil organic carbon content and BD (Bayat *et al.*, 2017). Studies show that physico-chemical properties on upper slopes are better than those on lower slopes (Liu *et al.*, 2017). This condition will also illustrate the difference in the amount of SCS between slope positions and indicates that the upper slope has higher SCS than the lower slope. Singh and Benbi (2018) reported the results of their research that SCS values are different at different slope positions, which are the upper slope, middle slope and lower slope where the three slope positions are in different land use, however the results of this research did not reveal the amount of SCS at the foot of the slope.

The outlined results only report the relationship of elevation and SCS, as it studies the elevation and its aspect on SCS (Bangroo *et al.*, 2017), as well as the slope position which only examines the upper and middle slopes with their

SCS (Singh and Benbi, 2018; Nozari and Borůvka, 2023). Highlands with their various elevations are also associated with slopes and their various positions (Singh, 2018), hence examining the co-effects of elevation and slope position on SCS content of highland soils is needed. This research aims to determine the amount of SCS in each soil horizon and solum, elevation, slope position as well as the interaction effect of elevation and slope position on SCS in Arabica coffee plantation in the Gayo highlands.

MATERIALS AND METHODS

Research site

The research was conducted from September 2023 to February 2024 in Gayo highland coffee plantation, Bener Meriah District, Aceh Province (Fig 1). Geographically, Bener Meriah District is located at 4°33'50"- 4°54'50"N and 96°40'57" - 97°17'00"E.

The climate data used an annual average climate data collected in the last 15 years (2009-2023), such as rainfall, temperature and humidity data obtained from the Climate Station of the Meteorology, Climatology and Geophysics Agency of Indrapuri, Aceh Besar. The area has an average rainfall of 2,936 mm/year. The mean annual optimum temperature is 20.7°C and the mean annual relative humidity is 83% which belongs to the hyperthermic temperature regime.

The geology of the area consists of young alluvium, upper conglomerate member, Bampo formation, Baong formation, Bruksah formation, Kluet formation, Keutapang formation, Tuan unit and Volcanic. The volcanic material is the largest group found in this area.

Data collection and soil properties parameters

Soil samples were obtained through representative soil profiling, where the position/point of the representative soil profile was determined based on the elevation and slope position. In this study, the elevation consists of 4 elevation levels: 700-715, 1000-1060, 1300-1351 and 1600-1616 m.a.s.l. Furthermore, there are 3 slope positions: the foot of slope, middle slope and upper slope.

Soil profiles at each elevation and slope position were made to a length of 1.5 m×width of 1.0 m×depth at which no further excavation or parent material could be found. All soil profiles that became sampling points were within Arabica coffee plants with a uniform age (5 years). This intends to eliminate the effect of plant age differences on the soil properties to be studied. Soil sampling was performed on each horizon after drawing and measuring the boundaries of each horizon pedogenetically as well as giving symbol to each horizon. The soil samples taken consisted of undisturbed soil samples (with a ring of 53 mm diameter and 100 cm³ volume) and disturbed soil samples. Each 1.5 kg of disturbed soil sample taken from each horizon was put into a plastic bag for the purpose of analysis.

Undisturbed soil samples were taken for BD analysis using model C53 ring sample kit (Grossman and Reinsch, 2002), while the disturbed soil samples were taken for OC analysis using Walkley and Black method. The undisturbed soil samples were air dried and sieved with a size of 10 mesh before use, specifically for the determination of OC, the samples used were those that passed the 70 mesh sieve. The determination of SCS was based on the adjusted formula of FAO (2019).

$$\text{SCS (MgC ha}^{-1}\text{)} = \text{OC (\%)} \times \text{BD (g/cm}^3\text{)} \times \text{dh (cm)}$$

Where

SCS= Amount of soil carbon stock measured in MgC.ha⁻¹ in each soil horizon.

OC= Amount of soil organic carbon content measured in per cent.

BD= Amount of bulk density measured in g/cm³.

Dh= Horizon thickness which is determined based on drawing horizon boundaries pedogenetically.

In order to obtain the amount of SCS from the solum, add up the SCS values from the highest horizon to the lowest horizon in one soil profile. The average amount of SCS from the solum at each elevation was obtained from the total SCS from the solum of the soil profiles of the three slope positions divided by three.

Data analysis

Data on soil properties, particularly BD, OC and SCS were analyzed and presented according to the results of the 12 soil profiles. SCS data results were also presented according to elevation, slope position and soil horizon. Furthermore, to determine the effect of elevation and slope position on SCS, a two-way anova with unequal number of replicates was used, where elevation differences and slope position differences are the treatments and SCS levels are the affected parameters.

RESULTS AND DISCUSSION

Bulk density and organic carbon

The values of BD and OC in the study area were varied either between soil horizons, elevations or slope positions

(Table 1). The values of BD ranged from 0.56 to 1.58 g/cm³. The lowest value was found in the Bw2 horizon, elevation of 1600-1616 m.a.s.l, foot of slope, whereas the highest value was found in the BC horizon, elevation of 700-715 m.a.s.l, middle slope. Generally, BD increased from the upper horizon to the lower horizon, the data also showed that BD decreased as the elevation increased and were relatively similar within the slope position. The dynamics of BD in a soil can be affected by various factors, especially OM, soil fraction and soil structure. The increase in BD as soil depth increases can be due to the increase in coarse fraction, soil compaction and decrease in soil OM content (Shan *et al.*, 2019). Moreover, BD can also increase as the soil depth decreases which can be due to a decrease in soil porosity (Munty *et al.*, 2021). The low BD at the elevation of 1600-1616 m.a.s.l can be caused by a high OM and finer soil texture. Soils with higher OM and finer soil fractions will have lower BD values (Ruehlmann, 2020; Azuka and Idu, 2022).

Soil OC content also varied within the soil horizon, elevation and slope position. The OC ranged from 0.27-3.18% where the lowest was found in the BC horizon with the elevation of 700-715 m.a.s.l in the middle slope, while the highest was found in the Bw horizon with the elevation of 1600-1616 m.a.s.l in the lower slope. The OC of the upper horizon is higher than that of the lower horizon, this is because the OC tends to increase as the elevation increases. The OC content at the lower slope is higher than the middle and upper slopes. The variation of OC in the soil profiles is mainly due to its translocation from the upper horizons to the lower horizons which is possible as OC can be carried along with the water movement and then distributed and stored in the soil depending on the soil properties such as being held in clay textures or denser layers, so that they do not continue to scour (Yang *et al.*, 2022). Despite this, the fact shows that the lower amount of OC is more likely due to the higher amount of OM at the surface compared to those below (Wang *et al.*, 2021). The low amount of OC at lower elevations is related to the weathering of OM where at these elevations the process of weathering is more intense due to higher temperatures,

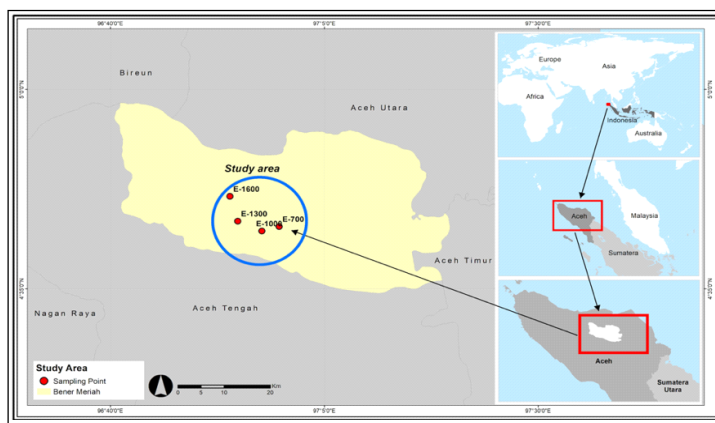


Fig 1: Location of the study area.

whereas at higher elevations the temperature is lower which can inhibit the process of OM weathering by microorganisms (Barros *et al.*, 2021). The high amount of OC at the lower slope compared to middle and upper slope is also related to the accumulation of OC at the lower slope which is carried from the upper and middle slope by water scouring, where Liu *et al.* (2017) also found that the SOC content was high or increased on foot of slopes.

Soil carbon stocks

The amount of SCS in each horizon from the 12 representative soil profiles observed is presented in Fig 2 and it can be seen that the amount of SCS in each horizon is relatively varied, ranging from 5.97 to 84.56 MgC.ha⁻¹. The lowest SCS level (5.97 MgC.ha⁻¹) was found in BC horizon at elevation of 700-715 m.a.s.l at the middle slope, while the highest amount of SCS (84.56 MgC.ha⁻¹) was found in Bw horizon at the same elevation at the foot of slope. In general, though, it can be seen that the amount of SCS decreases from the upper horizon to the foot of horizon. The data shown in Fig 3 also informs that the SCS of each soil profile varies among different elevations and slope positions. The variation in SCS of each horizon is due to the distribution of OC content, BD value and horizon thickness, all of which are variables that determine SCS (Poeplau and Gregorich, 2023). The high amount of SCS in the Bw horizon in this case is more affected by the horizon thickness and soil BD than its OC. However, overall, it can be seen that the OC also determines the amount of SCS in a soil profile whereby the OC tends to decrease from the upper horizon to the lower horizon which has caused the distribution of SCS to decrease as the horizon deepens. Studies by Zeng *et al.* (2021) also reported that OM or its fractions are materials that contribute significantly to the amount of carbon stock value of a soil. The same condition was also revealed by Mueller and Koegel-Knabner (2009) stating that OC content is a variable that determines the amount of SCS, where the amount depends on the distribution pattern of OC in the soil profile. The variation of SCS in soil profiles across elevations and slope positions is also controlled by OC and BD which are caused by land management practices such as coffee plantation, which have contributed to soil properties including OC and BD, as well as to the horizon thickness in the study area. This phenomenon was also stated by Hartemink *et al.* (2020) that variations in soil properties and horizon thickness can be affected by its management practices.

The amount of solum SCS at various elevations and slope positions is presented in Fig 3a, the average amount of solum SCS at each elevation is shown in Fig 3b and the average amount of SCS at slope positions is shown in Fig 3c. The amount of solum SCS at various elevations and slope positions appears to be highly variable both within the elevation and slope positions ranging from 73.91-218.25 MgC.ha⁻¹. The average amount of solum SCS at each elevation presented in Fig 3b ranged from 127.57-157.35 MgC.ha⁻¹. The highest amount was found at the highest

Table 1: Value of bulk density and organic carbon according elevation and slope position.

Slope position	Elevation (m a.s.l)														
	700-715					1,000-1,060					1,300-1,351				
	Hor.	Depth	BD	OC	Hor.	Depth	BD	OC	Hor.	Depth	BD	OC	Hor.	Depth	BD
Foot of slope	Ap	0-28	0.98	2.78	Ap	0-30	0.87	2.62	Ap	0-23	0.90	2.18	Ap	0-29	0.86
	Bw	28-57	1.35	2.16	AB	30-58	0.93	2.52	Bw1	23-40	0.94	1.82	Bw1	29-57	0.82
	Bg1	57-86	1.54	1.08	Bw	58-88	1.12	1.13	Bw2	40-56	0.82	0.97	Bw2	57-79	0.56
	Bg2	86-95	1.50	0.68	-	-	-	-	BC	56-81	0.93	0.88	BC	79-94	0.92
Middle slope	Ap	0-15	1.28	1.33	Ap	0-27	0.77	2.20	Ap	0-18	1.09	2.22	Ap	0-35	0.96
	AB	15-42	1.22	0.81	Bw	27-53	0.87	2.01	AB	18-43	1.40	1.88	AB	35-53	0.89
	Bw	42-69	1.42	0.41	BC	53-81	1.12	1.99	Bw1	43-63	0.92	1.52	Bw1	53-69	0.93
	BC	69-83	1.58	0.27	-	-	-	-	Bw2	63-80	0.77	1.00	Bw2	69-85	0.72
Upper slope	Ap	0-27	1.15	1.35	Ap	0-8	0.82	2.20	BC	80-95	0.79	1.31	Ap	0-27	0.95
	Bw1	27-51	1.36	1.88	BA	8-33	0.85	1.95	Ap	0-17	1.02	2.39	Bw	27-47	0.85
	Bw2	51-80	1.36	0.56	Bw	33-59	0.86	1.73	BC	32-44	1.49	1.52	BC	47-61	0.67
	BC	80-109	1.36	0.72	BC	59-83	0.80	1.38	-	-	-	-	-	-	-

Note: Hor. (horizon), BD (bulk density-g/cm³), OC (organic carbon-%).

elevation which is 1600-1616 m.a.s.l while the lowest amount was found at the elevation of 1300-1351 m.a.s.l. The average amount of solum SCS based on the slope position as shown in Fig 3c ranged from 133.40-167.34 MgC.ha⁻¹. The lowest average was found at the upper slope and the highest was found at foot of slope.

The various amount of solum SCS as shown in Fig 3a seems to follow the distribution pattern of soil OC, BD and solum thickness which are also variable. However, when looking at the average amount of solum SCS according to the elevation (Fig 3b), the highest amount was found at the highest elevation which is 1600-1616 m.a.s.l. The high amount of solum SCS at this elevation

is strongly affected by the OC, meanwhile the BD is relatively low and solum thickness is thinner than solum at other elevations (Fig 3). It is understood that the high amount of OC at high elevations is caused by the inhibition of the decomposition process of SOM due to low temperature and several studies have revealed that temperature has a significant effect on the availability of soil OC (Barros *et al.*, 2021). If the environmental temperature is low, the activity of decomposing microorganisms is also low, resulting in high soil OC (Barros *et al.*, 2021). Other studies also suggest that SCS are higher or increase as the elevation increases (Massaccesi *et al.*, 2020; Sheikh *et al.*, 2020).

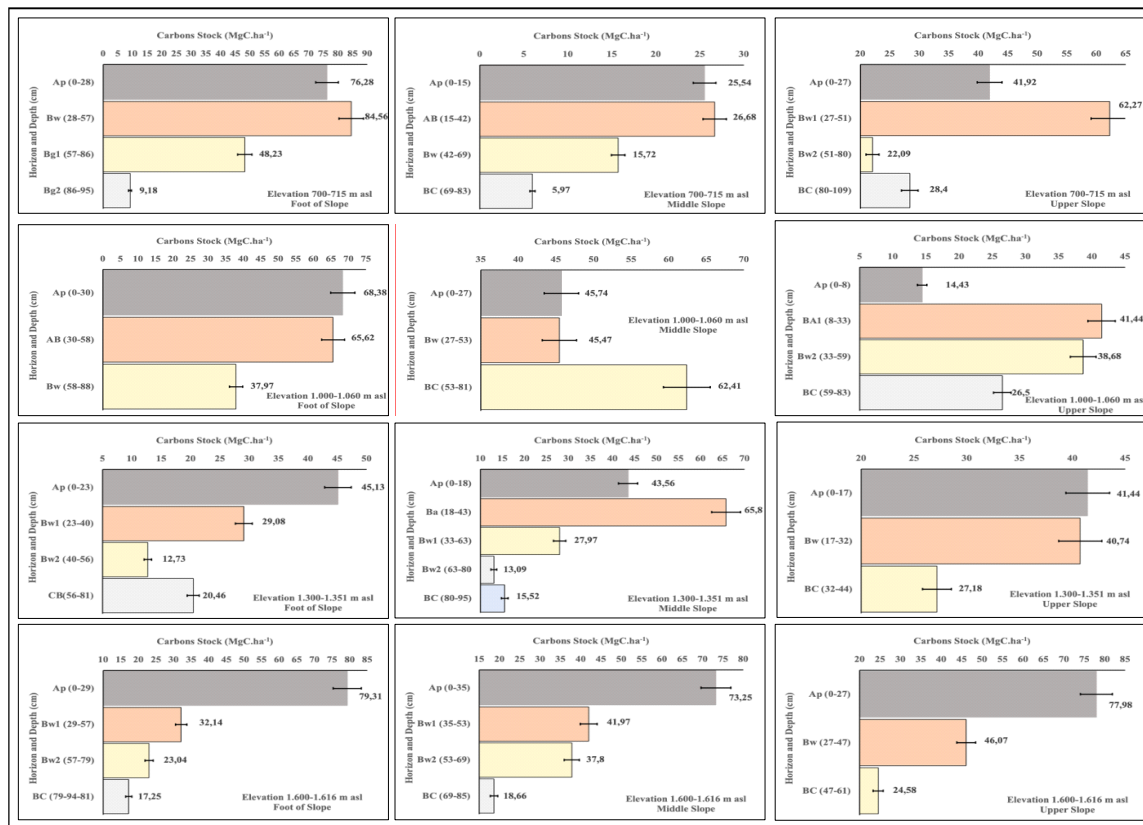


Fig 2: Soil carbon stock levels for each horizon at four elevations and slope positions.

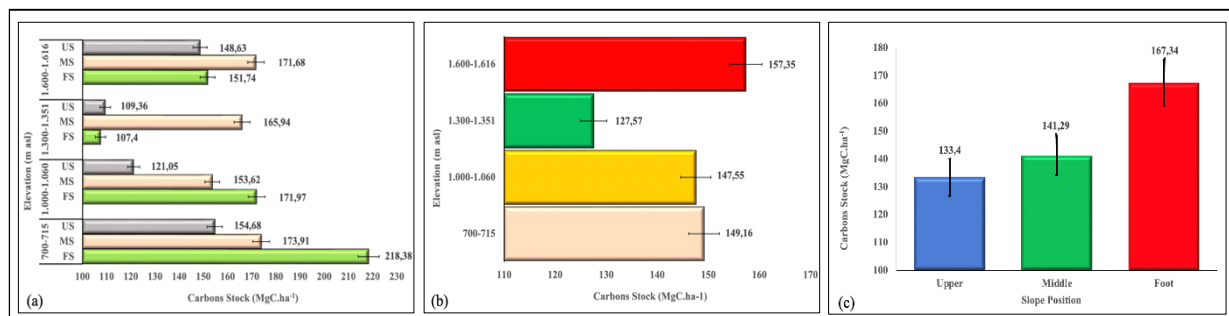


Fig 3: Number of solum SCS at various elevations and slope positions (a), mean SCS of the solum for each elevation (b) and SCS average by slope position (c).

Table 2: The effect of elevation and slope position on SCS of Arabica coffee plantation in gayo highlands.

Elevation (m.a.s.l)	Slope position		
	Foot of slope	Middle slope	Upper slope
700-715	7.01 A a	4.22 B b	6.14 A a
1000-1060	7.54 A ba	7.17 A ab	5.45 A b
1300-1351	5.10 C a	5.56 AB a	6.05 A a
1600-1616	5.93 B a	6.42 A a	6.89 A a

Note: The numbers followed by the same capital letters in column and small letters in row are not significantly different according to the LSD 5%.

Relationship of elevation and slope position on soil

The results on the analysis of variance on the effect of elevation and slope position on SCS in Arabica coffee plantations in Gayo highlands are presented in Table 2.

Based on the analysis of variance presented in Table 2, it can be seen that elevation and slope position significantly interacted with SCS. The table also shows that the interaction between elevation and slope position resulted in the highest SCS of 7.54 with the combination of 1000-1016 m.a.s.l in elevation and foot of slope position. This is reasonable as at these elevations the amount of SCS is higher which is due to not only a higher OC but also a thicker pedogenic horizon. If the horizon thickness is higher, the SCS value will also be higher. Horizon thickness/depth is one of the variables that determine the amount of SCS as shown in the equation of SCS calculation (FAO, 2019).

Previously, it was mentioned that the high amount of SCS at the lower slope can be caused by the high amount of OC coming from the slope above, either at the summit or foot slope. This occurred as a result of water scouring or soil erosion. Similar conditions were also reported by Liu *et al.* (2017) who found that soil organic carbon levels were higher at the foot of slope compared to the upper slope.

CONCLUSION

The amount of soil SCS in each horizon in Gayo highland coffee plantations varied as well as the amount of solum SCS at each elevation. The highest mean amount of solum SCS was found at the elevation of 1600-1616 m.a.s.l. The average amount of solum SCS at each slope position was varied, where the average amount is obtained at the foot of the slope. The combination of elevation and slope position increased the amount of SCS, with the highest amount found at the elevation of 1000-1060 m.a.s.l. and at the foot of the slope position.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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