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SOIL PHYSICO-CHEMICAL PROPERTIES IN A SELECTIVELY LOGGED FOREST AT GUNUNG RARA FOREST RESERVE, SABAH, MALAYSIA

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Abstract: The tropical rainforest has various lists of crucial functions in forest productivity. However, unsustainable logging method has led to the decline of soil fertility in the forest. This study aimed to investigate the impacts of different logging methods on the soil's physical and chemical properties at Gunung Rara Forest Reserve, Sabah, Malaysia. The logging treatments were supervised logging with climber cutting (SLCC) and conventional logging (CL), and a virgin forest (VF) was used as the control plot. The size for each plot was one hectare and each was replicated into four plots making the total plots 12. Soil sampling was done at four depths (0–10 cm, 10–20 cm, 20–50 cm, and 50–100 cm) for soil analysis and bulk density. The finding shows that the soil properties in the treatment plots were not significantly different from the untreated plot. The soil organic matter, total nitrogen, and total carbon decreased with soil depths. The soil in all study areas was found acidic, ranging from 4.12 to 4.46. The soil textures were clay, sandy clay loam, and sandy loam. The SLCC plot recorded a higher mean of soil organic matter (5.93–7.40%), total phosphorus (0.08–0.09 meq/100 g), and cation exchange capacity (5.69–7.05 meq/100 g) compared to other plots. This study highlights the importance of analysing the impact of different logging methods on the soil's physicochemical properties.

Keywords: selective logging, logged forest, virgin forest, tropical forest, soil organic matter.

Introduction

Tropical rainforest-covered almost 45% of the total forest area in the terrestrial biosphere and is widely known as the home for numerous flora and fauna species (FAO & UNEP, 2020). It also provides various ecosystem services, thus exposing it to countless human activities that lead to large-scale deforestation and degradation (Chadid *et al*., 2015). This matter of fact has subsequently caused damage to the habitat, increased soil compaction, and decreased soil fertility (Akbar *et al*., 2010). Soil, often described as the medium for plants to grow, has numerous lists of crucial functions especially in supporting the forest ecosystem, making it an important element to be conserved and protected (Nortcliff, 2006). Several severe threats to the soil ecosystem were identified by FAO and ITPS (2015) in their report on the status of the world's soil resources. These threats include soil erosion, organic carbon change, nutrient imbalance, and contamination (Amanullah *et al.,* 2017; Suhaili *et al*., 2021). The usage of heavy machinery during logging was one of the major causes of these threats (Schwartz *et al*., 2012).

Remodelling the past logging method into more sustainable forest harvest operations is important in preserving the forests' ecosystem services (Lasco *et al*., 2006). Selective logging is a common practice that has long been implemented in South East Asia (SEA). It was considered a better logging practice than clearcutting as it was designed to maintain the forest cover while allowing appropriate use of the resource inside (Gatti *et al*., 2015; Lussetti *et al*., 2016). However, according to Lussetti *et al*. (2016), although the selective logging method targets only the valuable timber that passes a certain diameter at breast height (DBH), it still causes much negative impact on the forest, such as damaging the top layer of the soil and the neighbour trees and increasing tree mortality as it was done in an unsupervised manner. This method was more well-known as conventional logging, in which the trees were felled before a trail was made and no guidelines were given to the operational team before timber extraction was done (Lussetti *et al*., 2016).

Supervised logging, considered a more practical and easily applicable procedure, was later introduced as an alternative to the Reduce Impact Logging (RIL) method and an improvement to the conventional logging method (Lussetti *et al*., 2016). This method includes (i) directional felling which was done to protect the other potential crop trees and to provide a safe work environment to the forestry worker and (ii) providing planned skid trails before starting the falling activity (Forshed *et al*., 2006; Lussetti *et al*., 2019).

About 75% of trees in the tropical forest are invaded by the lianas, making it the biggest competitor for the tree to get sufficient light and nutrients from the soil (Estrada-Villegas and Schnitzer, 2018). In addition, liana's presence during felling activity in the forest could negatively affect the nearby stands by pulling them together (Lussetti *et al.*, 2019). Some studies on liana removal show that removing lianas increased 20% of the light penetration into the tropical forest floor (Rodriguez-Ronderos *et al*., 2016) and increased tree growth rates (Alvarez-Cansino *et al.,* 2015). While Lussetti *et al*. (2016) reported that the combination of supervised logging with climber cutting helped decreased the mortality rate and promoted faster recovery of highly valuable dipterocarp species. This study combined the supervised logging method with a pre-harvest climber cutting further to reduce the harvest damage to the forest ecosystem.

This study investigates the impact of the different selective logging methods on the soil's physical and chemical properties after 26 years of logging. The information from this study would fill in the gap from the previous study (Forshed *et al*., 2006; Forshed *et al*., 2008; Lussetti *et al*., 2016; Lussetti *et al.,* 2019) in which more focuses on the impact of logging on the forest structure and recovery of stand development after logging.

Materials and Methods

Study Area

This study was conducted inside the Gunung Rara Forest Reserve, Tawau, Sabah, Malaysia (Figure 1). The coordinates for the study site were approximately 4° 33' N, 117° 02' E and covered approximately 3000 hectares in area. Gunung Rara Forest Reserve is a virgin tropical rainforest dominated by dipterocarp trees and there were about 230 species of trees were identified inside. This forest was gazetted as Class VI (Virgin Forest) under the Forest Enactment 1968 and this classification means there are no logging activities allowed to be done inside. According to Tangah & Chung (2011), this forest class was only open for research, education, and gene bank purposes (Suhaili *et al*., 2020). This study site has a high annual rainfall range between 2700–3400 mm per year and an altitude between 300–600 above sea level (Lussetti *et al*., 2019).

Procedure

Experimental Design

The plot was established from March 1992 until June 1992, while the harvesting activity was conducted in June 1993 and completed in August 1993 (Forshed *et al*., 2006). Table 1 shows the differences in the stand characteristic of the trees inside both treatment plots and unlogged forests before and after the logging activities. The plot size was 60 x 60 m (0.36 ha). Two types of selective logging methods have been done in this experimental area: Supervised logging (SL) and Conventional logging (CL), and each of the treatments was paired with a pre-harvest climber cutting. For this study, the measurement focused more on Supervised logging with climber cutting (SLCC) and Conventional

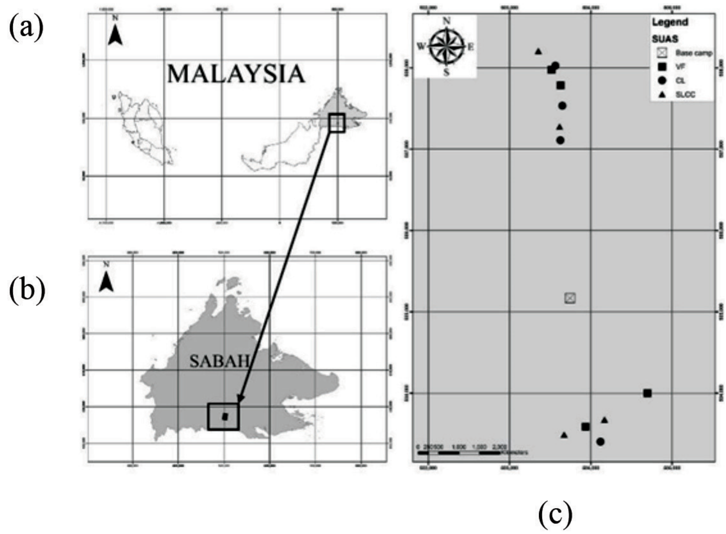

Figure 1: (a) Map of Malaysia, (b) Map of Sabah, Malaysia showing the location of all study sites, (c) Plot layout of the logging treatments and unlogged forest. The legend indicates VF= virgin forest, CL= conventional logging, and SLCC= Selective logging with climber cutting. All these plots were established inside the Gunung Rara Forest Reserve, Tawau, Sabah, Malaysia (4° 33' N, 117° 02' E)

logging (CL) without climber cutting area. A supervised logging method is more detailed than a conventional one. In supervised logging, the tree will only be extracted after a skid trail was systematically aligned to each other, and tractors were not allowed to open a new trail to skid the logs.

Meanwhile, the total opposite was implemented in conventional logging which the tree can be fallen before the presence of the crawler tractor and fall in any direction, which could damage other trees surrounding it. In addition, a block of the untreated area and the virgin forest were established as the control plot. Each treatment and control block was then replicated into 4 plots, making the total number of plots in the study area 12.

Soil Sampling

The field data collection was done twice in January 2019 and September 2019. Two types of soil were taken: the mixed soil samples taken for the soil physical and chemical analysis and the undisturbed soil for bulk density analysis. The sample for soil bulk density was collected using a 98.125 cm^3 bulk density ring. The soil samples

Table 1: The stand density, mean DBH, basal area, and aboveground biomass of the supervised logging with climber cutting (SLCC), conventional logging (CL), and virgin forest (VF) before and after logging activities

Study Areas	Stand Density (trees ha^{-1})			Mean DBH (cm)			Basal Area (m^2 ha^{-1})			Aboveground Biomass (Mg ha^{-1})*		
	1992	1993	2017	1992	1993	2017	1992	1993	2017	1992	1993	2017
SLCC[1]	519	420	532	22.57	22.01	24.31	32.67	23.14	35.54	266.20	182.51	285.66
CL[2]	509	397	538	23.35	23.34	23.99	33.63	26.08	37.31	278.11	213.03	307.02
VF[3]	535	534	518	23.24	23.04	23.81	35.96	35.30	37.35	295.66	290.29	311.13

Note: [1]Supervised logging with climber cutting, [2]Conventional logging, [3]Virgin forest. *Calculated using Basuki *et al.* (2009). The values stand for the mean of the measurements.

were collected at four different depths, which are 0–10 cm, 10–20 cm, 20–50 cm, and 50–100 cm. All samples were brought to the laboratory for analysis.

Laboratory analysis

All mixed soil samples were air-dried at room temperature and were sieved using a 2 mm sieve to remove the unwanted materials such as roots, rocks, and other foreign materials before being analysed for their Physico-chemical properties. Soil bulk density was expressed as the ratio of dry mass (after oven-dried at 105 °C for 24 h) over its volume (Han *et al*., 2016). Soil moisture content was determined by calculating the soil water loss after being dried at 105 °C for 24 h (Shukla *et al.,* 2014). Then, the same sample was used to determine the percentage of soil organic matter by calculating the dry soil weight after being ignited using a furnace at 500 °C for 24 h. The Pipette method was used to determine the percentage of sand, silt, and clay inside the samples, and soil texture was determined using USDA Soil Texture Triangle (Day, 1965). Soil: water suspension (1:2.5) ratio method and a Mettler Toledo-FiveEasy (FE20) pH meter (Ohaus Corporation, Parsippany, NJ, USA) was used to measure the value of soil pH. An Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) analyser (PerkinElmer, Waltham, MA, USA) was used to measure the important elements in soil such as aluminium (Al^{3+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium (Na^{+}), potassium (K^{+}), and phosphorus (P^{3-}). The samples for the important elements in the soil were digested using an aqua regia solution (a mixture of hydrochloric acid and nitric acid) and filtered using a Whatman Sterile Membrane Filter with Absorbent Pads before being analysed using the ICP-OES analyser machine. The carbon and nitrogen concentration was determined by a dry combustion method at 900 °C using a Vario Max CN Elemental Analyser (Elementar Analysensysteme, Langenselbold, Germany) (Dieckow *et al.,* 2007).

Data analysis

Statistical analysis

The One-way Analysis of Variance (ANOVA) with a post hoc test using Tukey's test ($p< 0.05$) was performed to investigate the statistical differences between the logging treatments and the control plot. The statistical analysis was done using IBM SPSS Statistics 24 statistical software.

Results and Discussion

Soil Physical Properties

Analysing the physical properties of soil is important as it is a good indicator of the soil quality in the forest (Zhou *et al.,* 2015; Yin *et al.,* 2021). This study found that after 26 years of being logged, the soil physical properties in both treatment areas (supervised logging with climber cutting and conventional logging plots) are not significantly different compared to the unlogged area, the virgin forest. Figure 1a shows the mean percentage of soil moisture content. There were no significant differences ($p> 0.05$) were observed in the mean soil moisture content across the different logging treatments and the virgin jungle. However, the result shows the virgin forest holds the highest range percentage of soil moisture content with 3.49 ± 1.51% to 5.30 ± 2.16%, followed by the supervised logging with climber cutting treatment with 2.84 ± *1.02*% to 3.72 ± 1.26%. The conventional logging plots hold the least amount of soil moisture content from 2.25 ± *0.65*% to 2.48 ± *0.85*%, hence suggesting that the supervised logging with climber cutting treatment could recover the soil moisture content faster than the conventional logging treatment.

Sukhbaatar et al. (2019) studied the impact of varying selective logging intensities on soil properties and found that the reference plots had the highest soil moisture content, followed by the low-intensity logging treatments. As a result of clear-cutting and high-intensity logging, soil moisture content recovered more slowly than during low-intensity logging. Preserving a high level of soil moisture is crucial for the regeneration of trees, as soil moisture depletion could affect tree mortality rates and stunt the natural regeneration of woody plants (Sukhbaatar *et al*., 2019).

The conventional logging treatment recorded a higher range of soil bulk density compared to the supervised logging with climber cutting treatment, although there were no significant differences ($p > 0.05$) in the mean of soil bulk density between all study areas (Figure 1b). The values were from 1.22 ± *0.05 g cm*$^{-3}$ to 1.46 ± *0.05 g cm*$^{-3}$ and 1.19 ± 0.03 g cm^{-3} to 1.44 ± 0.02 g cm^{-3}, respectively. Yin *et al*. (2019) listed two factors that could reduce the value of bulk density: the alteration of root growth that loses the soil structure over time and the accumulation of litter on the soil surface that increases over time. Another factor that could influence the mean of soil bulk density is the density of soil particles such as sand, silt, clay and the amount of organic matter in the soil (Askin & Ozdemir, 2003; Yang & Chen, 2021).

The soil texture in all plots is relatively uniform each other (Table 2). Sands dominated the soil elements in all plots, followed by clay and the least was silt. Sand represents 30% to 72% of the elements, while clay represents 2% to 47%. On the other hand, silt only represents 2% to 26% of the elements. Both supervised logging with climber cutting and conventional logging treatments have sandy clay loam types of soil texture, while the virgin forest has sandy clay types of soil texture. Soil with a high percentage of sand tends to have a low quality of soil fertility and a low capability to retain water and nutrients (Djajadi *et al.,* 2011). Other properties that were influenced by the type of soil texture are the concentration of carbon and nitrogen, soil nutrient content, soil permeability, soil structure, and soil porosity (Amlin *et al*., 2014).

a)

b)

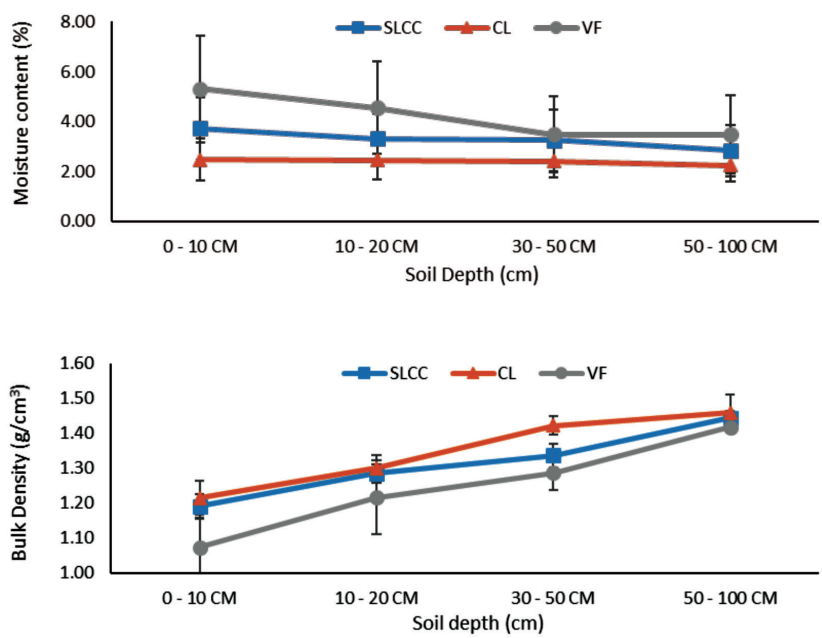

Figure 1: The soil physical properties: (a) soil moisture content (%), (b) soil bulk density (g cm^{-3}) at four different depths (0–100 cm) in supervised logging with climber cutting plots (SLCC), conventional logging plots (CL), and virgin forest plots (VF)

Table 2: The soil's texture at four different depths (0–100 cm) of supervised logging with climber cutting plots (SLCC), conventional logging plots (CL), and virgin forest plots (VF).

Depths (cm)	Clay (%)			Silt (%)			Sand (%)			Soil Texture		
	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]
0–10	52 ± 5.32	26 ± 1.28	29 ± 4.13	8 ± 1.22	3 ± 0.98	13 ± 1.97	33 ± 1.11	71 ± 2.76	54 ± 5.67	Clay	Sandy Clay Loam	Sandy Clay Loam
10–20	3 ± 1.22	31 ± 4.89	29 ± 3.18	21 ± 2.31	3 ± 0.98	5 ± 2.11	69 ± 4.76	65 ± 2.75	64 ± 3.48	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam
20–50	23 ± 1.43	21 ± 4.12	44 ± 2.19	10 ± 1.32	8 ± 1.01	8 ± 2.93	65 ± 3.85	69 ± 2.91	44 ± 3.29	Sandy Clay Loam	Sandy Clay Loam	Clay
50–100	8 ± 0.79	26 ± 4.10	47 ± 2.87	26 ± 1.54	5 ± 1.63	3 ± 1.76	65 ± 3.29	67 ± 1.65	43 ± 3.88	Sandy Loam	Sandy Clay Loam	Clay

Note: [1]Supervised logging with climber cutting, [2]Conventional logging, [3]Virgin forest. The values stand for the mean ± standard error of the measurements.

Soil Organic Matter, Acidity, and Nutrient Contents

Soil acidity and soil cation exchange capacity (CEC) are two main components of soil chemical properties that control soil function (Sung *et al*., 2017). Tropical forest generally has an acidic type of soil as it is exposed to many sources of organic matter such as the plant's litter, animal residue, and dead wood (Baldock & Nelson, 2000; Jeyanny *et al*., 2014; Turgut, 2015). Moreover, according to Mishra *et al*. (2021), forest soil has supposedly become slightly acidic, so a proper amount of nutrients can be supplied to the plants. This support the finding of this study in which the soil in all plots has an acidic type of soil ranging between 4.12 ± 0.05 to 4.46 ± 0.09 (Figure 2a). Sellan *et al*. (2021) and Wahab *et al*. (2021), in their study at Sabah, Malaysia, recorded a similar range of soil pH, which are from 4.08 ± *0.04 to 4.87 ± 0.03 and from 3.8 ± 0.24 to 4.73 ± 0.27, respectively.*

Soil organic matter is one of the major sources of plant nutrients and increasing its value could contribute to a higher carbon sequestration level in soil (Keen *et al*., 2011; Aoyama, 2015; Voltr *et al*., 2021). It also influenced other soil properties, such as water holding capacity, soil compaction, aggregate stability, and the cation exchange capacity (CEC) (Keen *et al*., 2011; Navarro-Pedreno *et al*., 2021; Okeke *et al*., 2022). This study found that the supervised logging with climber cutting plots holds a slightly higher range of soil organic matter which is between 5.93 ± 1.08% to 7.40 ± 1.06%, compared to the virgin forest plots which is between 5.06 ± 0.68% to 7.33 ± 0.59% (Figure 2b). However, no significant difference was observed in the mean value of soil organic matter across the different logging methods and the unlogged area. Over the year, litterfall and organic layer production on the forest floor may accumulate, which then improves the physicochemical properties of the soil and increases its nutrient content (Afifi Nazeri *et al.,* 2022). A study by Zhou *et al*. (2015) found that the higher cutting intensity has a bigger impact on the soil organic matter.

On the other hand, the lower cutting intensity could help the soil organic matter recover faster after 10 years of logging. They found that the value of soil organic matter in that plots is similar to the amount of soil organic matter in the non-cutting plots. As a matter of fact, the reduction of more canopy in the higher cutting intensity plots has increased the light penetration and consequently raised the temperature of the forest floor (Sukhbaatar *et al*., 2019). This enhanced the microbial decomposition of the organic matter, subsequently making it a carbon source as it releases carbon dioxide into the atmosphere (Aoyama, 2015; Navarro-Pedreno *et al.,* 2021; Samra, 2022). The undisturbed forests such as the virgin forest, intact forests, and wetlands naturally have a greater amount of soil nutrients than those disturbed by humans (Jamaluddin *et al*., 2020). Even after several years of logging, it was found that there was still an obvious effect of logging on the soil nutrients (Sukhbaatar *et al*. 2019). However, this study found a contrary result to the previous study, which found a slight increase in total phosphorus in the soils following supervised logging with climber cutting. The mean was ranging in between 0.08 ± 0.01 to 0.09 ± 0.02 meq/100 g, compared to both the virgin forest plots and conventional logging plots, which is between 0.06 ± 0.01 to 0.08 ± 0.01 meq/100 g (Figure 2c).

The same goes for the mean range of the cation exchange capacity (CEC) in supervised logging with climber cutting (Table 3) shows that plots have recorded a higher CEC range than the virgin forest plots. The value ranged from 5.69 ± 1 to 7.05 ± 1.43 meq/100 g for supervised logging with climber cutting plots and from 4.22 ± 0.52 to 5.98 ± 1.52 meq/100 g for the virgin forest plots. As the CEC is the measurement of soil's capability to hold and release the positively charged nutrients such as magnesium, phosphorus, calcium, and potassium, the increase of CEC in the soil also

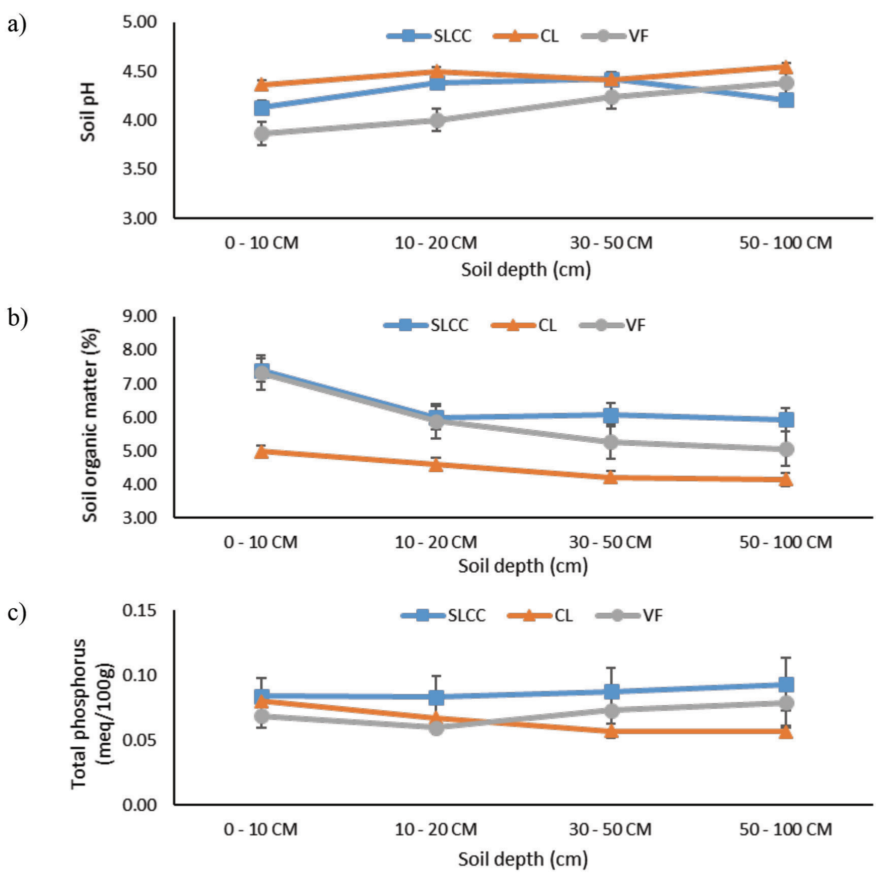

Figure 2: The soil chemical properties: (a) soil pH, (b) soil organic matter (%), (c) total phosphorus (meq/100 g), at four different depths (0 – 100 cm) in supervised logging with climber cutting plots (SLCC), conventional logging plots (CL), and virgin forest plots (VF)

leads to the increases in the essential nutrients that plants require to grow (Jeyanny *et al*. 2014; Astera 2018; Colmatetti *et al*. 2021). The result also shows that the conventional logging recorded the lowest range of soil CEC from 4.85 ± 0.85 to 6.01 ± 1.43 meq/100 g, suggesting that the recovery of soil nutrients in these treatment plots is slower compared to the supervised logging with climber cutting treatment plots.

Despite the increment in the value of soil CEC in the logged areas, according to Khairil *et al*. (2014), the mean range of CEC in this study area is still considered low. According to Jeyanny et al. (2014), a secondary lowland forest in Pahang, West Malaysia, had a CEC range of 10.21 to 15.79 cmol/kg. Suhaili et al. (2021) reported a higher range of CEC in intact forest and logged forest, which ranges from 10.75 ± 1.73 to 14.43 ± 1.48 meq/100 g and 9.63 ± 1.37 to 17.84 ± 5.31 meq/100 g, respectively.

While Akbar *et al*. (2010) performed their study at a rehabilitated forest and secondary forest in Sarawak, Malaysia showed a similar range of mean to this study which is 1.9 to 11.85 cmol/kg and 4.38 to 4.93 cmol/kg, respectively. The main factors influencing these differences were the amount of soil organic matter and the percentage of soil particles such as sand and clay. A clayish type of soil tends to have a higher CEC and soil organic matter compared to sandy soil, and an increasing value of sand in soil has reduced its capability to hold more cations compared to the clay and silt particles (Amlin *et al*., 2014; Amooh & Bonsu, 2015; Astera, 2018; Suhaili *et al*., 2021).

Soil Carbon and Nitrogen Concentration

When a woody plant such as a tree dies as a necro mass, the carbon stored inside will move into the soil (Astuti *et al*., 2022). The harvesting activity in the forest has declined the source of soil organic matter as there were no inputs from the plants, hence declining the amount of total organic carbon and nitrogen in the soil (Akbar *et al.,* 2010). Though the statistical analysis of one-way ANOVA showed there were no significant differences ($p > 0.05$) between the value of carbon concentration across the different logging treatments and virgin forest (Table 4), the finding shows that the conventional logging treatment tends to reduce more amount of carbon in soil compared to the supervised logging with climber cutting treatment. The result shows that even after 26 years of being logged, the conventional logging plots still show a lower range of carbon concentration which ranges from 0.30 ± 0.08 to 1.31 ± 0.16%, compared to the supervised logging with climber cutting plots which range from 0.42 ± 0.09 to 1.73 ± 0.24%. There were also no big differences between the mean range of carbon concentration in the supervised logging with climber cutting plots with the virgin forest plots, where the ranges are between 0.36 ± 0.05% and 1.99 ± 0.31%. The high percentage of sand particles in the conventional logging plots influenced the low amount of carbon concentration in its soil (Reyna-Bowen *et al*., 2019). Other than that, site preparation and management, parent materials, elevations, vegetations, climatic conditions, and the history of land use in that area are also some of the factors that affect the concentration of carbon in soil (Tian *et al*., 2010; Deng *et al*., 2016; Reyna-Bowen *et al*., 2019).

Nitrogen, alongside carbon, hydrogen, potassium, and sulfur, is one of the nine elements in the soil micronutrients that are required in a relatively high amount to support the growth and development of a plant (Amlin *et al*., 2014; Razaq *et al.,* 2017; Sukhbaatar *et al*., 2019). Since it has a positive correlation with the carbon concentration in soil (Deng *et al*., 2013; Cheng *et al*., 2016; Ngaba *et al*., 2020; Suhaili *et al*., 2021), the loss of soil carbon input and the current global climate change also impact the amount of nitrogen availability in the soil (Rennenberg & Dannenmann, 2015; Suhaili *et al*., 2021) Another important factor for soil capability and soil carbon storage is the C: N ratio of soil that indicate the soil fertility level and the decomposition rates of the organic matter (Swangjang, 2015; Yin *et al*., 2021). The result shows that the mean value of the C: N ratio in the treatment plots was lower compared to the virgin jungle plots (Table 4). The value

Table 3: The acid cations and base cations that made up soil cation exchange capacity (CEC) at four different depths (0 – 100 cm) in supervised logging with climber cutting plots, conventional logging plots, and virgin forest plots

Depth (cm)	Acid Cations (meq/100 g)						Base Cations (meq/100 g)					
	H^+			Al^{3+}			Mg^{2+}			Ca^{2+}		
	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]
0 – 10	0.65 ± 0.15	0.70 ± 0.16	0.40 ± 0.02	4.14 ± 0.92	3.48 ± 0.73	3.29 ± 0.42	0.33 ± 0.13	0.28 ± 0.09	0.17 ± 0.06	0.16 ± 0.04	0.10 ± 0.03	0.06 ± 0.02
10 – 20	0.53 ± 0.13	0.59 ± 0.04	0.33 ± 0.04	4.77 ± 1.07	3.99 ± 0.86	4.01 ± 0.35	0.39 ± 0.16	0.29 ± 0.11	0.18 ± 0.07	0.12 ± 0.03	0.07 ± 0.02	0.04 ± 0.02
20 – 50	0.53 ± 0.13	0.72 ± 0.17	0.28 ± 0.04	5.68 ± 1.05	3.28 ± 0.90	4.73 ± 0.61	0.35 ± 0.15	0.16 ± 0.05	0.22 ± 0.07	0.04 ± 0.01	0.10 ± 0.05	0.05 ± 0.02
50 - 100	0.47 ± 0.11	0.58 ± 0.05	0.28 ± 0.03	5.14 ± 1.05	4.70 ± 1.44	4.97 ± 1.24	0.68 ± 0.39	0.22 ± 0.07	0.24 ± 0.13	0.08 ± 0.02	0.08 ± 0.02	0.07 ± 0.03

Depth (cm)	Base Cations (meq/100 g)						CEC (meq/100 g)		
	Na^+			K^+					
	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]
0 – 10	0.06 ± 0.02	0.09 ± 0.02	0.07 ± 0.03	0.35 ± 0.06	0.32 ± 0.06	0.23 ± 0.04	5.69 ± 1.22	4.97 ± 0.67	4.22 ± 0.52
10 – 20	0.07 ± 0.03	0.05 ± 0.01	0.06 ± 0.01	0.37 ± 0.11	0.33 ± 0.07	0.25 ± 0.05	6.25 ± 1.45	5.31 ± 0.79	4.87 ± 0.45
20 – 50	0.04 ± 0.01	0.14 ± 0.11	0.04 ± 0.01	0.41 ± 0.12	0.46 ± 0.19	0.33 ± 0.03	7.05 ± 1.43	4.85 ± 0.85	5.64 ± 0.72
50 - 100	0.07 ± 0.01	0.06 ± 0.01	0.10 ± 0.04	0.53 ± 0.19	0.39 ± 0.12	0.33 ± 0.09	6.96 ± 1.66	6.01 ± 1.43	5.98 ± 1.52

Note: [1]Supervised logging with climber cutting, [2]Conventional logging, [3]Virgin forest. The values stand for the mean ± standard error of the measurements.

was ranging in between 12.61 ± 2.89 to 18.38 ± 5.66 in supervised logging with climber cutting plots, 15.22 ± 2.71 to 19.74 ± 2.57 in conventional logging plots, and 12.91 ± 2.24 to 20.98 ± 2.06 in virgin forest plots. According to Yin et al. (2021), a lower C:N ratio value indicates better soil fertility and faster carbon and nitrogen mineralisation rates.

Suhaili *et al*. (2021) studied different land-use changes in montane forests in Sabah, Malaysia, which recorded a similar C:N ratio trend to this study. The forests with a disturbance history (logged-over forest and plantation forest) currently undergoing a regeneration process have a lower C:N ratio than the intact forest. Aiba & Kitayama (2020) explained that younger soil typically has a higher nutrient concentration than old soil but eventually will decline over time because of nutrient leaching (Turner & Condron, 2013; Yin *et al*., 2021).

Conclusion

Overall, after 26 years of being logged, the soil condition in supervised logging with climber cutting and conventional logging treatments was relatively similar to that in virgin forest areas. The accumulation of litterfall and organic layer on the surface of the soil over the year has improved the soil's physicochemical properties, thus making the soil condition comparable with the unlogged area. The soil in this study area was also found acidic, ranging from 3.87 to 4.54. The sandy clay loam and sandy clay predominated the soil texture in the study areas. Sand compromised up to 70% of the soil elements. Clay and silt, on the other hand, represent up to 47% and 26%, respectively. A slight increase in the mean could be observed in the supervised logging with climber cutting treatments after being compared with the virgin forest plots despite no significant difference between the mean based on the statistical analysis of one-way ANOVA. It shows a higher range of soil organic matter (5.93–7.40%), total phosphorus (0.08–0.09 meq/100 g), and soil cation exchange capacity (CEC) (5.69–7.05 meq/100 g). While soil in the conventional logging treatments still has the highest bulk density value (1.22–1.46 g cm^{-3}) and the lowest percentage of organic matter (4.15–4.98%) even after 26 years of being logged. This study highlights the importance of analysing the impact of different logging methods on the soil's physicochemical properties.

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Table 4: The carbon and nitrogen concentration and carbon: nitrogen (C:N) ratio at four different depths (0–100 cm) of supervised logging with climber cutting plots, conventional logging plots, and virgin forest plots

Depths (cm)	Carbon (%)			Nitrogen (%)			C:N		
	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]	SLCC[1]	CL[2]	VF[3]
0–10	1.73 ± 0.24a	1.31 ± 0.16a	1.99 ± 0.31a	0.18 ± 0.05a	0.11 ± 0.04a	0.17 ± 0.04a	13.07 ± 4.37a	15.22 ± 2.71a	12.91 ± 2.24a
10–20	0.95 ± 0.18a	0.91 ± 0.23a	1.01 ± 0.17a	0.07 ± 0.02a	0.08 ± 0.04a	0.05 ± 0.01a	16.25 ± 2.82a	15.59 ± 3.11a	20.98 ± 2.06a
20–50	0.64 ± 0.11a	0.52 ± 0.09a	0.68 ± 0.16a	0.04 ± 0.13a	0.03 ± 0.01a	0.04 ± 0.01a	18.38 ± 5.66a	19.74 ± 2.57a	18.94 ± 2.73a
50–100	0.42 ± 0.09a	0.30 ± 0.08a	0.36 ± 0.05a	0.04 ± 0.01a	0.02 ± 0.01a	0.02 ± 0.01a	12.61 ± 2.89a	16.05 ± 1.28a	17.31 ± 1.26a

Note: The values stand for mean ± standard error of the measurements. The same letter within the row shows no significant differences (p> 0.05) between the mean of measurements across the different study plots based on Tukey's test.

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