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Impact of Malayan Uniform System and Selective Management System of Logging on Soil Quality in Selected Logged-over Forest in Johor, Malaysia

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Abstract: Understanding the effects of various forest management systems, including logging practices, on soil properties is essential for implementing sustainable management strategies. In Malaysia, two types of forest management systems were commonly used: Malayan Uniform System (MUS) and Selective Management System (SMS) practices. However, their effects on soil quality remained elusive, especially after decades of recovery. To address this need, we selected three plots for the MUS and SMS in Johor, Malaysia, to assess soil properties in logged-over forest plots. All the plots were natural forest reserves. Soil properties analyzed include soil acidity, electrical conductivity, cation exchange capacity, selected nutrient contents, and soil compaction. Generally, the results of the study indicate that forests logged using the SMS exhibit superior soil quality compared to those logged using the MUS according to several key soil properties. Specifically, significantly higher cation exchange capacity, potassium content, calcium content, and magnesium content with lower soil compaction was observed in the SMS when compared to MUS plots. In short, the SMS enhances soil quality more effectively than the MUS, even with a shorter logging cycle. This is because the SMS does not harvest all trees and distributes the impact of harvesting more evenly over time, rather than concentrating it at a single time point. Ultimately, this highlights that the SMS can play a significant role in promoting sustainable forest management practices by preserving soil quality.

Keywords: tropical forest rehabilitation; deforestation; soil quality; sustainable forest management

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1. Introduction

Soil, encompassing the largest carbon pool on Earth's land surface, plays a vital role in a multitude of ecological processes that directly impact the survival and long-term existence of aboveground vegetation [1]. Forest soil can be considered as any soil that has developed under the influence of forest cover [2]. Soil quality encompasses a comprehensive evaluation of its physical and chemical properties, and it plays a critical role in fundamental processes within forest ecosystems, including carbon storage and biomass production [1]. Thus, studying soil quality in various forest management approaches could potentially unlock valuable insights into the long-term ecological mechanisms.

Tropical rainforests are renowned for their remarkable diversity and abundance of woody and herbaceous species [3] and for their capability to ameliorate and perform as a regulator of greenhouse gases in our world [4]. The silvicultural systems applied in tropical forest ecosystems are the clear-felling or clear-cutting, selection-felling, and shelterwood systems. Malaysia has extensive experience in forestry management, with the Forestry Department of Peninsular Malaysia being established in 1901 [5]. The Malayan Uniform System (MUS) was first implemented in 1955 [6], which is basically a system for converting the virgin tropical lowland rainforest to a more or less even-aged forest. According to the guidelines of the MUS, all mature trees of commercial species above 45 cm in DBH were to be removed in a single harvesting [7]. Thereafter, the Selective Management System (SMS) was adopted in 1978 to replace the MUS, which is the monocyclic system. The SMS is a bicyclic tropical shelterwood system that was implemented to enhance forest management practices [8]. The management approach comprises a reduced-impact logging regime aimed at achieving sustainable polycyclic management (cycles of 25–30 years) for the remaining hill dipterocarp forests [9–11].

Timber harvesting and logging play a crucial role in the forestry sector by creating space for the establishment of new stands and mitigating potential negative impacts associated with leaving stands unharvested beyond their harvesting age [12]. However, these activities have a substantial negative influence on the physical and chemical properties of soil and subsequently reducing site productivity [12–14]. For instance, several key soil parameters are particularly affected by logging, including soil bulk density, total porosity, organic matter, and total nitrogen and phosphorus content [13]. Some studies highlighted that logging can alter soil composition and result in a significant reduction in soil nutrients that can last for decades, highlighting the long-term impacts of these disturbances on forest soils [15]. Minor alterations in these factors such as soil carbon and nitrogen can have profound negative consequences on soil biogeochemical cycles and disrupt soil ecology, leading to an imbalance within the ecosystem that can be detrimental [16]. Even though selective logging's related disturbances can lead to varied responses in forest soil characteristics [17] and on forest structure, composition, and regeneration dynamics by destroying over 50% of trees across all taxa and size classes [18], on the other hand, it was reported that selective logging with low and medium intensities can have a positive impact on the natural regeneration [13]. In sustainable forestry practices, several key objectives are prioritized to ensure the long-term viability and health of forests. Among these objectives, optimizing productivity, maintaining soil properties, and promoting natural regeneration stand out as crucial components [13,19,20]. To ensure the long-term productivity and regeneration of forests, it is crucial to implement sustainable management practices that prioritize the maintenance of both the forest's productive capacity and the nutrient reserves in the soil [13,21]. The physical and chemical characteristics of soils play a crucial role in supporting tree growth and facilitating forest reproduction [12,13]. Productivity and soil sustainability can be evaluated using soil quality indices, which are important for ensuring sustainability in forest management [4].

Multiple studies have demonstrated that selective logging can significantly modify soil physical and chemical properties, leading to the depletion of soil organic carbon, nitrogen, and phosphorus stocks, particularly in areas that have experienced higher levels of disturbance. For example, a previous study conducted in Southern Cameroon examined the changes in soil organic carbon and nutrient stocks in rainforests under conventional selective logging compared to reduced-impact logging, underscoring that the disturbances associated with logging management systems can cause pronounced changes in soil characteristics and nutrient stocks [17]. The findings of a study in Africa also indicated that there was a significant impact of selective logging activities on soil organic carbon levels [22]. Additionally, a study conducted in Myanmar confirmed that forest disturbances can modify soil properties, with varying impacts depending on the type of disturbance, and that the subsequent recovery pattern of the forest is influenced by soil conditions after abandonment [23]. To date, such information is very limited for tropical rainforests in Malaysia. Hence, there is an increasing need to assess the post-disturbance responses of soil conditions in order to inform and guide sustainable forest management practices.

Understanding the impact of forest harvesting is critical to sustainable forest management [24]. Selective forest harvesting activities in Peninsular Malaysia are now conducted in accordance with the Sustainable Forest Management (SFM) concept, prioritizing environmental and forest structure aspects [25]. The SMS effectively contributes to forest conservation and sustainability by minimizing reinvestment in rehabilitation work, enhancing environmental stability and quality, reducing logging waste, and optimizing the utilization of forest resources. This is supported by a study that assesses the effectiveness of the SMS in retaining forest sustainability using geospatial technology [10]. The study reported tree density exceeding 32 trees/ha, tree volume surpassing 40 m^3/ha, and forest density exceeding 85% under the SMS [10]. Another study also reported that the SMS is more focused on conserving genetic diversity compared to the MUS because of the major finding that the loss of genetic diversity in some targeted species was higher in the MUS compared to the SMS, suggesting that the SMS is more effective in conserving genetic diversity [26]. However, there is a lack of studies with specific emphasis on soil quality. Hence, this study was carried out to compare the impacts of the MUS and SMS systems on soil quality in a tropical rainforest ecosystem in Malaysia. To support effective sustainable forest management practices, it is crucial to gather qualitative data on the impact of disturbances [23], including logging-based management regimes. Therefore, this study focuses on examining soil properties in tropical rainforests following two management systems.

2. Materials and Methods

2.1. Location

There were 3 plots of logged-over forest managed using the Malayan Uniform System (MUS) and another 3 managed using the Selective Management System (SMS) (Figure 1, Table 1). The plots were chosen from the natural forest reserves based on the type of logging system practiced. The three plots that were logged using the MUS were from before 1978. In contrast, the SMS logging approach was practiced after 1978. The variation in logging years is attributed to the operational periods of the state, as logging could not be conducted simultaneously.

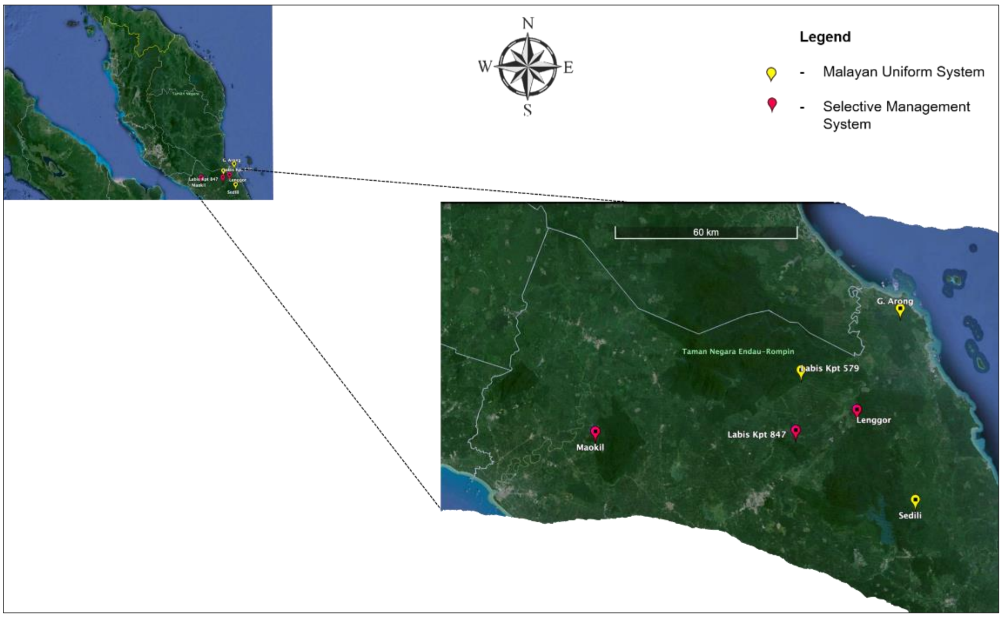


Figure 1. Location of the study area (forest reserves) in Johor, Malaysia.

Table 1. Sampling plot details.

Logging System	Location	Logging Year	Years after Logging	Notation
Malayan Uniform System (MUS)	Ulu Sedili Forest Reserve, Cpt 58	1959	64	MUS1
	G. Arong Forest Reserve, Cpt. 3A	1962	61	MUS2
	Labis Forest Reserve, Cpt. 579	1969	54	MUS3
Selective Management System (SMS)	Maokil Forest Reserve, Cpt. 148	1978	45	SMS1
	Labis Forest Reserve, Cpt. 847	1979	44	SMS2
	Lenggor Forest Reserve, Cpt. 162	1983	40	SMS3

Note: Cpt represents Compartment.

2.2. Soil Quality Samplings

Composite soil samples were collected from each designated forest reserve at a uniform depth of 0–30 cm. Soil samples were collected randomly at 100 m × 100 m areas for each forest reserve. These samples were formed by randomly combining individual soil cores within each forest reserve. Following collection, the composite samples were stored in polyethylene bags and air-dried at room temperature for 48 h at the laboratory facility. Standard soil analysis methods were employed to assess various soil parameters, including pH, electrical conductivity (EC), cation exchange capacity (CEC), nutrient content (including carbon, nitrogen, and individual nutrients), and bulk density. Five replicates were made from each composite sample.

2.3. Soil Analyses

Soil bulk density and porosity were determined using the disturbed soil sample technique described by Gupta [27]. Soil texture was analyzed using the established universal pipette method [27]. Soil pH in water (pHw) was measured in a 1:2.5 ratio of soil to distilled water [28]. Electrical conductivity was determined using a 1:1 ratio of soil to distilled water and measured with an EC meter. Carbon, nitrogen, and sulfur contents were quantified using a dry combustion technique employing a CNS analyzer (LECO Corporation, St. Joseph, MI, USA) [29]. Exchangeable base cations (K^+, Mg^{2+}, and Ca^{2+}) were extracted using 1 M ammonium acetate (NH4OAc) solution and subsequently analyzed via an Atomic Absorption Spectrophotometer (AAS) (Waltham, MA, Perkin Elmer, USA). Exchangeable aluminum was extracted using 1 M potassium chloride (KCl) solution and titrated with 0.01 M hydrochloric acid (HCl) solution [30]. Available phosphorus was extracted using the Bray and Kurtz II method extracting solution, with concentration determination performed using an Autoanalyzer (SEAL Analytical, Inc., Mequon, WI, USA) [31].

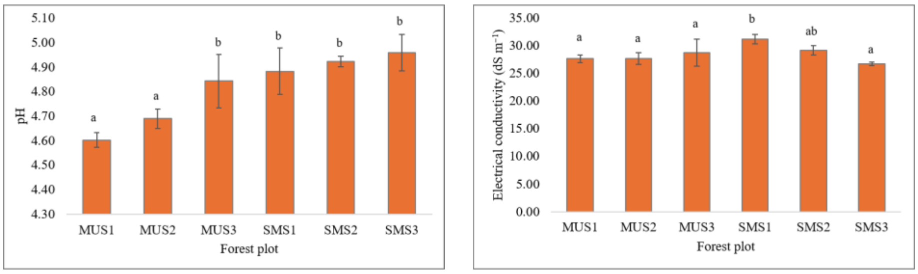
2.4. Statistical Analyses

Significance differences in soil quality parameters were determined using One-way ANOVA. The factor considered in this analysis was the variation among different forest plots. Then, any significant differences detected among the plots were analyzed following a post hoc Tukey's test. The Tukey's test compared all possible pairs of means and identified which pairs exhibited statistically significant differences. Principal component analysis was performed for follow-up conclusive interpretation. The PCA biplot is a widely recognized and utilized tool for investigating the link between measured variables. It allows for the visualization of data, identification of variable relationships, and assessment of variable influence on principal components. Microsoft Excel 2010 and R software version 4.2.1 were used for analyzing the data and elaborating the figures.

3. Results

3.1. Comparison of Soil Properties under MUS and SMS

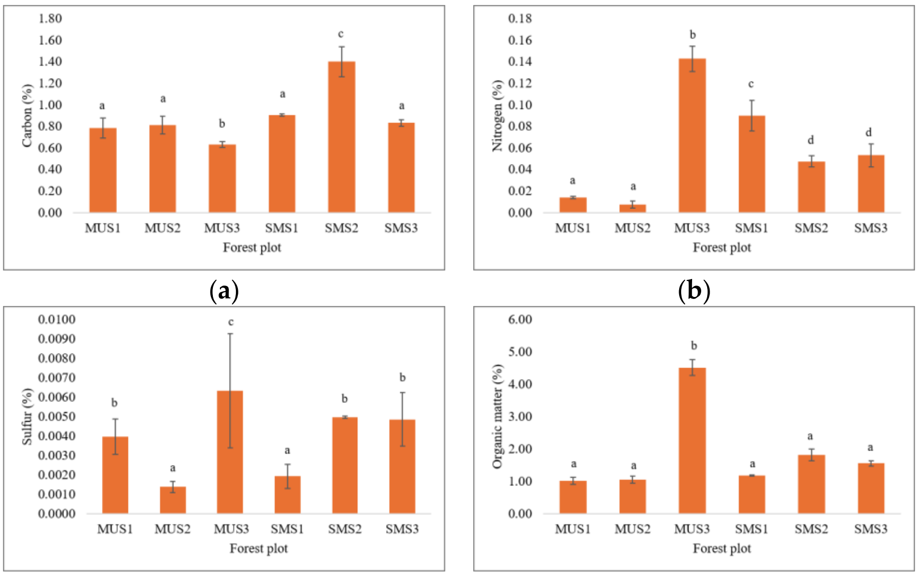
Soils in all plots had acidic properties (with a maximum of 4.96 and a minimum of 4.60). SMS3 had the highest pH value among all six, followed by SMS2, SMS1, MUS3, MUS2, and MUS1, respectively. The lowest pH value was at MUS1, which was 4.60. There were significant differences detected between the soil pH value of the MUS and SMS, except in the MUS3 plot (Figure 2a). The MUS3, SMS1, SMS2, and SMS3 plots had higher pH values as compared to MUS1 and MUS2. As for electrical conductivity, SMS1 and SMS2 showed the highest value of EC (Figure 2b). Specifically, no significant differences were detected between the EC of the MUS and SMS, except in the SMS1 plot.



(**a**) (**b**)

Figure 2. (**a**) Total mean soil acidity, (**b**) total mean electrical conductivity of forest plots. Different letters are significantly difference following One-way ANOVA and Tukey's post hoc test ($p < 0.05$).

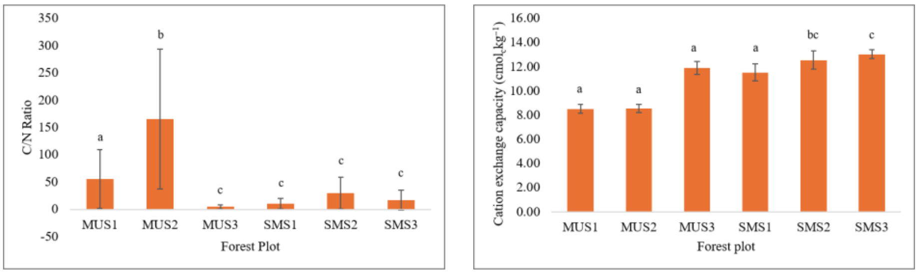
The content of the carbon ranged from 0.65% to 1.38%, with the minimum in MUS3 and maximum in SMS2. SMS2 is significantly higher than MUS3. However, the general trend of the results showed higher values were observed in the SMS plots. SMS2 has the highest value of carbon, followed by SMS1, SMS2, MUS1, and MUS2 (Figure 3a). The significant results were observed only in MUS3 and SMS2, which are the lowest and highest ones, respectively. The nitrogen contents varied from 0.01% to 0.14%, with the minimum in MUS1 and maximum in MUS3. The nitrogen content of MUS3 has the highest value followed by SMS1, SMS2, and SMS3 (Figure 3b). The nitrogen of MUS1 and MUS2 plots showed the lowest nitrogen value. The sulfur content in MUS3 was the highest, followed by SMS2, SMS3, and MUS1 (Figure 3c). The lowest sulfur values were found in plots MUS2 and SMS1. The organic matter value of MUS3 was the highest while MUS1, MUS2, SMS1, SMS2, and SMS3 showed no significant differences (Figure 3d).



(**c**) (**d**)

Figure 3. (**a**) Total mean carbon, (**b**) total mean nitrogen, (**c**) total mean sulfur, (**d**) total mean organic matter of forest plots. Different letters are significantly different following One-way ANOVA and Tukey's post hoc test ($p < 0.05$).

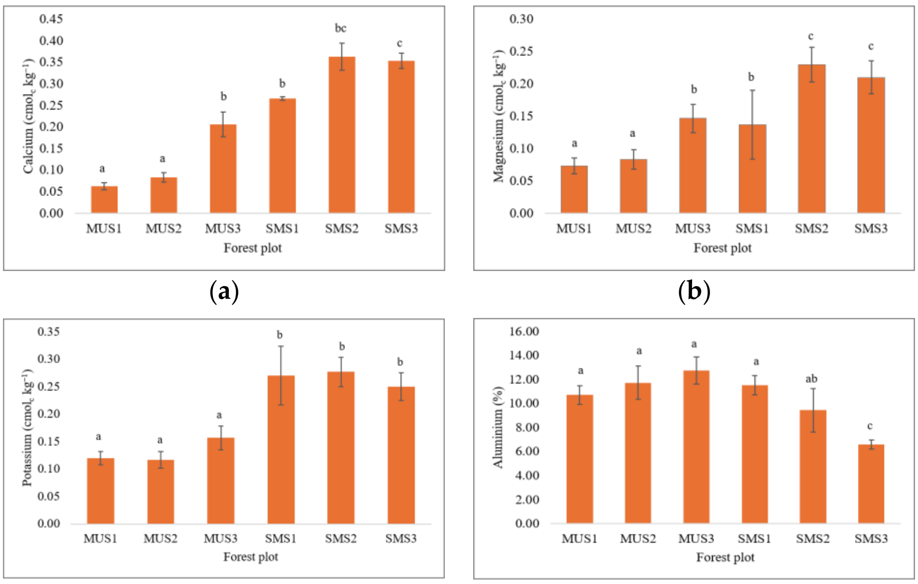
The C/N ratio determination in the present study gave us an insight into the mineralization and immobilization of nutrients in the soil for plant uptake. MUS2 had the highest C/N ratio of 165.30. The plots of MUS3, SMS1, SMS2, and SMS3 showed a C/N ratio below 20 (Figure 4a). The Cation exchange capacity (CEC) varied from 8.52 to 13.23 $cmol_c\ kg^{-1}$ with the minimum in MUS2 and the maximum in SMS3. All plots showed a low cation exchange capacity value of less than 15 $cmol_c\ kg^{-1}$ (Figure 4b). A low value of CEC shows soil is low in fertility and this is normal for tropical-weathered soil. However, SMS2 and SMS3 plots had the highest CEC as compared to MUS plots.



(**a**) (**b**)

Figure 4. (**a**) Total mean C/N ratio, (**b**) total mean cation exchange capacity of forest plots. Different letters are significantly different following One-way ANOVA and Tukey's post hoc test ($p < 0.05$).

As for calcium and magnesium contents, the SMS2 and SMS3 plots showed the highest calcium and magnesium followed by SMS1, MUS3, MUS1, and MUS2 (Figure 5a,b). Exchangeable bases of potassium in SMS plots showed no significant difference from the MUS plots (Figure 5c). SMS plots had a higher range of K as compared to MUS plots. As for the aluminum content, SMS3 had the lowest (Figure 5d).



(**a**) (**b**)

(**c**) (**d**)

Figure 5. (**a**) Total mean calcium, (**b**) total mean magnesium, (**c**) total mean potassium, (**d**) total mean aluminum of forest plots. Different letters are significantly different following One-way ANOVA and Tukey's post hoc test ($p < 0.05$).

As for the sodium content, MUS3, SMS1, SMS2, and SMS3 showed no significant differences and had the lowest Na level as compared to MUS1 and MUS2 (Figure 6a). Regarding the bulk density, the MUS plots were found to have higher values when compared to the SMS plots (Figure 6b).

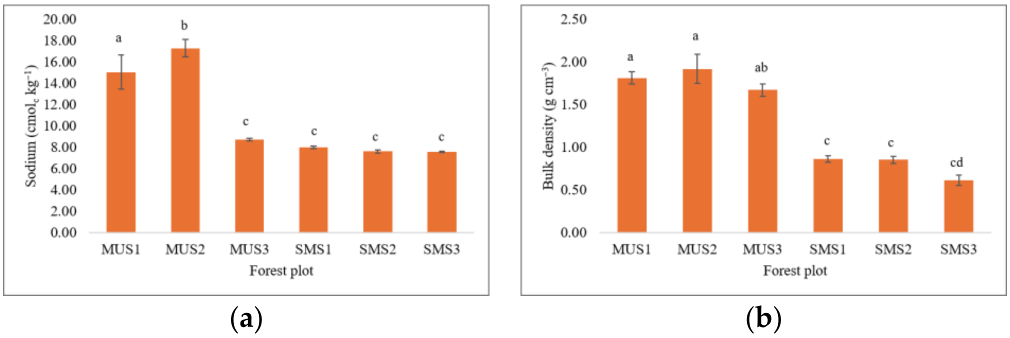


Figure 6. (**a**) Total mean sodium (**b**) total mean bulk density of forest plots. Different letters are significantly different following One-way ANOVA and Tukey's post hoc test ($p < 0.05$).

3.2. Principal Component Analysis of Soil Properties under MUS and SMS

The interpretation of the individual statistical results supported the better role of the SMS when compared to the MUS. To support this observation, we utilized all the measured soil variables under all plots of MUS and SMS to conduct a principal component analysis (PCA). The first component explained 59.0% while the second component explained 20.9% of the total variance, respectively. Then, they were plotted as a biplot (Figure 7).

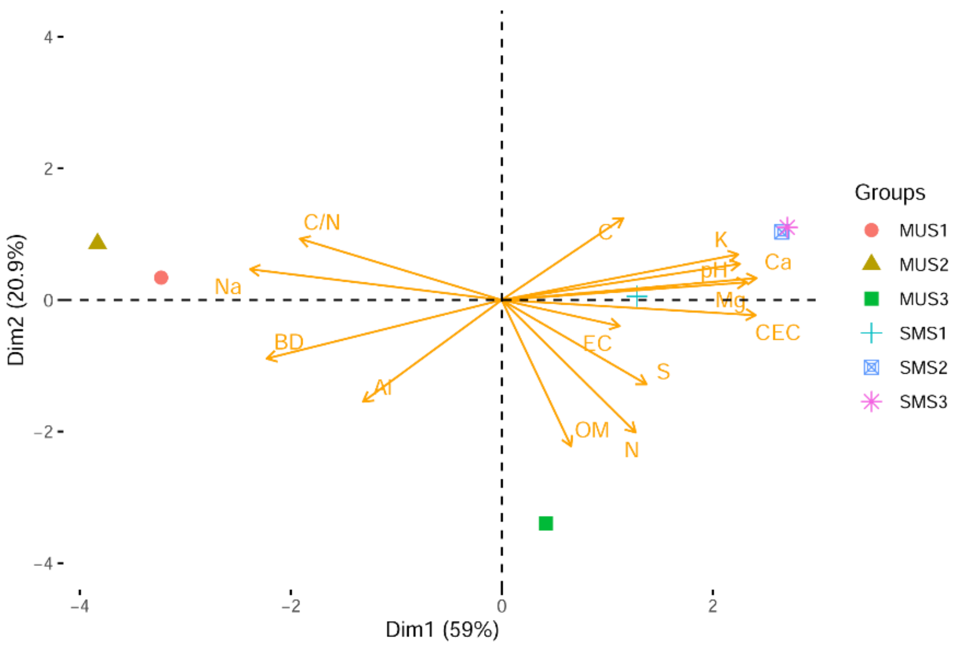


Figure 7. Principal component analysis of MUS and SMS among the soil variables measured. C: carbon, K: potassium, Ca: calcium, Mg: magnesium, CEC: cation exchange capacity, EC: electrical conductivity, S: sulfur, N: nitrogen, OM: organic matter, Al: aluminum, BD: bulk density, Na: sodium, C/N: carbon to nitrogen ratio.

The biplot analysis revealed interesting insights about the positioning and correlation of the SMS and MUS plots. Specifically, the SMS plots were positioned on the right side of the plot, indicating a positive correlation with the first component. Conversely, two of the MUS plots were positioned on the left side of the plot, signifying a negative correlation with the first component. Furthermore, the first component demonstrated a strong positive correlation with most of the important nutrient variables. However, it exhibited a negative correlation with sodium and bulk density. These findings suggest that positive indicators are positively correlated with the first component, as well as with the SMS plots. Based on the biplot analysis, it can be inferred that the SMS outperformed the MUS in this aspect.

This observation aligns with the majority of our study's individual results, reinforcing the significance of the biplot analysis.

4. Discussions

One of the crucial physicochemical characteristics of soil is its acid-based properties, which greatly influence soil processes and forest ecosystems by limiting nutrient availability, reducing microbial activity, and regulating plant growth [32,33]. Maintaining an optimal pH level is essential for ensuring adequate plant nutrition and promoting healthy growth [33]. Research has shown that harvesting slash after clearcutting can lead to an acidification of the organic horizon in acid forest soils. Plots subjected to full slash harvest had lower pH values on the forest floor compared to slash-covered plots, and the exchangeable acidity was significantly higher on the slash-cleared plots [32]. In the present study, the soil pH in all plots showed acidic properties, with a mean pH of 4.69 that is considered normal for tropical rainforests [3]. Specifically, the study found that all sampled soils had acidic properties (pH range: 4.60–4.96), consistent with the acidic soil pH range (3.5–5.5) observed in most Malaysian tropical rainforests [3,34,35], which is attributed to long-term weathering and imbalanced precipitation and evapotranspiration. The impact of logging on soil acidity can vary depending on factors such as soil pH, climate, and tree species [36]. Significant differences were observed in the soil pH values of the MUS and SMS plots, with the exception of the MUS3 plot. These findings suggest that tree species composition may be a contributing factor to the observed differences within the same system. However, additional research is necessary to confirm the underlying causes of these differences.

A low pH typically limits nutrient acquisition through solubilization, decomposition, and uptake, while also increasing the recalcitrance of soil organic phosphorus to microbial mineralization and reducing phosphorus solubility [37]. Specifically in this study, a low significant pH level was found in two of the MUS plots when compared to the SMS plots. It can be highlighted that the SMS may exhibit improved nutrient acquisition potential due to its higher pH levels. As for electrical conductivity (EC), SMS1 and SMS2 show the highest value of EC. There is a negative correlation between soil pH and soil electrical conductivity, meaning that low soil pH tends to encourage higher soil electrical conductivity [38]. However, our study found no significant effects in terms of EC between the MUS and SMS, except in SMS1. The observed differences in the soil EC value of the SMS1 plot may potentially be attributed to various factors, including variations in the quantities of sand, clay, organic matter, and moisture content. It is well established that the soil composition significantly influences the magnitude of soil EC [39].

Nutrient transformations during long-term ecosystem development have significant impacts on the productivity, composition, and diversity of plant and microbial communities [40]. These transformations involve the cycling and availability of essential nutrients, such as carbon, nitrogen, phosphorus, and others, within the ecosystem. The interactions between plants, microbes, and the environment play a crucial role in these processes [40]. In this context, we measured the essential nutrients availability under the MUS and SMS systems. The SMS plots had higher calcium, magnesium, and potassium contents while the MUS plots were found to have higher aluminum and sodium contents. Therefore, it is assumed that the SMS is less destructive to understory vegetation and litter, leading to reduced exposure of soil aggregates to air. This, in turn, can help mitigate soil erosion and minimize nutrient leaching following heavy rainfalls. According to Zhou et al. [41], there is a notable effect of increasing cutting intensity on soil nutrient levels. Even at lower cutting intensities, there exists a potential for nutrient loss; however, the majority of soil physical properties exhibit the capacity to recover under low to medium cutting intensities [41]. These findings supported the outperformance of the SMS in maintaining soil nutrient quality compared to the MUS.

Soil C is a vital component of forest ecosystems, contributing to ecological, biogeochemical, and hydrological processes [42]. Given its significance and the recognition of soil's critical role in climate change mitigation strategies, there has been a growing interest in understanding the effects of forest management on soil carbon [43]. A critical review conducted by Nave et al. [43] indicated that deforestation leads to a decrease in soil carbon stocks. Reforestation efforts have shown promising results in increasing soil carbon stocks; however, forest harvesting does not affect soil carbon stocks, and suggested partial harvest systems require further research. In the present study, the significant results were observed only in MUS3 and SMS2, which are the lowest and highest ones, while other plots showed no significant differences. Generally, SMS1 and SMS2 plots were observed with the highest soil carbon. Thus, the SMS is believed to have ecological benefits such as increased carbon sequestration and minimized carbon loss from the soil due to the less intense impact of harvesting over time rather than being more concentrated at a single time point as the MUS does.

Nitrogen (N) is also vital for healthy forest ecosystems, playing a crucial role in various functions, such as the production and transformation of soil organic matter, as well as influencing the soil's physicochemical and biological properties [16] and playing a vital role in photosynthesis in plant leaves for the growth of forest trees [44]. In many forest ecosystems, N is a critical limiting factor. This means that its availability has a significant impact on the productivity and overall health of the ecosystem. Moreover, there was a strong coupling relationship between carbon and nitrogen [44]. In the present study, MUS1 and MUS2 plots showed the lowest N content. Sulfur (S) is also a crucial macronutrient that constitutes a significant portion of plant tissue and soil organic matter [40]. This study revealed no significant effect between the SMS and MUS, except in MUS3. When an outlier (MUS3 plot) was neglected from the comparison, the SMS plots consistently showed higher organic matter and N and S contents. After logging activities, it is possible to observe a potential shift in the forest composition within the same system. This shift may be attributed to different tree species or vegetation types becoming dominant in the area [45,46]. Some of these species or vegetation types might have a greater impact on the accumulation of organic matter, leading to higher levels of nutrients and organic matter in the soil of the MUS3 plot. Given these findings, it is recommended that further research should prioritize the investigation of the vegetation dynamics within the MUS3 plot to enrich the current findings of soil quality.

Harvesting is a major land use disturbance in forest soils and causes a dramatic shift in various environmental factors that influence the cycling and stability of soil organic matter [47,48]. The presence of a higher amount of soil organic matter contributes to increased soil porosity and looseness, which in turn reduces soil bulk density. This relationship implies that as organic matter content increases, the soil becomes more porous and loose, resulting in a decrease in soil bulk density [49]. Soil bulk density is a crucial indicator of a soil's ability to function in terms of providing structural support, facilitating water and solute movement, and promoting soil aeration [12]. Soil bulk density is influenced by several environmental factors, including water content, aeration, root penetration, the quantity of clay, soil texture, previous land use, and management activities [50]. It is worth noting that bulk density plays a crucial role in regulating the soil's capacity to store organic carbon [51]. In tropical regions, the soil typically exhibits a low bulk density [50]. High soil bulk density can hinder root development, restrict the uptake of water and nutrients by plants, and diminish fertilizer efficiency [50]. In this study, SMS plots showed significantly lower bulk density when compared to MUS plots. This may be attributed to several factors. One possible explanation is that the SMS involves the removal of trees with lower intensity, leaving a greater proportion of the forest intact. This preservation of vegetation and organic matter contributes to a higher soil organic carbon content, which in turn can reduce bulk density. Additionally, the selective removal of trees allows for the maintenance of a more diverse and interconnected root system, which helps to improve soil structure and porosity. These factors collectively contribute to a lower bulk density in areas subjected to the SMS compared to the MUS.

The plots of MUS3, SMS1, SMS2, and SMS3 showed a carbon-to-nitrogen (C/N) ratio below 20. There is an increased risk of nitrogen leaching and gaseous losses of nitrous oxide (N_2O) when the soil C/N drops below 20 [52]. According to the review of Hume et al. [24], compared to the forest floor soil layer, clearcutting effects have been found to result in greater increases in soil carbon and nitrogen concentrations in the mineral soil layer. This is likely due to higher leaching losses and subsequent vertical redistribution from the forest floor, which is associated with the greater intensity of the harvest [24]. This is also consistent with the observation of Kafle [53], who reported that both the bulk density and (C/N) ratio were observed to increase as the soil depth increased. On the other hand, the tree species composition also plays a significant role in the dynamics of carbon accumulation and decomposition as it affects the quality and quantity of organic matter reaching the soil, which primarily originates from litter and the decomposition of plant roots [54,55]. Another prior study highlighted that high plant diversity can decrease the (C/N) ratio [56]. Accordingly, such kinds of multidimensional studies should also be incorporated to furnish the results.

The CEC is a metric for fertility, nutrient retention, and safeguarding groundwater from cation contamination. In this study, the CEC ranged from 8.52 $cmol_c\ kg^{-1}$ to 13.23 $cmol_c\ kg^{-1}$, with higher CEC values indicating increased soil fertility and improved cation movement within the soil [57]. Therefore, the ability of soils with higher CEC values to hold more cation nutrients makes them more desirable. In the present study, SMS3 plots have a generally higher CEC as compared to the MUS plots, suggesting their potential for enhanced nutrient retention and making them a more preferable option.

Overall, the findings from the biplot analysis indicated that most soil nutrient indicators are positively correlated with the SMS plots, indicating that the SMS outperformed the MUS in this aspect. This observation is consistent with the majority of our study's individual findings, providing valuable insights into the impact of these two systems on soil quality.

5. Conclusions

This study assessed the post-logging responses of soil conditions under two types of forest management systems in Malaysia in order to support effective sustainable forest management practices. The results indicated that forests logged using the Selective Management System (SMS) exhibit superior soil quality compared to those logged using the Malayan Uniform System (MUS) according to the observed significantly higher cation exchange capacity, potassium content, calcium content, and magnesium content with lower soil compaction status. Interestingly, these improvements in soil quality are observed despite the shorter logging cycle associated with the SMS. This suggests that the selective approach of not harvesting all trees and implementing a specific period of logging in the SMS plays a significant role in enhancing soil quality. In summary, the study findings support the notion that the SMS is more effective than the MUS in improving soil quality due to the less intense impact of harvesting over time rather than being more concentrated at a single time point as the MUS is. This is an important consideration, as it demonstrates that the SMS can better contribute to sustainable forest management practices by preserving soil quality, even with a shorter logging cycle.

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Data Availability Statement: The original contributions presented in the study are included in the article, further reasonable inquiries can be directed to the corresponding author.

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