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Assessing the Effectiveness of Buffer Zones in Logged Malaysia Borneo Tropical Forests using Tropical Soil Quality Index (TSQI)

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ABSTRACT

Tropical forests face increasing pressure from logging activities, necessitating sustainable management practices to balance economic demands with ecological preservation. This study investigates the effectiveness of buffer zones in maintaining soil quality in logged tropical forests of Sarawak, Malaysia. We compared soil properties and calculated Tropical Soil Quality Index (TSQI) scores across three forest management conditions: natural forest, logged forest with buffer zones, and logged forest without buffer zones. Topsoil samples (0-20 cm depth) were collected from multiple plots within each condition and analyzed for pH, total carbon, total nitrogen, available phosphorus, and exchangeable cations. TSQI scores were calculated following established methods. Results showed that natural forests and logged forests with buffer zones achieved similar TSQI percentages of 50%, while logged forests without buffer zones scored significantly lower at 30%. Buffer zones effectively maintained soil pH, organic carbon, nitrogen, available phosphorus, and exchangeable cations at levels closer to those of natural forests. These findings highlight the importance of buffer zones in mitigating the negative impacts of logging on soil quality. The study provides valuable insights for forest managers and policymakers, supporting the implementation of buffer zones as a key component of sustainable tropical forest management practices. Further research is recommended to assess long-term effects and optimize buffer zone design for maximum soil conservation benefits.

Keywords: Tropical forest management, soil quality, buffer zones, logging impacts, Tropical Soil Quality Index (TSQI)

INTRODUCTION

Tropical forests play a crucial role in global biodiversity conservation, carbon sequestration, and climate regulation. However, these ecosystems face increasing pressure from human activities (Rajoo *et al*., 2023), particularly logging and forest conversion. Borneo's forests have experienced significant degradation due to logging activities, with impact varying across different regions (Gaveau, *et al*., 2014). Sarawak, in Malaysian Borneo, has implemented sustainable forest management (SFM) practices, however, there are some emerging challenges to sustainable development and forest conservation (Naito & Ishikawa, 2020). SFM practices are essential to balance economic demands with ecological preservation in tropical regions. One such practice is the implementation of buffer zones; Areas within logging coupes where selective logging practices are employed to maintain higher stand density and reduce forest openings compared to non-buffer logged areas (Broadbent *et al*., 2006).

Buffer zones have been widely adopted in tropical forest management, yet their effectiveness in maintaining ecosystem functions, particularly soil quality, remains understudied. Soil quality is a critical factor in forest ecosystem health, influencing nutrient cycling, water retention, and overall forest productivity (Doran and Parkin, 1994; Aiza *et al*., 2022; Karam *et al*., 2013). In tropical forests, where nutrient cycling is tightly coupled with organic matter dynamics, maintaining soil quality is especially crucial for ecosystem resilience and recovery after disturbance (Sayer, 2006).

To assess soil quality in complex ecosystems like tropical forests, researchers have developed various soil quality indices. These indices integrate multiple soil properties to provide a comprehensive measure of soil health and function (Karlen *et al*., 2003). Among these, the Tropical Soil Quality Index (TSQI) has emerged as a valuable tool for evaluating soil quality in tropical ecosystems, incorporating key parameters such as soil pH, organic carbon, nitrogen, available phosphorus, and exchangeable cations (Arifin *et al*., 2012).

While numerous studies have examined the impacts of logging on tropical forest soils (Nussbaum *et al*., 1995; Pinard *et al*., 2000), few have specifically investigated the role of buffer zones in maintaining soil quality in these systems. This research gap is particularly significant given the widespread implementation of buffer zones in tropical forest management and their potential importance in mitigating the negative impacts of logging on soil resources.

The present study aims to address this knowledge gap by comparing soil quality between logged forests with and without buffer zones in Sarawak, Malaysia. Specifically, we seek to evaluate the effectiveness of buffer zones in maintaining soil quality parameters as measured by the Tropical Soil Quality Index (TSQI). By comparing TSQI scores and individual soil properties across different forest management conditions (natural forest, logged forest with buffer zones, and logged forest without buffer zones), we aim to contribute to the growing body of knowledge on sustainable tropical forest management practices and offer practical implications for forest managers and policymakers.

MATERIALS AND METHODS

Study sites

This study was conducted in two Forest Management Units (FMUs) in Sarawak, Malaysia: Raplex FMU and Anap Muput FMU. These sites represent typical logged tropical forests in Southeast Asia (Sodhi *et al*., 2010). Both FMUs are logged forests where their natural primary forests have been extracted for harvesting timber and comprising forest structures with various stages of regeneration. Only certain areas are designated for conservation, serving as buffers for various purposes such as river reserves, water catchment areas, threatened ecosystems, and common-use forests for the communities within the FMU (Forest Department Sarawak, 2019). Buffer zones in permanent forests serve as a means to mitigate logging impacts, preserve ecological functions, and as a conservation area (Oldfield, 1988; Stuebing, 2005).

Raplex FMU includes 63,993 ha of mixed dipterocarp forests featuring areas of riparian zones, fragments of heath forest, and ridge vegetation. This FMU located in the Kapit division lies on a grid between the latitudes N2°16” to N2°40” and longitudes E113°14” to E113°50”. The forest is mainly undulating to hilly terrain with a slope range from the lowest 5 degrees up to more than 35 degrees. The forests are in the elevation range of 90 to 750 meters above sea level. The FMU was certified under the Programme for the Endorsement of Forest Certification (PEFC) in 2019, with Reduced Impact Logging (RIL) practices implemented from that year (Putz *et al*., 2008).

Anap Muput FMU encompasses 83,535 ha and is located between the latitudes N2°08’ to N2°32’ and longitudes E112°37’ to E113° in the Tatau district of the Bintulu division. The FMU falls mostly on mixed dipterocarps forests with elevation ranges from less than 100 to 900 meters above sea level. with gradients ranging from 5 degrees to 25 degrees. The license area received PEFC certification in 2008. RIL practices were initiated prior to 2008 in this FMU (Pinard *et al*., 2000).

As a benchmark for undisturbed forest conditions, samples were also collected from Gunong Pueh Forest Reserve, a 4,081-ha area gazetted as a permanent forest in 1927 with no logging or forest extraction activities (Forest Department Sarawak, 2020). The forest reserve has only been a research site for numerous scientists and biologists due to its uniqueness and habitat of various forest species. The FR and its vicinity feature two primary habitat types: the lowland forests and the lower montane forest that is located above 1000 m above sea level (Moultan, 1913).

Experimental design

Specific zones in the FMU are conserved and act as buffers for several functions including river reserves, water catchment sites for clean water sources, conserving threatened habitats, and communal forests to support communities' livelihoods that are impacted by commercial forest activities (Diway, 2023). Forest areas in logging coupes that are allocated as buffer zones for conservation follow criteria prescribed in the Green Book: Manuals, Procedures, and Guidelines for Forest Management Certification (Natural Forest) (2019). As for river water protection in the FMU, guidelines from the Irrigation and Drainage Department have been adopted where buffer widths of 5 to 50 meters of natural vegetation are preserved along rivers (Ligtermoet, 2009).

We investigate the role of forest zoning in mitigating the logging impact and minimizing soil erosion by testing three scenarios of permanent forest management across three different forest conditions: (1) natural forest (undisturbed), (2) logged forest with buffer zones, and (3) logged forest without buffer zones.

Buffer zones in this context refer to areas within logging coupes where selective logging practices are employed, maintaining higher stand density and less forest openings compared to non-buffer logged areas (Broadbent *et al*., 2006).

Soil sampling and analysis

Topsoil samples (0-20 cm depth) were collected using auger (**Figure 1**) from multiple plots within each forest management condition. In Raplex FMU, samples were collected from logging coupes, skid trails, feeder roads, and logging roads to represent various disturbance levels within logged areas (Sidle *et al*., 2004). Simple random sampling was employed, where three 100m X100m sampling plots were established at each study site and five composite samples were obtained from each sampling plot. The collected soil samples were air-dried, pounded, sieved and stored in plastic containers prior to being analysed.

Soil samples were analysed for selected chemical properties using standard methods. Soil pH was measured in a 1:2.5 soil:water suspension using a pH meter (Thomas, 1996). Total Carbon and Nitrogen were determined using dry combustion method with a CN analyzer (Nelson & Sommers, 1996). Available Phosphorus was extracted using the Bray II method and quantified calorimetrically (Bray & Kurtz, 1945). Exchangeable cations were extracted with 1M ammonium acetate at pH 7.0 and measured using atomic absorption spectrophotometry (Sumner & Miller, 1996).

Tropical Soil Quality Index (TSQI) calculation

Tropical Soil Quality Index (TSQI) scores were calculated for each forest management condition following the method described by Arifin *et al*. (2012). Each soil parameter was assigned a score based on predefined thresholds, and these scores were summed to obtain the total TSQI score. The TSQI percentage was then calculated as:

TSQI % = (Total Score / Maximum Possible Score) * 100

where Total TSQI is the sum of individual soil property index values based on the scoring system outlined in Tables 1 and 2 of Arifin *et al*. (2012).

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics version 25. Descriptive statistics, including means, medians, and standard deviations, were calculated for all soil properties grouped by forest management condition and soil depth. To assess the differences in soil properties among the forest management conditions and soil depths, two-way analysis of variance (ANOVA) was conducted. Tukey's Honestly Significant Difference (HSD) post-hoc test was performed to determine significant differences among forest management conditions when the main effect was significant ($p < 0.05$).

Figure 1: Some sampling at Raplex FMU

RESULTS AND DISCUSSION

Soil pH

Table 1 shows the soil properties and TSQI scores for all the study sites. The topsoil pH varied significantly among the different forest management conditions. Natural forests exhibited the highest pH (4.65 ± 0.07), followed by logging with buffer (4.32 ± 0.12), and logging without buffer (4.08 ± 0.07). These values indicate that all soils are strongly acidic, which is typical for tropical forest soils (Sayer & Tanner, 2010).

The lower pH in logged areas, particularly without buffer zones, suggests increased soil acidity due to disturbance. This acidification could be attributed to the removal of base cations through timber extraction and increased leaching (Nykvist & Sim, 2009). The slightly higher pH in areas with buffer zones indicates that these zones may help mitigate some of the acidifying effects of logging.

Soil pH plays a crucial role in nutrient availability. In strongly acidic soils (pH < 5.5), the availability of essential nutrients such as phosphorus, calcium, and magnesium is typically reduced, while the solubility of potentially toxic elements like aluminum increases (Pennock *et al*., 2015). The observed pH differences among management conditions may therefore have significant implications for overall soil fertility and forest productivity.

Soil total carbon and nitrogen

Total carbon content was highest in the natural forest (2.25 ± 0.07%), followed by logging with buffer (1.21 ± 0.17%), and lowest in logging without buffer (0.77 ± 0.11%). A similar trend was observed for total nitrogen, with values of 0.185 ± 0.007%, 0.105 ± 0.021%, and 0.077 ± 0.011% for natural forest, logging with buffer, and logging without buffer, respectively.

The higher carbon and nitrogen contents in natural forests reflect the undisturbed accumulation of organic matter over time. Logging, especially without buffer zones, significantly reduces these levels, likely due to increased erosion, reduced litter input, and accelerated decomposition rates following canopy opening (Don *et al*., 2011). The intermediate values in logged areas with buffer zones suggest that these zones help retain some organic matter, potentially by reducing erosion and maintaining a more stable microclimate.

The C:N ratios are 12.16, 11.52, and 10.00 for natural forest, logging with buffer, and logging without buffer, respectively. These ratios fall within the range typically observed in tropical forest soils and indicate good quality organic matter that can be readily decomposed by soil microorganisms (Gregorich *et al*., 2015).

Soil available phosphorus

Available phosphorus (P) showed a clear declining trend from natural forest (5.65 ± 0.21 mg/kg) to logging with buffer (2.89 ± 0.59 mg/kg) and logging without buffer (1.39 ± 0.30 mg/kg). These levels are generally low, which is characteristic of highly weathered tropical soils where P is often a limiting nutrient (Turner *et al*., 2018).

The lower available P in logged areas, particularly without buffer zones, could be due to several factors including reduced organic matter input, increased P fixation in more acidic conditions, and potential loss through erosion. This reduction in available P could have significant implications for forest productivity, as P is essential for many plants physiological processes including photosynthesis and energy transfer (Vitousek *et al*., 2010).

The higher P levels maintained in areas with buffer zones suggest that these zones may help preserve some of the mechanisms of P cycling and retention that operate in natural forests, such as the activity of mycorrhizal fungi and the maintenance of a closed nutrient cycle (Bünemann *et al*., 2016).

Cation exchange capacity (CEC)

All exchangeable cations (Ca, Mg, K, Na) showed a similar pattern with the other soil properties, with the highest levels in natural forest, intermediate levels in logging with buffer, and lowest levels in logging without buffer. This is reflective of the CEC values, with natural forest having the highest (11.35 ± 0.21), followed by logging with buffer (6.27 ± 0.81), and logging without buffer (5.21 ± 0.37). Despite CEC being an evaluated parameter under TSQI, these cations play crucial roles in soil structure and plant nutrition.

Exchangeable Ca, for example, is important for cell wall development and root growth, while magnesium is a central component of chlorophyll (Marschner, 2012). The lower levels of these cations in logged areas, especially without buffer zones, could lead to nutrient deficiencies and negatively impact forest regeneration and growth. The retention of higher levels of exchangeable cations in areas with buffer zones suggests that these zones help maintain soil fertility by reducing leaching and erosion losses. This highlights the importance of buffer zones in sustainable forest management practices (Bruijnzeel, 2004).

TSQI cores

The Tropical Soil Quality Index (TSQI) scores revealed interesting patterns across the three forest management conditions. Both natural forest and logged forest with buffer zones achieved TSQI percentages of 50%, while logged forest without buffer zones exhibited a markedly lower TSQI percentage of 30% (**Table 1**). This parity between natural forest and logged forest with buffer zones suggests that buffer zones may play a crucial role in maintaining soil quality parameters in managed tropical forests.

Table 1: Soil properties and TSQI scores for study sites

Parameter	Natural forest (values)	Natural forest (TSQI)	Logging with buffer (values)	Logging with buffer (TSQI)	Logging without buffer (values)	Logging without buffer (TSQI)
pH	4.65 ± 0.07a	2	4.32 ± 0.12b	2	4.08 ± 0.07c	2
Total Carbon (%)	2.25 ± 0.07a	1	1.21 ± 0.17b	1	0.77 ± 0.11c	0
Total Nitrogen (%)	0.185 ± 0.007a	1	0.105 ± 0.021b	1	0.077 ± 0.011c	0
Available P (mg/kg)	5.65 ± 0.21a	0	2.89 ± 0.59b	0	1.39 ± 0.30c	0
Ex. Ca (cmolc/kg)	0.470 ± 0.014a	0	0.209 ± 0.061b	0	0.134 ± 0.030c	0
Ex. Mg (cmolc/kg)	0.275 ± 0.007a	0	0.131 ± 0.033b	0	0.102 ± 0.020c	0
Ex. K (cmolc/kg)	0.185 ± 0.007a	0	0.072 ± 0.018b	0	0.051 ± 0.011c	0
Ex. Na (%)	0.135 ± 0.007a	1	0.041 ± 0.018b	1	0.031 ± 0.010b	1
CEC (cmolc/kg)	11.35 ± 0.21a	-	6.27 ± 0.81b	-	5.21 ± 0.37c	-
Total Score / Maximum Possible Score		5/10		5/10		3/10
TSQI %		50%		50%		30%

Note: Values are presented as mean ± standard deviation. Different superscript letters within a column indicate statistically significant differences between forest types ($p < 0.05$) based on Tukey's HSD test.

The TSQI percentages can assist in evaluating the soil quality of tropical forests, but they also highlight the complexities of standardizing soil quality assessments in these diverse tropical ecosystems. It is fair to state that the undisturbed forest should have soil quality that merits a score higher than 50%. This outcome underscores the challenge of developing a universally applicable soil quality index for tropical forests, given the wide variability in soil types, climatic conditions, and ecological factors across different tropical regions (Bonell and Bruijnzeel, 2005).

Rather than interpreting TSQI scores as absolute indicators of soil quality, it may be more appropriate to view them as relative measures for comparing different management practices within a specific context. In this light, the TSQI can serve as a valuable benchmark for assessing the effectiveness of buffer zones in maintaining soil quality similar to that of natural forests. The equivalent scores between natural forests and logged forests with buffer zones suggest that these buffer areas may be successful in preserving key soil properties and processes that contribute to overall soil quality.

Conversely, the substantially lower TSQI score (30%) for logged forests without buffer zones indicates a significant deviation from the soil conditions found in natural forests. This highlights the importance of buffer zones in mitigating the negative impacts of logging on soil quality. It suggests that the absence of buffer zones may lead to substantial alterations in soil properties that are reflected in the composite TSQI score.

Effectiveness of Buffer Zones in Maintaining Topsoil Quality

The presence or absence of buffer zones in logged areas appears to exert a substantial influence on several key soil properties that contribute to the overall TSQI score. Soil pH, a critical factor in nutrient availability and microbial activity, tends to be better maintained in areas with buffer zones. Bruijnzeel (2004) suggests that this pH stability can be achieved even with minimal forest cover, because it reduces soil erosion and maintains a more stable microclimate. Thus, buffer zones can help mitigate soil acidification processes often associated with intensive logging practices.

Organic carbon and nitrogen levels also show notable differences between logged areas with and without buffer zones. The higher retention of these elements in buffer zones aligns with findings by Don *et al*. (2011), who reported that forest disturbance can lead to significant losses of soil organic carbon. Buffer zones likely contribute to organic matter conservation by reducing erosion, maintaining litter input, and preserving soil structure, all of which are crucial for sustaining soil organic matter pools.

Available phosphorus, often a limiting nutrient in tropical forest ecosystems, also appears to be better preserved in logged areas with buffer zones. This observation is consistent with the work of Turner *et al*. (2018), who emphasized the importance of maintaining phosphorus cycling mechanisms in tropical forests. Buffer zones may help preserve the complex biological and chemical processes that govern phosphorus availability, including mycorrhizal associations and organic matter decomposition.

The retention of exchangeable cations, particularly calcium and magnesium, is another key difference observed between logged areas with and without buffer zones. These cations play a vital role in plant nutrition and soil structure. The higher levels of exchangeable cations in buffer zones suggest that these areas may be more effective at preventing nutrient leaching and maintaining the soil's cation exchange capacity, which is vital for long-term soil fertility (Marschner, 2012).

Implications for soil fertility and plant nutrition

The maintenance of soil quality parameters in buffer zones, as reflected in the TSQI scores, has significant implications for soil fertility and plant nutrition in managed tropical forests. The preservation of a more favorable pH in buffer zones likely promotes better nutrient availability, particularly for phosphorus and base cations, which are often limiting factors in tropical soils (Sayer and Tanner, 2010). This improved nutrient availability can have cascading effects on plant growth, forest regeneration, and overall ecosystem productivity.

The conservation of organic carbon and nitrogen in buffer zones supports robust soil microbial communities and enhances nutrient cycling processes. Gregorich *et al*. (2015) emphasized the importance of soil organic matter in maintaining soil structure, water retention, and nutrient supply. By preserving these organic matter pools, buffer zones may help sustain long-term soil fertility and resilience in the face of disturbance.

Higher levels of exchangeable cations in buffer zones enhance the soil's capacity to retain and supply essential nutrients to plants. This improved cation retention is crucial for supporting forest regeneration and maintaining ecosystem services in logged areas (Bruijnzeel, 2004). The preservation of cation exchange capacity in buffer zones may help mitigate the nutrient losses often associated with intensive logging practices, potentially supporting faster forest recovery.

The maintenance of phosphorus availability in buffer zones is particularly significant given the critical role of phosphorus in tropical forest ecosystems. Vitousek *et al*. (2010) highlighted the pervasive nature of phosphorus limitation in tropical forests and its implications for ecosystem processes. By helping to preserve phosphorus cycling mechanisms, buffer zones may play a crucial role in sustaining forest productivity and resilience in the face of disturbance.

While this study did not directly measure erosion rates, the higher TSQI scores in buffer zones suggest that these areas may be more effective at controlling soil erosion compared to non-buffer logged areas. Sidle *et al*. (2004) discussed the complex relationships between forest management practices and erosion processes in steep tropical terrain. The potential erosion control benefits of buffer zones may help maintain topsoil thickness and preserve nutrient-rich upper soil layers, which are crucial for forest regeneration and long-term ecosystem health.

In conclusion, the analysis of TSQI scores and individual soil parameters underscores the potential importance of buffer zones in sustainable tropical forest management. By maintaining soil quality closer to that of natural forests, buffer zones appear to preserve key soil properties and processes that are fundamental to forest ecosystem function and resilience. These findings suggest that the implementation of buffer zones in logging operations may be an effective strategy for balancing timber extraction with the conservation of soil resources and ecosystem services in tropical forests.

Management implications

The findings of this study underscore the significant role of buffer zones in maintaining soil quality in logged tropical forests, with important implications for sustainable forest management practices. The comparable TSQI scores between natural forests and logged forests with buffer zones suggest that well-implemented buffer zones can effectively mitigate the negative impacts of logging on soil quality. These results provide a strong rationale for the widespread adoption and careful design of buffer zones in tropical forest management plans.
The width and design of buffer zones are critical factors in their effectiveness.

Riparian vegetation of 5 to 50 meters widths that are retained along rivers as adopted in the FMUs (Ligtermoet, 2009) is important to reduce and mitigate sediment and erosion impacts of logging activities in Sarawak (Douglas, 2022). With specific dimensions of buffers in place, compliance with the adherence to existing measures for conservation and reduced logging impact should be followed.

The composition and structure of vegetation within buffer zones also play a crucial role in their effectiveness. Our results indicate that buffer zones help maintain higher levels of soil organic carbon and nitrogen, suggesting the importance of preserving a diverse, multi-layered vegetation structure within these areas. The effectiveness of buffer zones in logging forests is influenced by the intensity of harvesting operations affecting forest canopy cover (Axelsson & Anderson, 2012), highlighting the need for efficient management of these zones. Forest managers should aim to retain or restore a mix of native tree species, understory vegetation, and ground cover in buffer zones to maximize their soil protection functions (Dosskey *et al*., 2010). Using various native species for forest restoration in degraded landscapes is crucial to enhance biodiversity and ecosystem resilience. Planting species-rich mixtures associated with high functional diversity would accelerate the recovery of forest stand structure and canopy cover in selectively logged areas (Veryard, *et al*., 2023).

The significant difference in soil pH and available nutrients between buffered and non-buffered logged areas highlights the need for careful management of soil resources during and after logging operations. In areas without buffer zones, additional soil conservation measures may be necessary to mitigate the impacts of logging on soil quality. These could include techniques such as reduced-impact logging, minimizing the use of heavy machinery, and implementing erosion control measures on skid trails and logging roads (Putz *et al*., 2008).

The preservation of higher levels of exchangeable cations in buffer zones suggests that these areas may serve as important nutrient reservoirs in logged landscapes. Forest managers should consider the potential role of buffer zones in supporting forest regeneration and maintaining long-term site productivity. This may involve adjusting silvicultural practices in areas adjacent to buffer zones to take advantage of potential nutrient spillover effects (Brosofske *et al*., 1997).

Given the critical role of phosphorus in tropical forest ecosystems and the observed differences in available P between buffered and non-buffered areas, special attention should be given to phosphorus management in logged forests. This may include the selective retention of P-rich tree species within buffer zones and the careful management of organic matter to maintain P cycling processes (Turner *et al*. ,2018).

The implementation of buffer zones should be integrated into broader landscape-level forest management strategies. This includes considering the connectivity of buffer zones across the landscape to enhance their effectiveness in soil conservation and other ecosystem services such as biodiversity conservation and water quality protection (Naiman *et al*., 2010).

Regular monitoring of soil quality parameters, using indices such as the TSQI, can provide valuable feedback on the effectiveness of buffer zone management strategies. We recommend that forest managers incorporate soil quality assessments into their monitoring protocols, using natural forest conditions as a benchmark for evaluating the success of buffer zone implementations in logged areas.

By incorporating these management implications into tropical forest management practices, it may be possible to better balance the economic demands of timber production with the ecological imperative of maintaining soil quality and associated ecosystem services in these vital ecosystems.

CONCLUSION

This study demonstrates the significant role of buffer zones in maintaining soil quality in logged tropical forests. The comparable Tropical Soil Quality Index (TSQI) scores between natural forests and logged forests with buffer zones suggest that well-implemented buffer zones can effectively mitigate the negative impacts of logging on soil properties. Key findings include the preservation of soil pH, organic carbon, nitrogen, available phosphorus, and exchangeable cations in buffer zones, highlighting their importance in sustainable forest management.

However, several limitations of this study should be acknowledged. The research was conducted in a specific geographical area, and the applicability of these findings to other tropical forest ecosystems may vary. The study focused on topsoil properties, and a more comprehensive analysis including deeper soil layers could provide additional insights. Furthermore, the research represents a snapshot in time, and long-term studies would be valuable to assess the durability of buffer zone effects on soil quality.

Future research directions should include long-term monitoring of soil quality in buffer zones to assess their effectiveness over time, and other important soil properties namely biological and physical properties. Soil erosion is also another aspect that should be focused on.

In conclusion, this study provides strong evidence for the effectiveness of buffer zones in maintaining soil quality in logged tropical forests. While further research is needed to refine buffer zone management strategies, the findings support the wider implementation of buffer zones as a key component of sustainable tropical forest management practices.

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