*Malaysian Journal of Soil Science 2025 Vol. 29: 157-164*

# Comparative Analysis of Soil Quality in Natural, Logged, and Plantation Forests in Kuala Kubu Bharu, Malaysia

**Azhar, M.A.A[1]; Rajoo, K.S.[1,3]*; Zahari, M.N.[2]; Ahmad, A.J.[2]; Aziz, M.R.[2]; Munawar, H.M.[2]; Razak, Q.N.A.[2]; Alias, M.N.[2]; Karam, D.S.[4]; Arifin, A.[5]; Bodos, V.A.[6] & Hamjah, A.[6]**

[1]*Department of Forestry Science, Faculty of Agricultural & Forestry Sciences, UPM Bintulu Campus Sarawak*
[2]*Green Afforestation International Network Sdn. Bhd., Level 17, Top Glove Tower, No.16. Persiaran Setia Dagang, Setia Alam, Seksyen U13, 40170 Shah Alam, Selangor, Malaysia*
[3]*Institute of EcoScience Borneo, UPM Bintulu Campus Sarawak*
[4]*Department of Land Management, Faculty of Agriculture, UPM, Malaysia*
[5]*Department of Forestry Science & Biodiversity, Faculty of Forestry & Environment, UPM, Malaysia*
[6]*Forest Department Sarawak*

**Corresponding author: keeren.rajoo@upm.edu.my*

## ABSTRACT

*Tropical forests provide critical ecosystem services, yet anthropogenic disturbances, particularly selective logging and land conversion, threaten soil quality and forest productivity. However, the exact impacts of this study on soil quality has not been adequately explored in tropical forests. Thus, this study evaluated topsoil (0–20 cm) physical and chemical properties and overall soil quality using the Tropical Soil Quality Index (TSQI) in natural forests, logged forests, and forest plantations in Kuala Kubu Bharu, Malaysia. A stratified random sampling approach was employed, with composite soil samples collected from 18 plots (six per forest type). Soil analyses included measurements of bulk density, coarse fragment content, pH, organic carbon, total nitrogen, and nutrient availability. Results revealed that natural forests maintained significantly better soil conditions, evidenced by lower bulk density (0.95 ± 0.05 g/cm³), higher organic carbon (2.44 ± 0.17%), and robust nutrient retention (CEC: 10.75 ± 0.11 cmol/kg) culminating in a TSQI of 60%. In contrast, logged forests exhibited severe degradation, with increased bulk density (1.55 ± 0.18 g/cm³), elevated coarse fragment content (58 ± 3.4%), and diminished nutrient levels, reflected by a TSQI of 13.33%. Forest plantations demonstrated intermediate characteristics with a TSQI of 46.67%. These findings underscore the need for sustainable forest management practices, including reduced-impact logging, targeted post-logging restoration, and improved silvicultural strategies in plantations. Future research should focus on refining the TSQI and incorporating seasonal and spatial variability to further inform adaptive management and optimal economic cut decisions in tropical forest ecosystems.*

**Keywords:** Soil quality, Tropical Soil Quality Index, forest plantation, Kuala Kubu Bharu, soil degradation

## INTRODUCTION

Tropical forests are critical reservoirs of biodiversity and essential providers of ecosystem services such as carbon sequestration, water regulation, and nutrient cycling. In Malaysia, particularly in the region of Kuala Kubu Bharu, these forests not only sustain a wide array of plant and animal life but also underpin local and regional climate regulation and hydrological processes. However, increasing anthropogenic pressures, most notably selective logging and the conversion of natural forests into plantations, are rapidly altering the intrinsic properties of these ecosystems (Shaliha-Jamaluddin *et al*., 2022), with profound implications for soil health and overall forest productivity (Karam *et al*., 2022).

Soil quality, defined by its physical, chemical, and biological attributes, is a key determinant of forest ecosystem functioning (Camenzind *et al*., 2017). In tropical regions, high rainfall and warm temperatures accelerate weathering and organic matter turnover, often resulting in acidic soils with low inherent fertility (Ligate *et al*., 2018). Traditional soil assessments focus on parameters such as bulk density, organic carbon, and total nitrogen, all of which directly influence water infiltration, root penetration, and nutrient availability. In addition to these conventional measurements, integrative tools like the Tropical Soil Quality Index (TSQI) provide a composite measure of soil health, enabling a more holistic evaluation of the cumulative impacts of land-use practices (Bodos *et al*., 2024).

Previous studies have revealed that selective logging tends to increase soil compaction and reduce organic matter content, leading to significant nutrient depletion (Picard *et al*., 2012). Conversely, forest plantations, while also subject to human intervention, generally exhibit intermediate soil conditions that reflect a balance between disturbance and recovery processes. Despite these insights, there remains a scarcity of comprehensive comparative studies that evaluate soil quality across natural forests, logged forests, and plantations using both traditional soil measurements and integrative indices (Allek *et al*., 2022). This knowledge gap hinders the development of targeted management strategies that could mitigate soil degradation and promote sustainable forest use.

The present study addresses this gap by comparing selected soil properties among natural forests, logged forests, and forest plantations in Kuala Kubu Bharu. The primary objectives are twofold. First, to assess and compare key physical and chemical soil attributes across these forest types; and second, to evaluate overall soil quality using the TSQI. By integrating detailed conventional measurements with an integrative quality index, the study aims to provide a detailed understanding of soil degradation patterns and restoration potential in tropical forest ecosystems.

## MATERIALS AND METHODS

### Study area

This study was conducted in Kuala Kubu Bharu, Selangor, Malaysia, a region characterized by a tropical rainforest climate with annual temperatures ranging from 26°C to 28°C and annual rainfall between 2,500 and 3,000 mm (**Figure 1**). These conditions promote intense weathering, resulting in soils that are typically classified as Ultisols; Acidic, nutrient-poor, and clay-rich. The research focused on three distinct forest types that represent a gradient of human disturbance:

i. Natural forests, which serve as a baseline for undisturbed soil conditions.
ii. Logged forests, where selective logging has led to notable soil compaction and nutrient depletion.
iii. Forest plantations, which due to management practices, display intermediate soil properties.

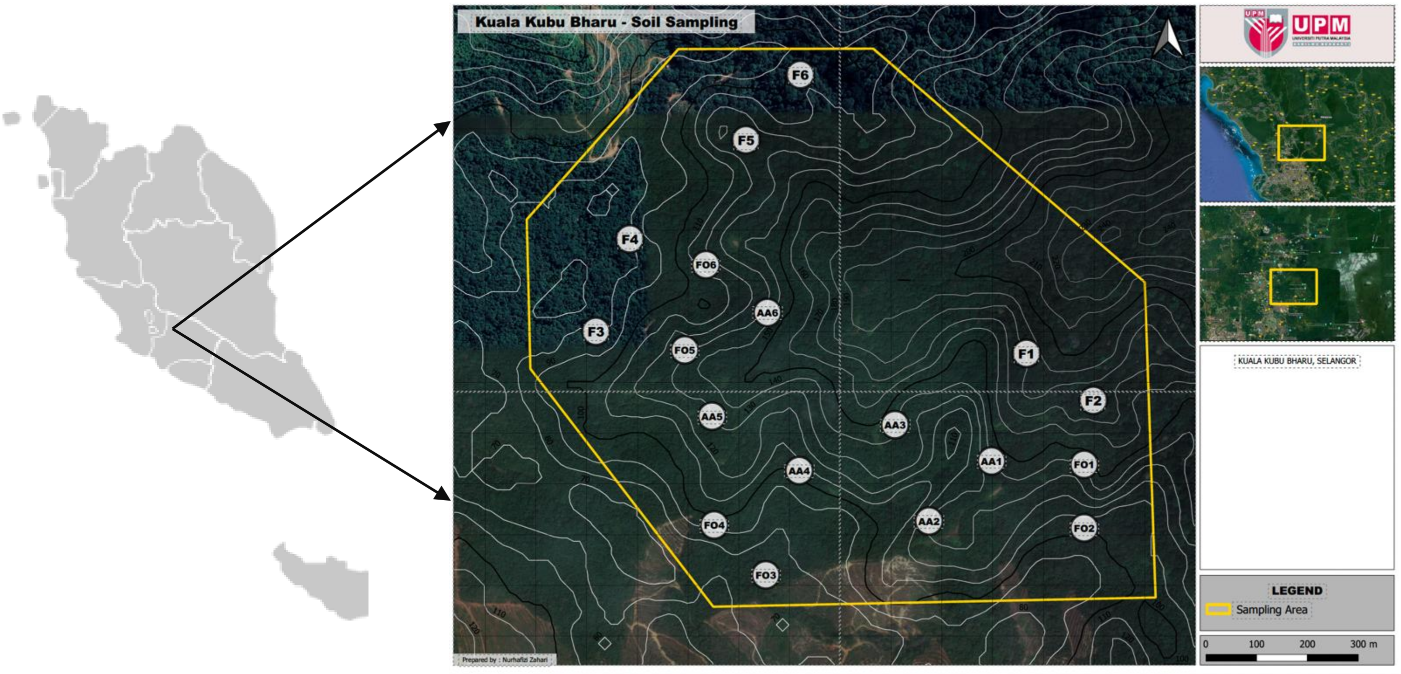


**Figure 1**. Sampling site at Kuala Kubu Bharu

**Sampling design and soil collection**

A stratified random sampling approach was implemented. In each forest type, six plots measuring 20 × 20 meters were randomly selected. Within each plot, five sub-samples were collected from evenly distributed points and combined into a single composite sample. Only topsoil samples (0–20 cm) were collected and analysed. This is due to the topsoil layer being the layer that is directly impacted by land use changes, and it can accurately reflect the conditions influencing water infiltration, root growth, and nutrient cycling, and it provided the most robust trends in soil quality parameters (Camenzind *et al*., 2017).

**Soil physical properties**

The physical condition of the soil was assessed by determining two primary parameters: bulk density and coarse fragment content. Bulk density was measured using the core method; 10 grams soil was extracted, oven-dried at 105°C until a constant weight was achieved, and then weighed to calculate density. Coarse fragment content was evaluated by air-drying the composite samples, sieving them through a 2 mm mesh, and calculating the percentage of material retained. These measurements offer insights into the soil's compaction and structural integrity, which are critical for water movement and root penetration.

**Soil chemical properties**

Chemical analyses were conducted to evaluate soil fertility. A 1:2.5 soil-to-water suspension was prepared for each composite sample to measure pH using a calibrated pH meter (Thomas, 1996), ensuring accurate representation of the soil's acidity. Organic carbon was determined by the dry combustion method, which provided a reliable estimate of the soil organic matter content (Nelson & Sommers, 1996). Total nitrogen was measured using the Kjeldahl digestion technique, and the carbon-to-nitrogen (C/N) ratio was subsequently calculated. This ratio serves as an indicator of organic matter decomposition and nutrient cycling efficiency, both of which are crucial for maintaining soil fertility in tropical ecosystems.

Nutrient availability was assessed by extracting available phosphorus using the Bray and Kurtz II method, which is particularly suited for acidic soils (Bray & Kurtz, 1945). Exchangeable cations (calcium, magnesium, potassium, and sodium) were extracted from the soil with a 1 M ammonium acetate solution at pH 7.0, and their concentrations were determined via atomic absorption spectrophotometry. The cation exchange capacity (CEC), which reflects the soil's ability to retain and exchange essential nutrients, was calculated as the sum of these exchangeable cations (Sumner & Miller, 1996).

**Tropical Soil Quality Index (TSQI) calculation**

The Tropical Soil Quality Index (TSQI) was used to measure the overall soil quality (Arifin *et al*. 2012). Each soil parameter was assigned a numerical score based on predefined thresholds, with higher scores indicating better soil conditions. The individual scores were summed and expressed as a percentage of the maximum possible score, thus providing a holistic metric that facilitates direct comparisons across the different forest types.

**Statistical Analysis**

Data were analyzed using SPSS Version 25.0. One-way analysis of variance (ANOVA) was performed to detect significant differences in soil properties among the three forest types. When significant differences were found, Tukey's Honest Significant Difference (HSD) test was used as a post hoc analysis to identify specific group differences. Pearson correlation analysis was also conducted to assess the relationships between various soil parameters. All statistical tests were conducted at a significance level of $p < 0.05$.

## RESULTS AND DISCUSSION

**Physical soil properties**

The physical properties soil is a useful indicator of forest health, as it influences water infiltration, root penetration, and overall ecosystem productivity (Ligate *et al*., 2018). **Table 1** summarizes the topsoil physical properties (bulk density and coarse fragment content) across the three forest types. In natural forests, the topsoil exhibited a relatively low bulk density of 0.95 ± 0.05 g/cm³ and a coarse fragment content of 15 ± 2.7%, indicative of well-structured, undisturbed soils. In contrast, logged forests displayed a marked increase in topsoil bulk density, reaching 1.55 ± 0.18 g/cm³, along with a substantial rise in coarse fragment content to 58 ± 3.4%. These elevated values are consistent with the effects of logging-induced compaction and disruption of soil structure (Camenzind *et al*., 2017). Forest plantations recorded intermediate values, with a bulk density of 1.10 ± 0.07 g/cm³ and coarse fragment content of 20 ± 2.5%, reflecting the partial mitigation of physical disturbance through management practices.

**Table 1.** Topsoil physical properties across forest types

| Forest type | Bulk density (g/cm³) | Coarse fragment content (%) |
|---|---|---|
| Natural forest | 0.95 ± 0.05b | 15 ± 2.7b |
| Logged forest | 1.55 ± 0.18a | 58 ± 3.4a |
| Forest plantation | 1.10 ± 0.07b | 20 ± 2.5b |

Note: Different superscript letters within a column indicate statistically significant differences in the soil property between forest types ($p < 0.05$) based on Tukey's HSD test.

The contrasting physical properties among the forest types highlight the profound impact of anthropogenic disturbance on soil structure. The low bulk density and minimal coarse fragment content in natural forests are favourable for water movement and root development, supporting robust vegetation growth and nutrient cycling (Ligate *et al*., 2018). Conversely, the significantly higher values observed in logged forests suggest severe soil compaction and fragmentation, which can hinder water infiltration and root expansion, ultimately impairing forest regeneration. The intermediate condition in forest plantations underscores the potential of well-managed silvicultural practices to partially restore soil integrity, although they do not fully replicate the conditions found in undisturbed natural forests (Turner *et al*., 2018). These findings reinforce the critical need for sustainable forest management practices that minimize soil compaction during logging operations and promote soil rehabilitation measures post-disturbance (Camenzind *et al*., 2017).

**Chemical soil properties**

Chemical properties of the soil are fundamental to understanding its fertility, nutrient cycling, and overall capacity to support vegetation (Rajoo *et al*., 2012; Rajoo *et al*., 2013). **Table 2** presents the topsoil chemical parameters measured across the three forest types. In natural forests, the topsoil exhibited a pH of 4.62 ± 1.23, organic carbon content of 2.44 ± 0.17%, total nitrogen of 0.108 ± 0.031%, and a C/N ratio of 22.81 ± 0.74. These values indicate a relatively nutrient-rich environment with active organic matter decomposition and balanced nutrient cycling. In contrast, logged forests recorded a slightly lower pH of 4.40 ± 0.98 and showed a marked reduction in organic carbon (1.27 ± 0.38%) and total nitrogen (0.048 ± 0.019%), accompanied by an elevated C/N ratio of 26.87 ± 0.42. The higher C/N ratio in logged areas suggests a slower rate of organic matter decomposition, which can further impede nutrient cycling. Forest plantations demonstrated intermediate conditions, with a pH of 4.71 ± 0.84, organic carbon content of 1.64 ± 0.18%, total nitrogen of 0.075 ± 0.008%, and a C/N ratio of 22.05 ± 0.61, reflecting partial mitigation of soil degradation through management practices.

**Table 2.** Topsoil chemical properties across forest types

| Forest yype | pH | Organic carbon (%) | Total nitrogen (%) | C/N Ratio |
|---|---|---|---|---|
| Natural forest | 4.62 ± 1.23a | 2.44 ± 0.17a | 0.108 ± 0.031a | 22.81 ± 0.74a |
| Logged forest | 4.40 ± 0.98a | 1.27 ± 0.38b | 0.048 ± 0.019b | 26.87 ± 0.42b |
| Forest plantation | 4.71 ± 0.84a | 1.64 ± 0.18b | 0.075 ± 0.008b | 22.05 ± 0.61a |

Note: Different superscript letters within a column indicate statistically significant differences in the soil property between forest types ($p < 0.05$) based on Tukey's HSD test.

These chemical analyses clearly demonstrate that natural forests maintain superior soil fertility, as evidenced by higher organic carbon and nitrogen levels, which are vital for sustaining nutrient cycling and supporting robust plant growth (Camenzind *et al*., 2017). The degraded chemical status in logged forests, marked by lower nutrient contents and a higher C/N ratio, points to the adverse effects of logging practices, including the potential for reduced organic matter decomposition and slower nutrient turnover. Forest plantations, while not matching the quality of natural forests, still preserve a moderate level of soil nutrients, likely due to active management interventions that partially counteract the negative impacts of soil disturbance (Camenzind *et al*., 2017).

Collectively, these findings underscore the importance of preserving natural forest conditions to maintain soil fertility, while also highlighting the need for improved management practices in logged and plantation forests to enhance soil chemical properties and promote sustainable ecosystem functioning.

**Nutrient Availability and Cation Exchange Capacity**

Nutrient availability and cation exchange capacity (CEC) are essential indicators of soil fertility and its capacity to support plant growth (Ligate *et al*., 2018). In this study, these parameters were determined from topsoil samples to evaluate the impact of different land-use practices on soil nutrient dynamics (Allek *et al*., 2022). **Table 3** presents the measured values for available phosphorus and exchangeable cations (calcium, magnesium, potassium, and sodium) along with the overall CEC for natural forests, logged forests, and forest plantations.

**Table 3.** Topsoil nutrient availability and cation exchange capacity

| Forest type | Available P (mg/kg) | Ex. Ca (cmol/kg) | Ex. Mg (cmol/kg) | Ex. K (cmol/kg) | Ex. Na (cmol/kg) | CEC (cmol/kg) |
|---|---|---|---|---|---|---|
| Natural forest | 4.32 ± 0.11a | 0.516 ± 0.014a | 0.284 ±a 0.011 | 0.163 ± 0.004a | 0.123 ± 0.008a | 10.75 ± 0.11a |
| Logged forest | 1.84 ± 0.22b | 0.140 ± 0.030b | 0.097 ± 0.031b | 0.066 ± 0.013b | 0.040 ± 0.006b | 4.95 ± 0.37b |
| Forest plantation | 4.18 ± 0.19a | 0.421 ± 0.014a | 0.256 ± 0.024a | 0.143 ± 0.009a | 0.105 ± 0.007a | 9.63 ± 0.18a |

Note: Different superscript letters within a column indicate statistically significant differences in the soil property between forest types ($p < 0.05$) based on Tukey's HSD test.

In natural forests, the topsoil exhibited an available phosphorus level of 4.32 ± 0.11 mg/kg. This relatively high phosphorus content, combined with elevated concentrations of exchangeable calcium (0.516 ± 0.014 cmol/kg), magnesium (0.284 ± 0.011 cmol/kg), potassium (0.163 ± 0.004 cmol/kg), and sodium (0.123 ± 0.008 cmol/kg), contributed to a robust CEC of 10.75 ± 0.11 cmol/kg. These values indicate a strong nutrient-retention capacity, which is critical for sustaining vegetation growth and maintaining soil fertility.

In contrast, logged forests demonstrated a pronounced reduction in nutrient availability. The available phosphorus in these soils decreased to 1.84 ± 0.22 mg/kg, while the concentrations of exchangeable cations were markedly lower—calcium at 0.140 ± 0.030 cmol/kg, magnesium at 0.097 ± 0.031 cmol/kg, and potassium at 0.066 ± 0.013 cmol/kg—with sodium dropping to 0.040 ± 0.006 cmol/kg. This significant decline in exchangeable cations resulted in a substantially lower CEC of 4.95 ± 0.37 cmol/kg, reflecting the adverse effects of logging-induced soil degradation on nutrient retention.

Forest plantations, meanwhile, maintained nutrient levels that were more comparable to natural forests. The topsoil in plantation areas recorded an available phosphorus of 4.18 ± 0.19 mg/kg, with exchangeable calcium at 0.421 ± 0.014 cmol/kg, magnesium at 0.256 ± 0.024 cmol/kg, potassium at 0.143 ± 0.009 cmol/kg, and sodium at 0.105 ± 0.007 cmol/kg. These factors culminated in a CEC of 9.63 ± 0.18 cmol/kg, indicating that management practices in plantations can partially mitigate the negative impacts of soil disturbance on nutrient availability.

The clear differences in nutrient availability and CEC among the forest types underscore the impact of land-use practices on soil fertility (Camenzind *et al*., 2017). Natural forests, with their high nutrient retention capacity, offer optimal conditions for plant growth and ecosystem stability. In logged forests, however, the significant reduction in both available nutrients and CEC indicates a compromised soil system that may hinder vegetation regeneration and overall forest recovery (Picard *et al*., 2012). Forest plantations, by maintaining nutrient levels closer to those in natural forests, demonstrate that appropriate management practices can mitigate some adverse effects of soil disturbance. These results emphasize the importance of implementing sustainable management and restoration strategies to enhance soil fertility and support long-term ecosystem resilience (Allek *et al*., 2022).

**TSQI Scores of study sites**

The Tropical Soil Quality Index (TSQI) offers an integrative metric that synthesizes various physical and chemical parameters into a single percentage score, thereby providing a comprehensive assessment of soil quality. In this study, TSQI was calculated for the topsoil to evaluate the cumulative impact of soil properties altered by different land-use practices. **Table 4** summarizes the TSQI scores for the topsoil from natural forests, logged forests, and forest plantations.

**Table 4.** TSQI scores for topsoil across forest types

| Forest type | TSQI score (%) | Total score / Maximum score |
|---|---|---|
| Natural forest | 60% | 9/15 |
| Logged forest | 13.33% | 2/15 |
| Forest plantation | 46.67% | 7/15 |

In natural forests, the TSQI reached 60%, corresponding to a total score of 9 out of a maximum possible 15. This high TSQI reflects favourable soil conditions, where optimal physical attributes such as low bulk density and minimal coarse fragments (Ligate *et al*., 2018), combined with robust nutrient levels and balanced chemical properties, support healthy ecosystem functioning. Conversely, logged forests exhibited a dramatically lower TSQI of 13.33% (2/15), indicating severe degradation. The markedly reduced score is largely attributable to increased soil compaction, higher coarse fragment content, and significant nutrient depletion resulting from logging activities (Picard *et al*., 2012). Forest plantations achieved an intermediate TSQI of 46.67% (7/15), suggesting that while management practices in these systems can partly mitigate soil disturbance, they do not fully restore the soil quality to the levels observed in undisturbed natural forests.

The substantially lower TSQI in logged forests underscores the cumulative negative impacts of logging on soil structure and fertility, while the intermediate TSQI in forest plantations highlights the partial recovery achievable through proper management. These findings advocate for the incorporation of TSQI as a monitoring tool in forest management, enabling targeted interventions to restore soil quality and maintain ecosystem sustainability.

## CONCLUSION

Natural forests, exhibiting low bulk density, high organic carbon and nitrogen levels, and a robust cation exchange capacity, underscore the benefits of maintaining undisturbed conditions. In contrast, the severe soil compaction, nutrient depletion, and low TSQI observed in logged forests point to the urgent need for targeted restoration practices. Specifically, implementing reduced-impact logging techniques can help limit the physical disturbance to soils, while post-logging rehabilitation measures, such as the application of organic amendments, mulching, and cover cropping, could accelerate the recovery of soil structure and fertility. In forest plantations, the intermediate soil quality highlights the potential of improved silvicultural practices to narrow the gap between managed and natural forests. Strategies such as diversifying tree species, transitioning from monocultures to mixed-species stands, and optimizing rotation lengths may bolster soil nutrient retention and microbial activity (Karam *et al*., 2013), ultimately enhancing the long-term sustainability of these systems. By integrating detailed soil assessments with strategic restoration and silvicultural interventions, forest managers can make informed decisions that balance economic objectives with the long-term health and resilience of tropical forest ecosystems.

## ACKNOWLEDGEMENTS

We would like to thank the management of Gain Green Development Sdn. Bhd. for assisting with this study.

## REFERENCES

Allek, A., Viany Prieto, P., Korys, K.A., Rodrigues, A.F., Latawiec, A.E. and Crouzeilles, R. (2022). How does forest restoration affect the recovery of soil quality? A global meta-analysis for tropical and temperate regions. *Restoration Ecology* 3(13): e13747. doi:https://doi.org/10.1111/rec.13747.

Arifin, A., Karam, D.S., Shamshuddin, J., Majid, N.M., Radziah, O., Hazandy, A.H. and Zahari, I. (2012). Proposing a suitable soil quality index for natural, secondary and rehabilitated tropical forests in Malaysia. *African Journal of Biotechnology* 11: 3297-3309.

Bodos, V.A., Rajoo, K.S., Karam, D.S. *et al*. (2024). Assessing the effectiveness of buffer zones in logged Malaysia Borneo tropical forests using Tropical Soil Quality Index (TSQI). *Malaysian Journal of Soil Science* 28(1): 293-304. ISSN 13947990

Bray, R.H. and Kurtz, L.T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59: 39-46.

Camenzind, T, *et al*. (2017). Nutrient limitation of soil microbial processes in tropical forests. *Ecological Monographs*, 88(17): 4–21. https://doi.org/10.1002/ecm.1279.

Karam, D.S., Arifin, A., Radziah, O. *et al*. (2013). Status of soil microbial population, enzymatic activity and biomass of selected natural, secondary and rehabilitated forests. *American Journal of Environmental Sciences* 9(4), 301–309. doi/ 10.3844/ajessp.2013.301.309

Karam, D.S., Ibrahim, Z., Rani, R., *et al*., (2022). A narrative review of the impact of forest rehabilitation programs on soil quality in Peninsular Malaysia. *Malaysian Journal of Soil Science* 26:1-16. ISSN 13947990

Ligate, E.J., Chen, C., and Wu, C. (2018). Evaluation of soil fertility status based on CEC and variation across disturbed and intact tropical coastal forests sites in Tanzania. *Asian Journal of Environment & Ecology* 6(2): 1-12. Article no.AJEE.40545

Picard, N., Gourlet-Fleury, S. and Forni, É. (2012) ‘Estimating damage from selective logging and implications for tropical forest management’, *Canadian Journal of Forest Research* 42(3), pp. 605–613.

Rajoo, K.S., Arifin, A., Karam, D.S. *et al*., (2012). Heavy metal uptake and translocation by *Dipterocarpus verrucosus* from sewage sludge contaminated soil. *American Journal of Environmental Sciences* 9(3): 259–268. doi/10.3844/ajessp.2013.259.268

Rajoo, K.S., Arifin, A., Karam, D.S. *et al*., (2013). Assessment of heavy metals uptake and translocation by *Aquilaria malaccensis* planted in soils containing sewage sludge. *American Journal of Applied Sciences* 10(9): 952–964. doi.org/10.3844/ajassp.2013.952.964

Shaliha-Jamaluddin, A., Ibrahim, Z., Karam, D. S., Rajoo, K. S., Jusop, S., Gandaseca, S., & Abdu, A. (2022). Soil fertility status of rehabilitated forest soil in Bintulu, Sarawak after 30 years of planting. *Malaysian Journal of Soil Science* 26(1): 133-150.

Sumner, M.E. and Miller, W.P. (1996). Cation exchange capacity and exchange coefficients. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis: Part 3 Chemical Methods*. Soil Science Society of America, Madison, WI, pp. 1201-1229

Thomas, G.W. (1996). Soil pH and soil acidity. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis: Part 3 Chemical Methods*. Soil Science Society of America, Madison, WI, pp. 475-490.

Turner, B.L., Brenes-Arguedas, T. and Condit, R. (2018). Pervasive phosphorus limitation of tree species but not communities in tropical forests. *Nature* 555: 367-370.