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Soil Fertility Status of Rehabilitated Forest Soil in Bintulu, Sarawak after 30 Years of Planting

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ABSTRACT

Rehabilitation of degraded forestland is critical because it aids in reducing soil nutrient loss, improving vegetation stand and/or composition, and addressing environmental concerns. Thus, the purpose of this study was to determine the soil fertility condition in soils in rehabilitated forests after 30 years of planting. This study was conducted in 16 plots of a 47.5-hectare rehabilitated forest at Universiti Putra Malaysia Bintulu Campus in Sarawak, Malaysia. As of 2010, around 350,000 seedlings from 128 Sarawak native species had been planted. Soil samples were taken from different depths at each site (0-15 cm and 15-30 cm). Soil chemical properties were determined using standard laboratory methods while soil compaction analysis was determined using the fall-corn-type soil penetrometer (Hasegawa Type H-60). Soil Fertility Index (SFI) and the Soil Evaluation Factor (SEF) were used to estimate soil fertility and site quality. The compaction rate for the soil at rehabilitated forest plots was inversely proportional to cumulative depth. The compaction rates for plots in years 1991 to 2000 showed an increase in compaction rates with the depth of soil. The total cumulative depth for plots 2001 to 2008 had a longer graph trend compared to the previous years. The principal component analysis (PCA) showed that pH, OM, exchangeable Mg, CEC, and available P all contributed positively to factor loading in PC1. Our data showed a moderately positive correlation between CEC and exchangeable (Exch.) Mg, CEC with OM and Exch. Na and Exch. K indicating that negative charges derived from organic matter played an important role in cation retention capacity, nutrient supply, and soil fertility. The SFI analysis (9.26) in rehabilitated forest planted in year 1991 indicated greatest accumulation of organic matter from litter fall. In addition, the SEF values of the rehabilitated forests in relation to planting years indicated an undulating trend. Generally, SFI and SEF exhibit strong correlations with soil chemical and biological features, implying that these two indices can be used as indicators of soil quality.

Key words: Rehabilitated forest, soil compaction, physico-chemical properties, soil fertility and soil indices (SFI and SEF)

INTRODUCTION

In most tropical countries, forests are frequently subjected to intensive logging, grazing, and shifting cultivation. With biodiversity conservation and management being a major forest management priority, and humans living in wooded regions being viewed as a barrier to efficient conservation, many measures to keep forest dwellers out of conservation zones have been tried, but with limited success (Ramakrishnan 2007). It is noted that Southeast Asia saw the greatest drop in forest area, losing about 2.8 million hectares each year. Indonesia, with about 1.9 million hectares lost each year, was the country with the largest forest loss, followed by Myanmar, Cambodia, Philippines, Malaysia, and the Democratic People's Republic of Korea (FAO 2007).

Deforestation is a visible manifestation of human activity in the environment. This alteration can have several interconnected repercussions, such as a loss in the chemical and physical quality of soil resources (Seeger and Ries 2008). Soil degradation is the total of geological, climatic, biological, and human variables that lead to the degradation of the soil's physical, chemical, and biological potential, putting biodiversity, land usage, and hence existence of human societies at risk. Forest rehabilitation can enhance forest areas while also conserve existing primary forests and improve environmental quality. Rehabilitation of degraded forestland has become significantly important as it helps to improve the loss of soil nutrients and improve vegetation stand or composition as well as address environmental concerns (Zaidey *et al.* 2010*)*. In Sarawak, Malaysia, it is noted that rehabilitation of degraded forestlands due to abandoned shifting cultivation has been successfully implemented under the ecosystem rehabilitation program (Kendawang *et al.* 2004) while in Peninsular Malaysia, degraded forestland due to excessive harvesting has also been rehabilitated by the enrichment planting technique (Arifin *et al*. 2008b; Hamzah *et al.* 2009).

Soil fertility is the capacity to receive, store and transmit energy to support plant growth. Biological processes have the potential to contribute significantly to chemical and physical processes that influence soil fertility. In short, soil that is rich in nutrients is fertile. In undisturbed rainforests such nutrients are recycled via the litter, slash and burn agriculture system and the mineralization of organic nutrients from the plant remains or on short-lived inputs from ash. The use of soil fertility indicators can assist in determining the influence of agricultural operations and forest management on soil attributes. Several challenges defining quality and variety of biological, chemical, and physical components that regulate soil processes complicate the evaluation of soil quality and the identification of critical soil composition that serve as indicators of the functional qualities of soil (Doran and Parkin 1994).

For a better understanding of effective soil management and conservation, knowledge of soil science is required for the rehabilitation of tropical rainforests on highly degraded land as well as soil under a rehabilitation program after many years of planting (more than 20 years old). As a result, a multivariate soil quality measurement approach may need to be used. Thus this study was conducted to (1) understand the relationship between the effects of soil compaction on soil chemical properties and soil fertility condition of rehabilitated forests; and (2) place emphasis on the significant soil properties identified based on PCA and the applicability of the proposed Soil Fertility Index (SFI) and the Soil Evaluation Factor (SEF) as alternative approaches to identify indicators for estimating soil fertility and site quality in plantations that are to be rehabilitated.

MATERIALS AND METHODS

General Background of Study Area

This study was conducted in sixteen plots (planted in years 1991 to 2008, excluding years 2002 and 2004, where there was no planting) of rehabilitated forest plots at Universiti Putra Malaysia Bintulu Campus in Sarawak, Malaysia (*Figure 1)*. This study which included Phases I, II and IV covered a total area of about 1.58 acres.

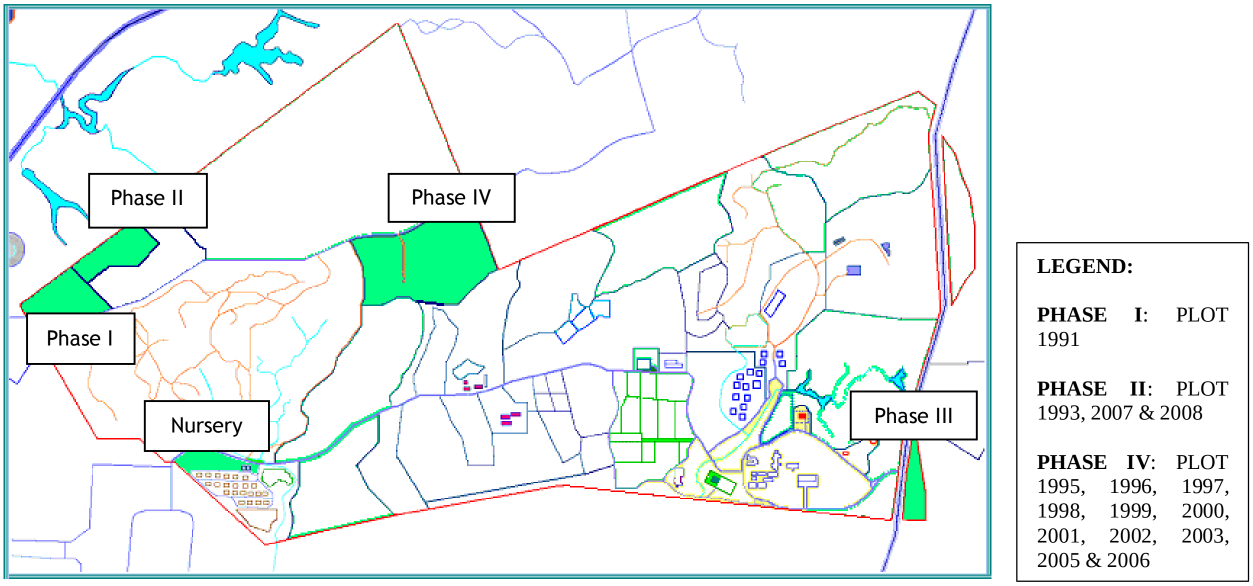


Figure 1. Location of Rehabilitated plots in UPM Bintulu Campus, Sarawak

Under the auspices of Mitsubishi Corporation, Japan, the Joint Research Project on Tropical Rainforest Ecosystem Rehabilitation began in July 1991. This was a collaborative project between Universiti Putra Malaysia (UPM) and Yokohama National University, Japan (YNU). The project's goals were to assess the health of recovered forests by using an interdisciplinary approach to measure indices of forest health quantitatively and qualitatively, and hence the long-term viability of forest resources. To determine the health of the recovered forest, the project undertook and integrated research findings in fields such as soil science, plant physiology, water science, biodiversity (terrestrial floral, wildlife, aquatic flora and fauna, insect, and microorganisms) and microclimatic variables.

The Miyawaki approach, which is being used in this project, is based on the notion of vegetation association and spontaneous regeneration acceleration (Miyawaki 1999). A total of 126 indigenous plants from the Dipterocarpaceae and Non-Dipterocarpaceae families were planted at a high density (3 seedlings/m^2) using this approach. The project began on a 47.5-hectare plot on the UPM campus in Bintulu, Sarawak. As of 2010, around 350,000 seedlings from 128 native Sarawak species had been planted. In addition, 100 study plots were constructed in the repaired area, with the growth of planted seedlings being observed on a regular basis.

Previously, plots 1991 and 1999 had been under shifting cultivation. *Ischaemum magnum*, *Miscanthus floridulus*, and *Trema orientalis* dominated the land before the start of the project. Plot 2008 was a regenerating forest with grassland species such as *Macaranga* spp. and *T. orientalis* dominating (Yusuf and Abas 1992). The Bintulu, Sarawak-based project is an excellent example of a highly effective forest regeneration effort in a degraded environment. It should be noted that the recovered forest site is a degraded plantation area. The regeneration began in 1991 and was completed in three phases. The age of the research plots/tree stands is estimated to be between 15 and 30 years old as of date.

Soil Taxonomy

The underlying soils of the sample plots are from the Berkenu and Nyalau series. Sandstone intercalated with ferrogenous shale is the parent material for both soil types. The Berkenu Series is classified as fine loamy, mixed, isohyperthermic Typic Paleudult. The structures are weak to moderate, medium subangular blocky, with uniformity improving with depth (Peli *et al.* 1984). The Bekenu Series, according to Paramananthan (2000), is a low-fertility soil. According to Peli *et al.* (1984), the Nyalau series is a coarse loamy, kaolinitic, and isohyperthermic form of Typic Dystropept. The topsoil is yellowish brown (10YR5/6) while the B horizon is bright yellowish brown (10YR 6/8) to yellowish orange (10YR 7/8). The strength, fineness, and subangularity of the blocky formations vary. The soil has a low response rate and is well-drained. The amount of organic matter in the soil is rather high, and it tends to increase with depth (Peli *et al.* 1984).

Rehabilitated Forest: The Forest Structure and Condition

A previous study by Kueh *et al.* (2011) at a similar location indicated that the rehabilitated forest had greater structure in comparison to the surrounding natural regenerating secondary forest as shown in Table 1. Forest structure evaluation reveals information about the biodiversity and health of the recovered forest. When compared to a naturally regenerating secondary forest, the accelerated natural regeneration approach for rehabilitating damaged forest areas shows improved structural metrics like DBH, height, and basal area. This can aid in the promotion of reforestation and forest restoration efforts in damaged areas. In general, rehabilitated damaged areas do not show full recovery in terms of height and extent of natural vegetation.

TABLE 1
Selected key forest structural characteristics of the study sites
Basal Area (m^2 0.04 h^{-1}) and Dbh (cm) and height (m) range in the study plots

	Plot 2008	**Plot 1999**	**Plot 1991**	**Plot NF**
Basal area				
(m^2 0.04 h^{-1})	0.02	0.08	1.56	1.64
Mean*	0.05^{-3}±$0.3x10^{-5}$ ($7.0x10.0^{-7}$-$0.54x10.0^{-3}$)	$0.35x10^{-2}$±$0.2x10^{-3}$ ($0.1x10.3^{-4}$-0.02)	$0.76x10^{-2}$±$0.8x10^{-3}$ ($0.1x10.0^{-3}$-0.09)	$0.30x10^{-2}$±$0.7x10^{-3}$ ($0.1x10.0^{-4}$-0.28)
Dbh (cm)				
Mean*	0.76±0.16 (0.04-2.61)	6.00±0.20 (0.82-15.50)	8.16±0.38 (1.31-35.10)	3.24±0.23 (0.41-59.80)
Heigh (m)				
Mean*	0.46±0.15 (0.01-1.40)	6.15±0.13 (1.49-10.73)	9.30±0.24 (2.00-20.50)	4.02±0.14 (0.30±26.80)

*Value are mean±S.E

Soil Sampling and Preparation

At selected rehabilitated forest plots, a 20 × 20 m research plot was established (1991 to 2008 planting sites). For sample replication, the plots were split into two subplots (10 x 10 m). Using an auger, five soil samples were taken at five randomly selected places in each subplot. The soil samples were taken at two distinct depths, ranging from 0 to 15 cm for topsoil and 15 to 30 cm for subsoil. The five soil samples for the subplots were then combined into one composite sample. Each composite sample was replicated three times. All soil samples were air dried at room temperature until completely dried. The soil samples were cleansed of plant debris and coarse stones after drying. The materials were then finely crushed with a mortar and pestle to pass through a 2-mm sieve. The ground samples were tagged and maintained in a sealable plastic bag.

Soil Compaction/ Hardness Analysis

The assessment of soil compaction at each rehabilitated forest plot was repeated thrice for the top, middle and bottom of the soil portions. Soil compaction was measured using fall-corn-type soil penetrometer (Hasegawa Type H-60) to a depth of 50 cm (*Figure 2*).

An one drop penetrability (ODP) figure was plotted to evaluate the soil hardness where the horizontal axis represents the penetrating depth (cm) per one drop of weight while the vertical axis shows the cumulative depth (cm). In this study, soil compaction was classified using the plotted values of the horizontal axis and are listed as follows: very hard, ODP < 0.5 cm; hard, ODP between 0.5-1.0 cm; moderate, ODP between 1.0- 2.0 cm; soft, ODP > 2.0 cm (Ishizuka *et al.* 1998). In other words, the harder the soil, the smaller the area in the Figure.

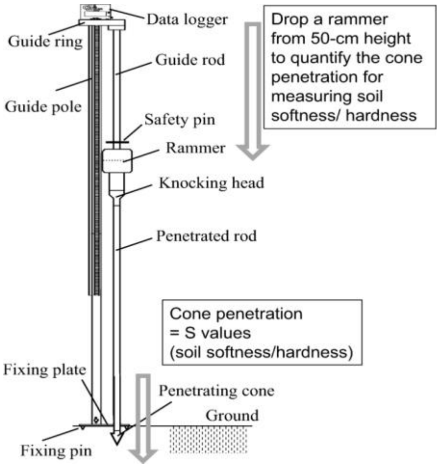


Figure 2. Diagram of a fall-corn-type soil penetrometer/ hardness (Hasegawa Type H-60)

Soil Chemical Analysis

The pH of the soil samples (1:2.5 – soil to water ratio) were measured using a pH meter. The pH of the soil was measured after 1 h of reciprocal shaking. The measurements were taken in soil to solution ratio (1:2.5) The loss-on-ignition approach was used to estimate organic matter and total organic carbon. The Kjeldahl technique (Bremner and Mulvaney 1982) was used to quantify total nitrogen while the LECO-412 machine was used to determine total carbon in soil. The Bray II technique was used to determine the amount of available phosphorus (Peter *et al.* 2001). The exchangeable cations (K, Ca, Mg, and Na) were extracted with 1 M NH_4OAc buffered at pH 7 and the Shimadzu AA-6800 AAS was used to determine the concentrations of K, Ca, Mg, and Na in the solutions. The cation exchange capacity (CEC) was also measured to access the negatively charged sites on the soil.

Data Analysis

Statistical Analysis System (SAS) version 9.1 was used for the statistical analysis. Analysis of variance (ANOVA) and Tukey's test were carried out to indicate the differences among the rehabilitated forests plot/years of planting. Pearson correlation analysis was carried out to indicate the relationship among the selected soil parameters. The variables that contributed significantly to the soil physico-chemical properties among the rehabilitated plots were accessed using Principal component analysis (PCA).

Soil Indices

Soil fertility was assessed using the Soil Fertility Index (SFI) (Moran *et al.* 2000) and the Soil Evaluation Factor (SEF) (Lu *et al.* 2002) at two different depths in rehabilitated forest plots. Based on the following equations, the SFI and SEF indices were derived to measure the intensity of land degradation in the research area:

$$SFI = pH + \text{Organic matter (\% dry soil basis)} + \text{Available P } (mg\ kg^{-1} \text{ dry soil}) + \text{Exchg. K } (cmol_c kg^{-1}) + \text{Exchg.Ca } (cmol_c kg^{-1}) + \text{Exchg. Mg } (cmol_c kg^{-1}) - \text{Exchg. Al } (cmol_c kg^{-1})$$

$$SEF = [\text{Exchg. K } (cmol_c kg^{-1}) + \text{Exchg. Ca } (cmol_c kg^{-1}) + \text{Exchg Mg } (cmol_c kg^{-1}) - \log (1 + \text{Exchg. Al } (cmol_c kg^{-1})] \times \text{Organic matter (\% dry soil basis)} + 5.$$

Both SFI and SEF indices were created and utilised to measure soil biomass and fertility conditions in the Amazon humid tropical forest of Brazil during secondary forest succession. In this study, the applicability of the SFI and SEF indices was utilised to compare soil fertility of restored and secondary forests.

RESULTS AND DISCUSSION

Effect of Soil Compaction/ Hardness on Chemical Properties of the Soils

In order to better understand the effects of soil compaction at rehabilitated forest plots/ areas, the distribution of soil compaction from plots 1991 to 2008 are presented in Figure 3 and Figure 4.

Based on Figure 3, it is noted that the compaction rate is inversely proportional to the cumulative depth. This is because compaction and topsoil removal normally result in 70% increase in bulk density and a 23% increase caused by subsoil compaction alone (Woodward, 1996). The compaction rate or trend showed an increase from 2 cm to 9 cm at plots 1991 to 2008 with no significant differences beyond this (see red box). It is noted that the compaction rate increased from topsoil to subsoils. As we can see from the figure, the compaction rate for plots 1991 to 2000 increased with an increasing depth of soil. The compaction values from 0-9 cumulative depth were very soft to soft, which indicate a less compact surface soil. This could be due to formation of a litter layer in the forest which contains much decomposition materials. According to Hasegawa (2008), soil hardness is assessed as "softness" (i.e., S-value, cm drop1), which characterizes soil penetration resistance based on the depth (cm) to which a cone (diameter: 20 mm) enters the soil per stroke when a 2-kg mass rammer is dropped from a height of 0.5 m. As a result, low "softness" suggests that the soil is hard. But towards cumulative depths (15 to 30cm), soil compaction rate increased. The soil was moderately hard as indicated by the total count/ total cumulative depth down to 50 cm which was less than 34 drops.

The compaction rate for planting years 2001 to 2008 shows the same compaction pattern as in years 1991 to 2000 (Figure 4). As we can see from the pattern, the total cumulative depth for plots 2001 to 2008 has a longer graph compared to the previous one, indicate that the soil within this year was more compacted. This could be attributed to the trees being still young and not being able to accord a wide canopy to cover the soil as well as considerably less formation of forest litter. The least compact soil was at plot 1991 with a total cumulative depth 24 and the most compact soil was at plots 2003 and 2008, respectively.

Hasegawa (2008) employed soil hardness to determine the influence of soil compaction on root development (i.e. soil penetrability). The crucial values of cone resistance that caused a slowdown in root growth vary from 1 to 1.7 MPa, whereas values that inhibit root growth range from 3 to 4 MPa, according to Hasegawa (2008). Thus, the vertical distribution of soil hardness and the measured depths of root penetration in soil profiles were used to assess the quality of the soil as a growing foundation; for example, if the soil conditions encourage tree development (Hasegawa, 2008).

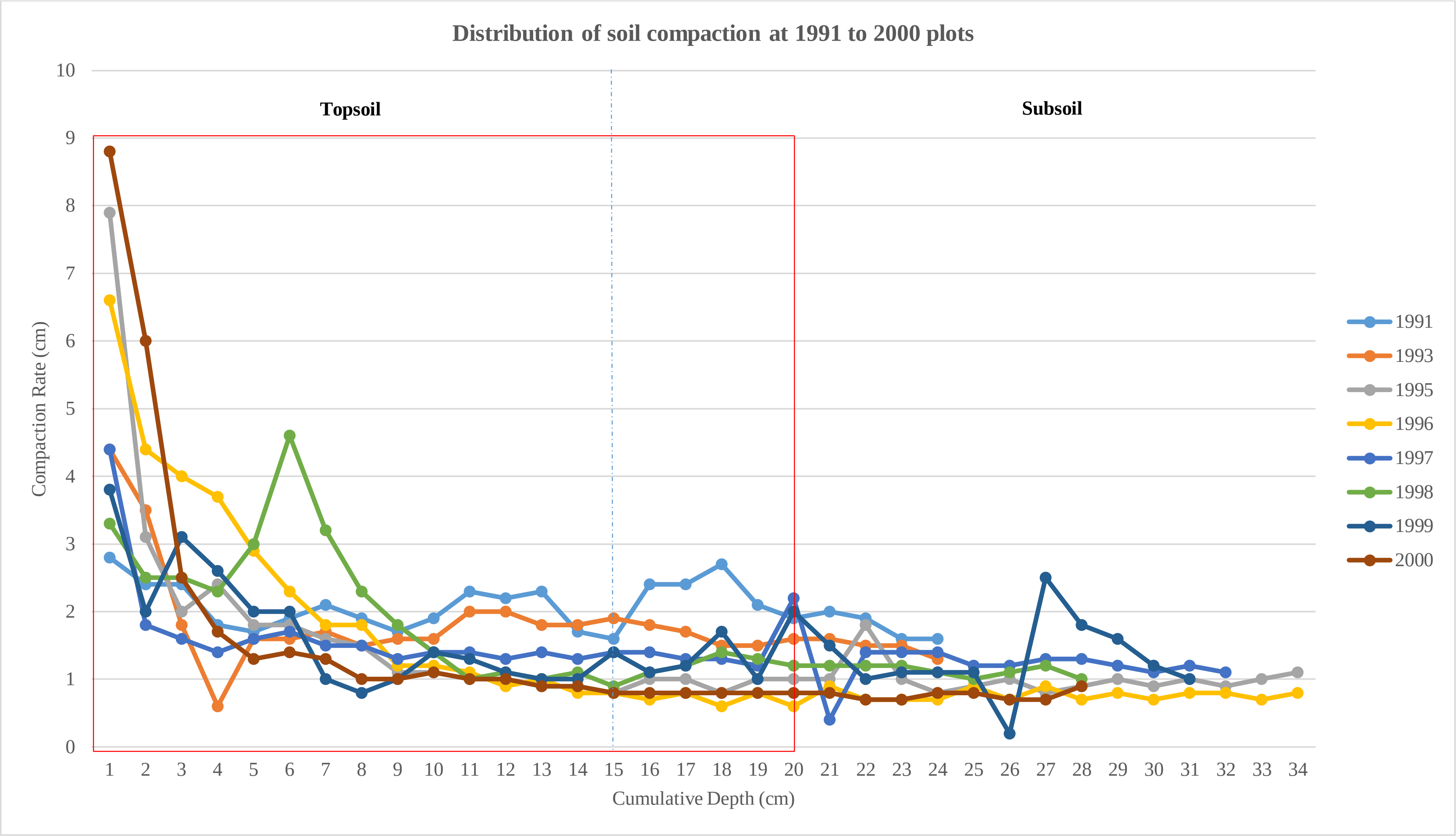


Figure 3. Soil compaction pattern at plots 1991 to 2000

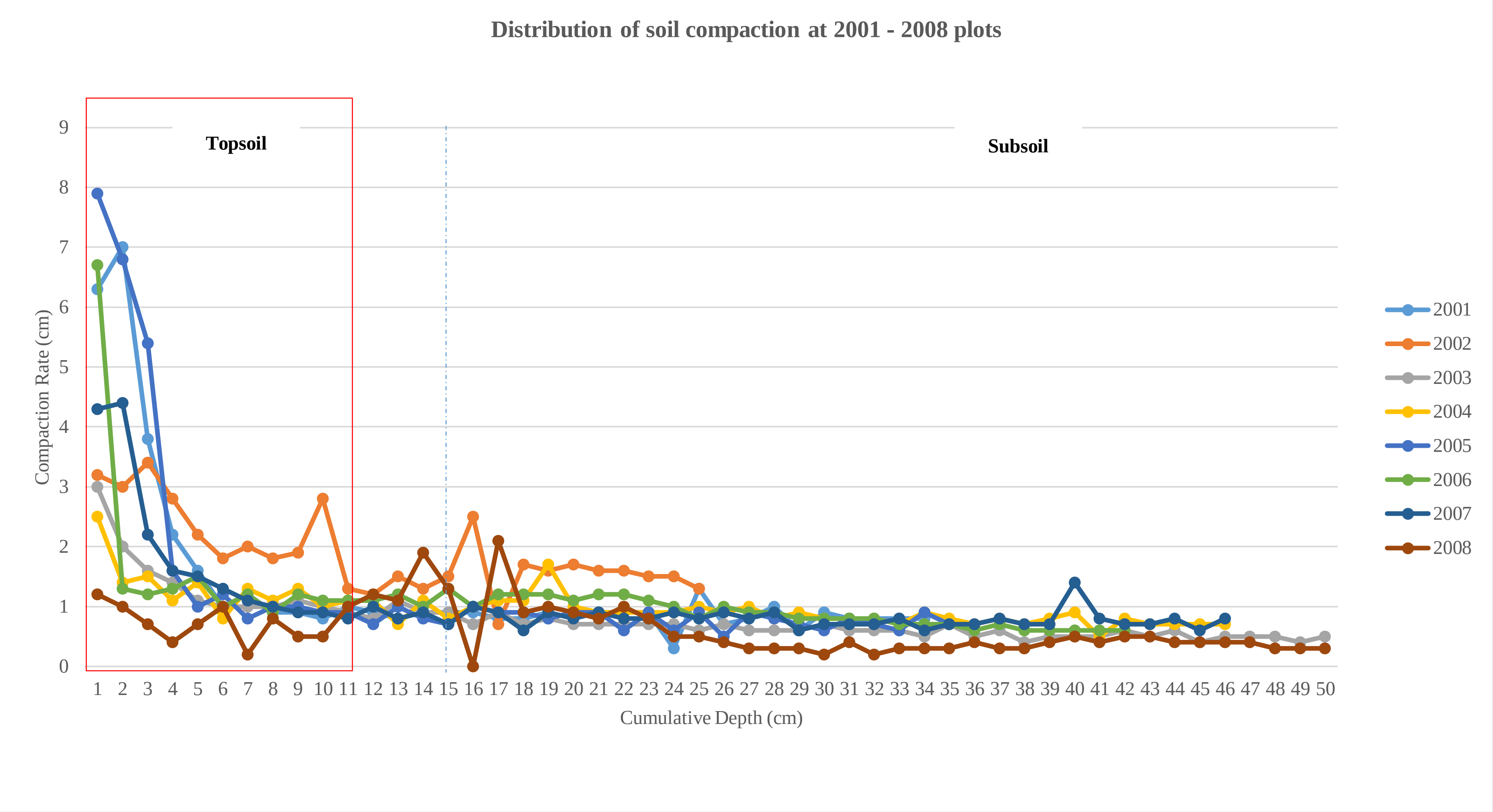


Figure 4. Soil compaction pattern at plots 2001 to 2008

Previous studies have found that surface pressure can cause soil particles to move closer together, thus reducing the volume of air voids (Craig 2004). Although compaction is inevitable and purposefully achieved by rollers on the construction sites to increase the bearing capacity of soils and aggregates for road construction, any soil compaction is unwanted in forest stands. Other effects of soil compaction are the direct damage caused to roots by the action of machine wheels on the forest floor (Craig 2004). Such impacts on soil structure may considerably reduce vegetation growth. Physical fertility of soil is determined by the way in which the essential growth requirements of plants are satisfied. The storage and delivery of water, nutrients, and oxygen for root absorption are all regulated by the physical quality of the soil (water infiltration rate, total plant-available water storage, air-filled porosity at the wettest drained state, structural stability to wetting, and salinity and sodicity balancing). These characteristics describe the structure of the soil and its structural stability (Cass *et al.* 1996).

Nowadays, most large-scale forest operations require the use of heavy machinery to increase safety and to be economically competitive. Such machinery may exert ground pressure reaching 300 kPa (Mungoven 1996) and used in harvesting operations such as “cut to length” (CTL) method. During mechanized forest operations, the highest degree of soil compaction on machine operating trails typically occurs within the first few traffic passes after which additional passes continue to increase soil density but at a lower rate (Aguilera Estaben *et al.* 2018). Trafficking of both harvester and forwarder on top of brush covered machine-operating trails can reduce soil compaction and lower soil penetration resistance by dispersing applied loads to a greater area (Suryatmojo 2014).

Soil Chemical Properties for Rehabilitated Forest Plots

Chemical properties of soils between study plots are shown in Table 2. The results show that the pH_w and pH_{KCl} for the plots are generally slightly acidic and range from pH 4.12 (plot 1997) to pH 4.35 (plot 2005) and pH 3.60 (plot 1991) to pH 3.85 (plot 1995). Because nutrients are less available to plants in acidic soils, serious plant nutritional deficiencies are common. Soil pH affects the availability of nutrients to plants. The availability of major plant nutrients such as nitrogen, phosphorous, potassium, sulphur, calcium, magnesium, and the trace element molybdenum are reduced and may be insufficient in acidic soils. In acidic soils, nutrients may not only be chemically less available to plants but may also be positionally less available due to poor root development. Plants are unable to investigate enough soil volume to compensate for diminished chemical availability when root development is constrained (Chris Gazey 2018).

Other than that, the results show that the OM in the soils ranges from 2.27 g kg^{-1} to 5.52 g kg^{-1}. This indicates that the OM content in the soil is slightly moderately available. Under acidic conditions, H is a component of the humus carboxyl (-COOH). When a soil is limed and the acidity is reduced, the H^+ from humic acids is extracted more readily and reacts with hydroxyl (OH-) to generate water. As the positively charged H is withdrawn, the carboxyl groups on the humus create a negative charge. When the pH of a soil rises, the release of hydrogen from carboxyl groups helps to buffer the rise in pH while also forming the CEC (negative charge) (Mielniczuk 1996). Decomposition of organic matter is a significant part of forest nutrient cycling because it controls the availability of nutrients to plants and, as a result, determines forest production (Xu *et al.* 2013). The pH of the soil has a significant impact on the breakdown of organic materials. The slower breakdown rates at high pH were unexpected, given that an earlier study had shown that decomposition occurs more quickly at lower pH (Chapin *et al.* 2002).

Total organic carbon (TOC) for the soil in all study plots ranged from 2.31 to 2.50 g kg^{-1}. For an Ultisol soil, the average organic carbon content of representative soils in relation to major land use for crop land is about 80 tons per hectare, secondary forest is about 180 tons per hectare and for primary forest, and it is about 240 tons per hectare, indicating that the TOC content in the rehabilitated forest plots is only moderate. Humus affects soil properties. As it slowly decomposes, it colours the soil darker, increases soil aggregation and aggregate stability, increases the CEC (the ability to attract and retain nutrients) and contributes N, P and other nutrients (Juma 1998).

TABLE 2

Chemical properties of soils between rehabilitated plots

Plot	Parameters										
	pH$_{w}$	pH$_{KCl}$	OM	TOC	CEC	Exch. Al	Exch. K	Exch. Ca	Exch. Mg	Exch. Na	Av. P
			(g kg^{-1})		(cmol^{+} kg^{-1})						(mg kg^{-1})
1991	4.21^{a}	3.60^{a}	**5.52^{a}**	2.31^{a}	4.71^{a}	2.70^{abc}	0.12^{ab}	0.14^{a}	0.09^{a}	0.02^{ab}	**1.88^{a}**
1993	4.18^{a}	3.69^{a}	4.52^{a}	2.43^{a}	3.54^{a}	2.47^{bcd}	0.06^{ab}	0.13^{a}	0.08^{a}	0.02^{ab}	1.32^{abc}
1995	4.21^{a}	**3.85^{a}**	3.86^{a}	2.31^{a}	4.68^{a}	2.40^{bcd}	0.07^{ab}	0.16^{a}	0.08^{a}	0.02^{ab}	1.31^{abc}
1996	4.19^{a}	3.83^{a}	3.25^{a}	2.35^{a}	3.26^{a}	1.95^{d}	0.06^{b}	**0.39^{a}**	0.07^{a}	0.02^{ab}	1.39^{abc}
1997	4.12^{a}	3.75^{a}	3.47^{a}	2.34^{a}	3.03^{a}	2.24^{bcd}	**0.47^{a}**	0.17^{a}	0.06^{a}	**0.04^{a}**	1.16^{bc}
1998	4.18^{a}	3.73^{a}	2.72^{a}	2.35^{a}	**5.48^{a}**	2.32^{bcd}	0.07^{ab}	0.14^{a}	0.10^{a}	0.02^{ab}	1.44^{abc}
1999	4.19^{a}	3.73^{a}	2.72^{a}	2.32^{a}	3.28^{a}	2.21^{bcd}	0.06^{b}	0.20^{a}	0.09^{a}	0.02^{ab}	1.52^{abc}
2000	4.24^{a}	3.78^{a}	2.23^{a}	2.32^{a}	4.40^{a}	2.18^{bcd}	0.34^{ab}	0.21^{a}	0.04^{a}	0.02^{ab}	1.31^{abc}
2001	4.22^{a}	3.81^{a}	2.34^{a}	2.33^{a}	2.52^{a}	2.06^{cd}	0.05^{b}	0.20^{a}	0.05^{a}	0.02^{ab}	1.30^{abc}
2002	4.23^{a}	3.60^{a}	3.53^{a}	2.34^{a}	3.15^{a}	2.71^{abc}	0.05^{b}	0.37^{a}	0.08^{a}	0.02^{ab}	1.44^{abc}
2003	4.19^{a}	3.70^{a}	2.97^{a}	2.34^{a}	3.64^{a}	**3.26^{a}**	0.05^{b}	0.14^{a}	0.05^{a}	0.02^{ab}	1.32^{abc}
2004	4.19^{a}	3.72^{a}	3.36^{a}	2.36^{a}	4.21^{a}	2.54^{bcd}	0.07^{ab}	0.18^{a}	0.04^{a}	0.02^{ab}	1.60^{ab}
2005	**4.35^{a}**	3.75^{a}	2.36^{a}	2.35^{a}	4.39^{a}	2.30^{bcd}	0.06^{b}	0.27^{a}	0.05^{a}	0.03^{ab}	1.32^{abc}
2006	4.19^{a}	3.81^{a}	2.27^{a}	2.34^{a}	3.90^{a}	2.80^{ab}	0.10^{ab}	0.47^{a}	**0.13^{a}**	0.02^{ab}	1.05^{bc}
2007	4.16^{a}	3.82^{a}	2.52^{a}	2.33^{a}	1.98^{a}	2.73^{ab}	0.05^{b}	0.28^{a}	0.04^{a}	0.02^{ab}	1.03^{bc}
2008	4.22^{a}	3.78^{a}	2.63^{a}	**2.50^{a}**	1.87^{a}	2.63^{abc}	0.17^{ab}	0.28^{a}	0.05^{a}	0.02^{ab}	0.90^{c}

Note: Means with the same letter are not significantly different.

Soil type, soil pH, and soil organic matter level are all factors that affect the cation exchange capacity (CEC). Sand, organic matter, silt, and clay particles all contribute to the composition of soils. Compared to clayey and silty soils, sand-rich soils have a lower cation-holding capacity. The CEC values for the study plot range from 1.87 cmol^{+} kg^{-1} (plot 2008) to 5.48 cmol^{+} kg^{-1} (plot 1998). CEC is an important predictor of soil fertility since it evaluates a soil's ability to store nutrients. Soils with a high CEC can hold more cations, making them (calcium, magnesium, and other cations) sufficient. Low CEC soils, on the other hand, are prone to cation deficiency. This low CEC values fits the case for plots 1998 and plot 2008. The CEC of various clay minerals and soil organic matter varies with pH. The CEC is lowest in soils with a pH of 3.5 to 4.0 and rises as the pH of an acid soil is increased by liming. It is also worth noting that at low pH, some positive charges may occur in specific soil mineral surfaces. Anions (negatively charged ions) like chloride (Cl^-) and sulphate are retained by these positive charges (SO_4^{2-}) (Leticia *et al.* 2008).

The exchangeable cations, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) are the primary ions linked to CEC in soils and are referred to as the base cations (Rayment and Higginson 1992). These cations are replaced by H^+, Al^{3+}, and Mn^{2+} when soils get more acidic, and conventional methods give CEC values that are substantially higher than that in the field (McKenzie *et al.* 2004). Non-exchangeable bases are unlikely to be useful to plants as nutrient sources, but their progressive release helps to restore the supply of exchangeable bases in the soil. If overall supply of exchangeable calcium, magnesium, and potassium in soils, representi the total supply of these bases, shortages in these bases for plant growth would appear in many soils within a few years (Day and Ludeke 1993).

The pH of the soil has an impact on phosphorus availability. Phosphorus reacts with iron and aluminium in acidic soils. This renders it inaccessible to plants. The availability of P in the soils is shown in Table 1 for each study plot. Organic matter decomposes faster in warm humid regions and slower in cool dry climates, releasing P. Phosphorus is released more quickly in well-aerated soils (where oxygen levels are higher) and considerably more slowly in saturated, moist soils. Soils with an intrinsic pH of 6 to 7.5 are excellent for P-availability, but pH values below 5.5 and between 7.5 and 8.5 limit P-availability to plants due to aluminium, iron, or calcium fixation, all of which are frequently linked with soil parent materials (Ismat *et al.* 2018).

Identifying Important Soil Properties in Relation to Soil Fertility in Rehabilitated Forests

At different years following planting in rehabilitated forest plots, Principal Component Analysis (PCA) revealed four major contributions for selected soil physicochemical parameters (Table 3). In general, four components (PC1, PC2, PC3, and PC4) accounted for 63% of total variability, and each component represented a series of variables, making analysis and interpretation easier.

The results from the topsoils showed that pH, OM, exchangeable Mg, CEC, and available P all contributed positively to factor loading in PC1. PC2 and PC4 were dominated by exchangeable bases and PC3 contributed to acidity and organic carbon of the soils. The presence of exchangeable Al in PC3 suggests that this cation has a substantial impact on soil quality in the soil ecosystem. Ca and Mg uptake can be inhibited by exchangeable Al (de Wit *et al.* 2010) which limit fine root development and contribute to soil nutrient imbalances (Angelica *et al.* 2012).

Thus, the information derived from the PCA allows the development of simplified indicators that can represent more complex variability of soil physico-chemical properties (Aiza-Shaliha *et al*. 2013; Arifin *et al*. 2008b). Organic matter and cation exchange capacity have a strong positive association, according to PCA data, which explains how nutrients in the soil are stored in organic matter. The decomposition of organic materials by soil microbes is aided by a certain range of relative humidity or carbon content in the soil (Van Eekeren *et al*. 2008). As a result, tree roots will be able to absorb nutrients generated by organic debris, allowing them to develop and mature. The availability of cations is reduced by soil acidity, which is reflected in exchangeable Al. CEC and organic matter content have a linear relationship, indicating that organic matter and CEC are at their optimal levels for soil nutrient supply and retention.

TABLE 3
Soil parameters used for PCA and results of PCA of the rehabilitated forest

	PC1	**PC2**	**PC3**	**PC4**
+ve relationship	pH_w, CEC, Exch. Mg, Available P and OM	Exch. K, Exch. Na	pH_{KCl}, Exch. Al, TOC	Exch. Ca,
Contribution	pH, CEC and organic matter content	Exchangeable bases	Acidity and organic carbon	Exchangeable bases
Total	3.07	1.41	1.35	1.13
Variance (%)	27.89	12.80	12.27	10.27
Cumulative (%)	27.89	40.691	52.96	63.23

Relationship between Selected Soil Parameters

Table 4 shows the results of correlation analysis among selected soil metrics. The correlation analysis of organic matter (OM) with cation exchange capacity (CEC) and exchangeable Mg for surface soils revealed a moderately positive correlation, indicating that negative charges derived from organic matter play an important role in cation retention capacity, nutrient supply, and soil fertility status of tropical soils like the one studied. The positive correlation indicate that they have an inversely proportional relationship. Jean-Fran and Chevalier (2006) found a favourable association between OM and selected soil characteristics (soil acidity and organic matter accumulation) in a study conducted in Loiret, France. Tilahun (2007) and Getahun *et al.* (2014) observed that OM is strongly and positively linked with cation exchange capacity, which is similar to our findings. According to Aubert *et al.* (2004), old-growth forests demonstrate that soil acidification occurs as a result of tree development, which has an impact on soil properties, especially when the litter is low in nutrients and high in secondary metabolites.

TABLE 4
Correlation between soil parameters of the soil

No.	Parameters	Correlation coefficient (R)
1	Cation exchange capacity x exchangeable Mg	0.654*
2	Cation exchange capacity x organic matter	0.691*
3	Exchangeable Na x exchangeable K	0.554*

Note: *, Significant difference (p<0.05) level using Pearson correlation

Assessing Soil Fertility Status of Rehabilitated Forests Using Soil Indices

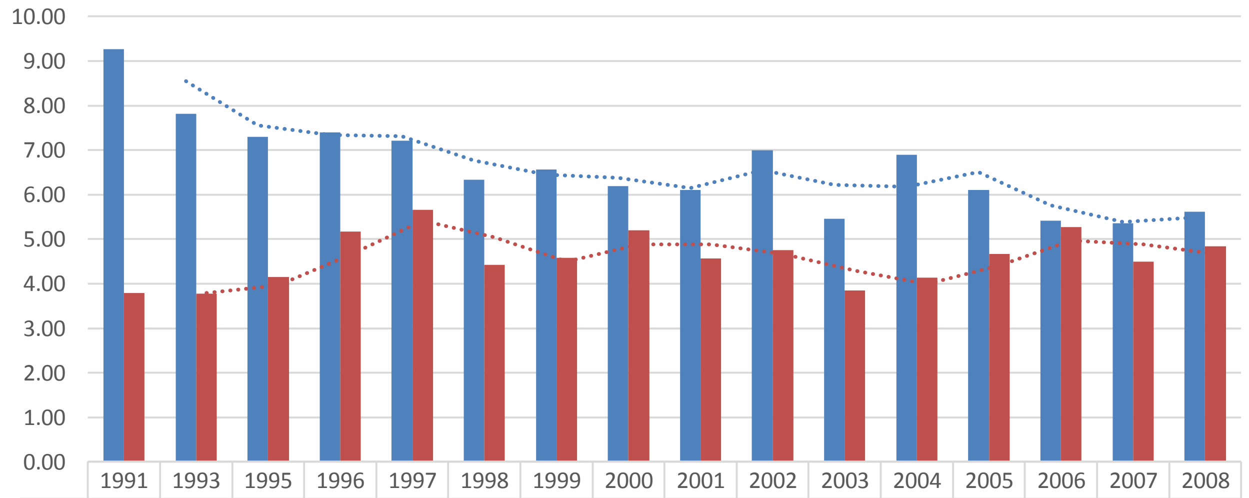
To determine the overall impact of a rehabilitation program on soil quality, the SFI and SEF for various years of planting were determined (Figure 5). Slightly decreased SFI values were observed towards the planting year. The greater fertility of soil in a rehabilitated forest planted in year 1991 (9.26) is attributed to the greatest accumulation of organic matter from litter fall. Meanwhile the least fertile soil was observed in rehabilitated forest planted in year 2007 (5.35).

As the surface soils were covered with *Imperata cylindrica*, the SFI value at plot 2007 was the lowest among the plots, possibly due to the high nitrogen intake of this species. The SFI value of rehabilitated forests declines as the planting year approaches, implying that the nutrient content has been continually absorbed by the tree or bush in an acidic soil with a large supply of exchangeable Al restricting the availability of nutrients (Wasli *et al*. 2011; Arifin *et al*. 2008a).

The SFI results show increasing values when the forest stand gets older (about 30 years after planting), indicating that the soil in plots are reaching optimum fertility. The index uses values of pH, organic matter, phosphorus, potassium, calcium, magnesium and aluminium (inverse value). Chemical characteristics of the soil appear to be an important factor in distinguishing between rates of restoration succession in various planting years. This is especially true when land use is taken into account as a factor influencing regrowth rates. Nutrient stock is generally concentrated in the vegetation and the organic horizon of the soil profile in nutrient-poor soils (Ultisol), rather than in the mineral soil itself (Moran *et al*. 2000).

Moreover, the SEF values of the rehabilitated forests in the planting years showed an undulating trend. SEF was found to be greater (5.66) for plot 1997, followed by plot 2006 (5.27) and plot 2000 (5.20), and least for plot 1993 (3.78). For rehabilitated forests, the SEF value of less than five indicates very low soil fertility (Lu *et al*. 2002). Some of the planting plots (Plots 1996, 1997, 2000 and 2006) showed a SEF value of more than 5, indicating that these plots had reached optimum soil fertility status. With reference to the results obtained for the chemical properties of the soil, the availability of exchangeable calcium, potassium and magnesium, and organic matter were high and contributed to the high SEF value. In contrast, the high concentration of Al in other plots might have restricted the availability of exchangeable bases.

When SEF was calculated for soil depth, the SEF values were found to decline in all land uses as soil depth increased (Panwar *et al*. 2011). Based on this finding, 30 years after restoring degraded forest land by planting indigenous dipterocarp species, it was still found to be insufficient to restore soil fertility to natural forest levels. However, in our study, some of the



	1991	1993	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
🟦 SFI	9.26	7.82	7.29	7.40	7.21	6.33	6.57	6.19	6.10	6.99	5.46	6.90	6.11	5.41	5.35	5.62
🟥 SEF	3.80	3.78	4.15	5.16	5.66	4.43	4.57	5.20	4.57	4.76	3.84	4.13	4.67	5.27	4.49	4.84

Figure 5. Soil Fertility Index (SFI) and Soil Evaluation Factor SEF) between plots for rehabilitated forests at surface soils

planting plots showed that the soil condition was moving towards reaching optimum fertility status.

CONCLUSION

Soil compaction has an impact on the physical qualities of the soil, plant growth, root growth, and crop output. Compaction damages the physical environment of the soil, which affects not only shoots but also root growth and development. Many plant nutrients (such as exchangeable cations and available P) are highly influenced by soil pH and cation exchange capacity. Organic matter is an important component of soils because it has an impact on physical and chemical characteristics of soils. Levels of exchangeable bases rise with high pH value. If significant amounts of exchangeable Al are found in soils with pH below 5.2, it can inhibit the availability of the nutrients. The availability of organic matter breakdown, exchangeable bases, and cation exchange capacity in the soil are all influenced by the state of pH in the soil. Organic matter, pH, available P, exchangeable Mg, and cation exchange capacity all show a significant positive association, indicating that the majority of nutrients are stored in surface soils. Soil organic matter has a significant connection with CEC and exchangeable Mg. This indicates that soil organic matter and cation exchange capacity have a direct proportional connection for the availability of the exchangeable bases. Our study shows that rehabilitating forests over arable land helped increase OM content, exchangeable cations, accessible minerals, micronutrients, and microbial activity. SFI and SEF have high substantial relationships with soil chemical and biological characteristics, indicating that these two indices can be employed as soil quality indicators. The period of time it takes for rehabilitated forests to revert to natural forest will be determined by a variety of environmental factors, including climate, disturbance severity and size, and distance from seed sources of natural forest species.

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