UNIVERSITI PUTRA MALAYSIA

ORGANIC MATTER, CARBON, AND HUMIC ACIDS IN REHABILITATED AND SECONDARY FOREST SOILS

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ORGANIC MATTER, CARBON, AND HUMIC ACIDS IN REHABILITATED AND SECONDARY FOREST SOILS

By

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Dear Dad, Kok Woon

Mom, Oi Lien,

Beloved Brothers and Sister, Men Hau,

Men Huan, Yit Qing

Thank you for your love and support

Special Thanks to Wei Han

ABSTRACT

Tropical rainforests cover about 19.37 million ha (60%) of Malaysia's total area and about 8.71 million ha can be found in Sarawak, Malaysia. Excessive logging, mining, and shifting cultivation contribute to deforestation in Sarawak. The objectives of this study were to: (i) Quantify soil organic matter (SOM), soil organic carbon (SOC), and humic acids (HA) in rehabilitated and secondary forest soils, and (ii) Compare SOM, SOC, and HA sequestrations of both forests at 0-15 cm and 15-30 cm depths. Soil samples were taken at 0-15 cm and 15-30 cm depths from rehabilitated and secondary forests located at Universiti Putra Malaysia, Bintulu Campus. Standard procedures were used to analyze the soil samples for bulk density, pH, texture, C (%), OM (%), N (%), C/N ratio, yield of HA (%), E_4/E_6, carboxylic-COOH, phenolic-OH, and total acidity. Carbon sequestered in the stated depths were quantified using standard procedures. Generally, the soil pH (1 M KCl and water) of the rehabilitated and secondary forests were similar regardless of depth. The texture of the rehabilitated forest soil was clayey (clay loam) compared to secondary forest soil (sandy clay loam). The bulk densities of the two forest soils increased down the soil profile but no significant difference were observed between these forest soils. Regardless of forest soil type and depth, the C (%) were similar and the fact that except for 15-30 cm of the secondary forest soil whereby the quantity of C sequestered was significantly lower than that of the rehabilitated forest soil, C sequestration was similar irrespective of forest type and depth. Nevertheless, stable C sequestered in HA were generally higher in the rehabilitated forest soil compared to the secondary forest soil. This was attributed to higher yield of HA in the rehabilitated forest soil. The C/N ratios of the forest soils increased with increasing depth suggesting more humification at 0-15 cm than 15-30 cm. The humification level of the two forest soils at 0-15 cm were similar but that of the rehabilitated forest soil was much humified at 15-30 cm compared to the secondary forest soil. The E_4/E_6, carboxylic-COOH, phenolic-OH, and total acidity of both forest soils were generally within the ranges reported by other authors. The SOM and amount of unstable C sequestered in the rehabilitated and secondary forest soils were similar but the stable C sequestered by HA was significantly higher in the rehabilitated forest soil compared to the secondary forest soil irrespective of depth. Hence, the finding suggest that the stability of C in HA realistically reflects C sequestration. This is partly because quantity of stable C depends on the amount of HA.

ABSTRAK

Hutan hujan tropika di Malaysia meliputi kawasan sebanyak 19.37 million ha (60%) dan 8.71 million ha daripada hutan hujan tropika tersebut terdapat di Sarawak, Malaysia. Aktiviti-aktiviti seperti pembalakan, perlombongan, dan pertanian pindah yang keterlaluan menyebabkan pemusnahan hutan di Sarawak. Satu kajian telah dijalankan dengan objektif berikut: (i) Mengkuantitikan bahan organik tanah (SOM), karbon organik tanah (SOC), dan asid humik (HA) dalam tanah hutan pemulihan dan tanah hutan sekunder, serta (ii) Membandingkan SOM, SOC dan HA yang terikat di dalam kedua-dua hutan pada kedalaman tanah 0 15 cm dan 15-30 cm. Sampel tanah diambil dari hutan pemulihan dan hutan sekunder, Universiti Putra Malaysia pada kedalaman 0-15 cm dan 15-30 cm. Ketumpatan pukal tanah, pH, tekstur, C (%), OM (%), peratus jumlah nitrogen (N), nisbah C/N, hasil HA (%), E_4/E_6, kumpulan -OH dan kumpulan -COOH serta jumlah asid ditentukan dan dianalisa mengikut prosedur yang biasa. Karbon yang terikat pada dua kedalaman tanah hutan juga dikuantitikan mengikut prosedur biasa. Pada umumnya, pH tanah (1 M KCl dan air suling) bagi hutan pemulihan dan sekunder adalah hampir sama sekiranya tidak mengambil kira kedalaman dua tanah tersebut. Tekstur hutan pemulihan mengandungi lebih peratusan tanah liat berbanding dengan hutan sekunder. Ketumpatan pukal tanah bagi kedua-dua hutan pula bertambah mengikut profil tanah tetapi tidak menunjukkan sebarang signifikan jika dibandingkan antara dua tanah hutan. Tanpa mengambil kira jenis tanah hutan dan kedalamannya, peratus C dan kuantiti C yang terikat adalah hampir sama. Walaubagaimanapun, kuantiti C yang terikat dalam hutan sekunder pada kedalaman 15-30 cm menunjukkan signifikan yang lebih rendah daripada tanah hutan pemulihan.

Namun begitu, stabil C dalam HA adalah lebih tinggi pada tanah hutan pemulihan disebabkan oleh kandungan HA yang lebih. Nisbah C/N tanah hutan yang bertambah mengikut kedalaman tanah menunjukkan terdapat lebih humifikasi pada 0-15 cm berbanding 15-30 cm. Walaupun tahap humifikasi kedua-dua tanah hutan pada 0-15 cm adalah sama, tetapi tanah hutan pemulihan menunjukkan lebih humifikasi pada 15-30 cm berbanding dengan tanah hutan sekunder. Kumpulan -OH dan -COOH, jumlah acid serta E_4/E_6 bagi kedua-dua tanah hutan amnya termasuk dalam lingkungan keputusan yang dilapor oleh penulis lain. Bahan organik tanah dan kuantiti C yang tidak stabil adalah hampir sama terikat dalam tanah hutan pemulihan dan sekunder. Walaubagaimanapun, stabil C yang terikat dalam HA adalah signifikan lebih tinggi dalam tanah hutan pemulihan berbanding tanah hutan sekunder tanpa mengambil kira kedalaman. Maka, penemuan ini mencadangkan bahawa kestabilan C dalam HA secara realistik menggambarkan kuantiti C yang terikat. Ini adalah kerana kuantiti C yang stabil bergantung kepada kuantiti HA.

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I certify that this research project report entitled **"Organic Matter, Carbon, and Humic Acids in Rehabilitated and Secondary Forest Soils"** has been examined and approved as a partial fulfillment of the requirement for the degree of Bachelor of Bioindustry Science in the Faculty of Agriculture and Food Sciences, Universiti Putra Malaysia Bintulu Campus.

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LIST OF ABBREVIATIONS TERMS

TOC – Total organic carbon

2 NPP – Net primary productivity

3 HA – Humic acids

4 SOM – Soil organic matter

5 N – Nitrogen

6 C/N – Carbon/nitrogen ratio

7 USDA – United State Department of Agriculture

8 NaOH – Sodium hydroxide

9 HCl – Hydrochloric acid

10 SAS – Statistical Analysis system

11 SSA – Specific surface area

12 MRT – Mean residence time

13 COOH – Carboxylic

14 OH – Phenolic

15 E_4/E_6 - ratio of absorption intensities at 465 and 665 nm

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CHAPTER 1

INTRODUCTION

Soil organic carbon (SOC) pool contains an estimated 1500 Gt C or 80% of the total terrestrial C store. Moreover, it is the largest near-surface C stores on the earth (Schlesinger, 1995; Amundson, 2001). Due to the enormous amount of C stored in soil organic matter (SOM), it plays an essential role in the global C balance and affects global warming. Moreover, this dynamic nature of soil component exerts a dominant influence on many soil physical, chemical, and biological properties (Brady and Weil, 2002). Tropical and subtropical forest soils account for around 30% of the total global SOM (Dalal and Carter, 2000), but SOC storage capacity has been dramatically reduced to around 212 Mt C year^{-1} by ongoing deforestation (Fearnside, 2000; Mayaux *et al.*, 2005).

Tropical rainforests cover about 19.37 million ha (60%) of Malaysia's total area and about 8.71 million ha can be found in Sarawak, Malaysia (Hamzah *et al.*, 1995). Excessive logging, mining, and shifting cultivation contribute to deforestation in Sarawak (Dimin, 1998). In addition, 69640 hectares of forests in Sarawak have been cleared for the necessary developmental projects such as Bakun hydroelectric project (Nik Muhamad, 1995). Generally, forests after being tempered with are left without proper silvicultural measures to stimulate development of valuable tree species for forest restoration. As a result, most of the disturbed forests are left to regenerate through natural processes. The total area of degraded and secondary forests is estimated to be

850 million hectares, corresponding to approximately 60% of the total area that is statistically classified as forests in the tropics (tropical Asia, tropical America, and tropical Africa) (Sips, 1993; FAO, 1995, 2001; Wadsworth, 1997). A rehabilitation programme initiated by Universiti Putra Malaysia (UPM), Malaysia and Japanese Center for International Studies in Ecology since 1990 has enabled establishment of indigenous tree species (Hamzah *et al.*, 1995; Alias *et al.*, 1998).

Innoprise-Face Foundation Rainforest Rehabilitation Project (INFAPRO) for rehabilitation of logged forest sequestered atmospheric carbon dioxide (CO_2) by fast growing indigenous tree species on degraded soils (Moura *et al.*, 1994). Tropical forest remains a viable resource for the economies of Malaysia, yet their potential as a C sink has received less attention (Fan, 1990; Vourlitis, 2002). Most studies have been focused on the C pools of forest floor, and above-ground biomass (Kimble *et al.*, 2002). Soil acts as a sink of C, by removing CO_2 from the atmosphere through photosynthesis, leading to subsequent storage of organic C through plant and microbial biomass and also remains as soil humus. It is estimated that the total global terrestrial biomass is almost as large as the atmospheric C pool. However, soil C stock is about equal to the sum of these two major C stocks, with its magnitude depending on the considered soil depth (Kimble *et al.*, 2002).

At the moment we do not know important environmental indicators such as the mechanism of soil C sequestration and humic substances (e.g. humic acids (HA)) accumulation in the afforested soils of the project at UPM. This is essential because SOC, the main form of sequestered C in the soil, relates to the proportion of net primary productivity (NPP) returned to the soil. Among the processes that lead to SOC sequestration are conversion of biomass into humus, aggregation to prevent C oxidation, and translocation of C into sub soil. Although well established and managed indigenous trees have a potential in C sequestration in biomass, the importance and mechanisms of C sequestration in soils on which these trees are grown are inadequately understood, partly because changes in C content, humic substances [(humic substances comprised about 60 to 80% of the SOM) (Brady and Weil, 2002)] and bulk density to a minimum depth of 1 m are seldom measured in soils; as a result, few attempts have been made to measure or model temporal changes in the SOC pool.

The objectives of this study were to: (i) Quantify SOM, SOC, and HA in the rehabilitated and secondary forest soils, and (ii) Compare SOM, SOC, and HA sequestrations of both forest soils at 0-15 cm and 15-30 cm depths.

CHAPTER 2

LITERATURE REVIEW

2.1 Scenario of Tropical Rain Forest

The tropical rain forests are extremely rich of their diversity of all life forms and restricted to a belt within 20 degrees north and south of the equator. Rainfall varies from 2000 to 4000 mm, evenly distributed throughout the year thus distinguish the tropical rain forest from the drought-deciduous tropical forest and the arid tropical regions (Young and Giese, 1990). Southeast Asia including Malaysia, Indonesia, New Guinea, the Philippines, and the northeast coast of Australia constitute the largest extent of tropical rain forest in the Eastern Hemisphere (Young and Giese, 1990).

Tropical forests are being destroyed at an alarming rate, threatening more than half of the planet's biodiversity with extinction (Sayer and Whitmore, 1991; Laurance *et al.*, 2001). Currently the main issues about tropical forests are deforestation and forest degradation that result in potentially disastrous environmental, economic, social and cultural effects.

Reduction of forest cover has been a major contributory source to increase carbon dioxide (CO_2) concentration in the atmosphere (Clarke, 1982; Houghton *et al.*, 1987; Houghton 1990). Due to reduction of tropical forests, the accumulation of CO_2 is decreasing through photosynthesis by tropical trees (Kira, 1991; Uchijima, 1991). Deforestation cause changes in evapotranspiration and potential greenhouse effects of trace gases released by clearing and burning (Bouwman, 1990) which may have regional and global effects on climate (Shukla *et al.*, 1990).

2.2 Tropical Secondary Forest

Tropical secondary forests are defined as "forests regenerating largely through natural processes after significant human and/or natural disturbance of the original forest vegetation, and displaying a major difference in forest structure and/or canopy species composition with respect to nearby primary forests on similar sites" (Albano, 2002). Regrowing forests not only differs in species composition and in physiognomy from primary forest but the species are also highly light demanding (International Tropical Timber Organization, 2002).

Conversion of forests to crops or pastures results in significant depletions of terrestrial C pools and in an increase of emissions of CO_2 to the atmosphere (Kauffman and Uhl, 1990). Tropical evergreen forests may contain 18-50 times more above-ground C per unit area than croplands (Houghton, 1999; Hughes *et al.*, 2000). It is the view of Jaramillo *et al.* (2003) that highest concentration of roots in the top 40 cm of soil, and the shallow depth at which large pools occur in secondary forests indicate forest susceptibility to natural disturbances. Root C pools have been found to range from 7.9 to

11.6 Mg ha^{-1} in primary forest, 2.1 to 9.6 Mg ha^{-1} in secondary forest and 1.0 to 1.9 Mg ha^{-1} in pastures (Jaramillo *et al.*, 2003).

2.3 Forest Rehabilitation

Tropical forests are robust and possess high elasticity, resistance and a high repair capacity which is often underestimated (International Tropical Timber Organization, 2002). Forest restoration can be a very cost effective measure just by enrichment planting to regain the ecological and protective functions of a forest ecosystem. In order to do a desired outcome, forest restoration needs to be based on sound ecological and silvicultural knowledge.

There are 20 million hectares of forests managed for production, conservation and protection purposes in Malaysia (Kobayashi *et al.*, 2001). However, some of the forest ecosystems have been degraded by improper harvesting by loggers and shifting cultivation. There have been many intensive efforts to conduct research on ecological basis for forest rehabilitation, species consideration and tree growth. The rehabilitation of 25000 hectares of degraded logged forest in Malaysia was carried out by enrichment planting and reclamation of degraded areas using indigenous tree species such as dipterocarps, fast growing pioneers and forest tree crops (Moura-Costa *et al.*, 1994).

A group of researchers from Universiti Putra Malaysia (UPM) have been working for past few years to identify suitable indigenous timber species and appropriate techniques to rehabilitate the degraded forest land. The planting of 3 seedlings per meter square with a mixed and random distance has been carried out in part of a rehabilitated forest (Azani *et al.*, 2001). The dense planting technique (3 seedlings m^{-2}) shortens the time for canopy closer and controls the weed growth. The soil of the ongoing project belongs to Nyalau series (*Typic Tualemkuts*) which is characterized by coarse loam, light yellowish brown to topsoil 9 cm deep with brownish yellow subsoil (Azani *et al.*, 2001).

2.4 Forest Soils and C Storage

Soils have a profound influence on both composition and productivity of a forest, and are considered as a component of the forest ecosystem where materials are added, transformed, translocated and lost because of natural cycling mechanisms (Young and Giese, 1990). The soils's ability to accumulate and preserve organic matter (OM) and thus to counteract the increasing concentration of CO_2 in the atmosphere has received growing interest in the last decade. Sorption to mineral surfaces seems to be a major process in the preservation of OM in soils. The organic C content of soil is positively related to the specific surface area (SSA), but large amounts of OM in soil results in reduced SSA depending on the amount absorbed and the type of mineral. Kaiser and Guggenberger (2003) found that mineralogy is the primary control of the relation between surface area and sorption of OM within same compartments (i.e. horizons).

Kimble *et al.* (2002) described that terrestrial ecosystems can be a major sink or source for C depending on soil environmental conditions. Conversion of forest land to cropland dramatically changes in soil C content and major emission of C into atmosphere. Hence, reforestation or afforestation plays important role in bringing C back into soil and forest have the potential to increase soil C in long term because of its long residence time.

2.5 Soil Organic Matter

Organic matter in the forest soil improves soil structure by binding mineral grains, thereby improving tilth, aeration, retention of moisture and increasing buffering and exchange capacity of soils (Young and Giese, 1990). Upon decomposition, SOM is an important source of plant nutrients. Most OM is added to forest soil in the form of litter, which includes freshly fallen leaves, twigs, stems, bark, cones and flowers. Litter is composed predominantly of cellulose and hemicellulose, lignin, proteins, and tannins.

Once the litter reaches the forest floor, a host of macroorganisms and miroorganisms act on it. As litter decomposes, CO_2, water, and energy are released. A by-product of litter decomposition is humus, which is dark mass of complex amorphous OM. Organic matter may be produced belowground by the annual turnover of small roots. The OM content of an undisturbed, mature forest soil represents the equilibrium between agencies supplying fresh organic debris and those leading to its decomposition.

The ratio of C to N is stable in soils where this equilibrium exists. The C/N ratio of surface mineral horizon of forest soils is usually wider than agricultural soils (15:1 to 30:1) (Young and Giese, 1990).

Soil organic matter is a major source and sink of atmospheric C in the global C cycle. The OM is highly heterogeneous and consists of numerous components, ranging from easily mineralizable sugars to recalcitrant aliphatic compounds. Residence times of C in these compounds in soil vary from a few minutes to thousands of years (Trumbore 1993; Lichtfouse *et al.*, 1995; Torn *et al.*, 1997). Models that describe the C usually differentiate between at least two pools of SOM, for example a labile and a stable pool. Labile pools of SOM have a mean residence time (MRT) from a few minutes to decades and stable pools have an MRT of hundreds to thousands of years (Hsieh, 1992). Hsieh (1996) found that the MRT of the stable pool is estimated to be 250-380 years in tropical soils and 850-3000 years in temperate soils.

Furthermore, it is widely assumed that the variations in turnover times of stable OM are related to interactions with mineral soil material, via physical and chemical stabilization (Martin and Haider, 1986; Theng *et al.*, 1992; Hsieh, 1996; Torn *et al.*, 1997; Romkens *et al.*, 1998). Lutzow *et al.* (2007) found that the fine clay fraction (<0.2 μm) are lower than in the coarser clay fraction of temperate top soil for the mean residence time (MRT) and turnover times. The proportion of allocated C decreased from 30–50% in coarser clay fractions (0.2–2 μm) to 4-20% of total organic carbon (TOC) in the fine clay fraction, and the turnover also decreased in fine clay as compared to the coarser clay fraction (Lutzow *et al.*, 2007).

Edwards and Bremner (1967) described that some fractions of OM undergo further biochemical stabilization and complexed with clays and other minerals, or physically protected within clay micro-aggregates. These biochemical and physical processes further increase the resistance of humus compounds to enzyme attack, with mineralization rates of some fractions ranging from 0.1 to 1% per year (Anderson and Spencer, 1991). Consequently clays have higher OM contents than sandy soils (Jones 1973; Buringh 1984).

Dissolved OM has a fundamental effect on the chemical and microbial properties of soils. The concentration and properties of dissolved organic C and N in soils are not only controlled largely by microbial activity, but also by sorption and desorption. Tree species and ground vegetation do affect the amount and quality of both undissolved and dissolved OM in soil (Hongve *et al.*, 2000). Tree species composition affects microbial processes in the soil, such as transformations of C and N (Priha and Smolander, 1999; Priha *et al.*, 2001) and soil chemical characteristics (Howard *et al.*, 1998). Northup *et al.* (1995) and Fierer *et al.* (2001) described that secondary compounds found in trees, especially phenolic compounds and tannins have fundamendal effects on C and N dynamics in forest soil.

2.6 Soil pH and SOM Preservation

Organic matter increases with declining pH, the most acidic, and organic; soils often lie in surface horizons. The pH of 3.5-5.5 is typical of Malaysia soil (Othman and Shamsuddin, 1982). In high acidic soils, microorganism decomposition activity is low, and low oxidation of OM, so OM is preserved (Kinraide, 2003). The sorption of C in soils also depends on pH (Jardine *et al.*, 1989; Weigand and Totsche, 1998). One reason for the dependence on pH is chemisorptive interaction between organic functional groups and Al and Fe oxide-hydroxides (Ochs *et al.*, 1994; Edwards *et al.*, 1996). The increase in pH can increase the charge of organic molecules and thus favors the detachment from organic and inorganic surfaces (Tipping and Woof, 1991). Another reason could be increased desorption of organic ligands from oxide surfaces due to the increased OH^- activity (Avena and Koopal, 1998).

Little effect of pH has also been reported for the release of C from soils (Kaiser and Zech, 1999; Reemtsma *et al.*, 1999). The reason being that there is little effect of pH and the strong effects of ionic strength and cations on the release of C. Munch *et al.* (2002) concluded that mobilization of colloidal OM is more important than desorption from soil surfaces.

2.7 Total C

Briefly, terrestrial ecosystems can be a major sink or source for C depending on soil environmental conditions (Kimble *et al.*, 2002). The soil acts as a sink for C, by removing CO_2 from the atmosphere by photosynthesis, leading to subsequent storage of organic C through plant and microbial biomass and by soil C.

About 10-20% of above-ground litter and 20-50% of root litter may be converted into humus (Nye and Greenland, 1960) and the rest is mineralized as CO_2. The rate of humus oxidation in the undisturbed forest would be considerably lower than in the tilled field because the litter would not be incorporated into the soil through tillage and the absence of physical disturbance would result in slower soil respiration. Organic C contents of subsurface horizons are generally much lower than those of the surface soil. Since most of the organic residues in both cultivated and virgin soils are deposited on the surface soil, OM tends to accumulate in upper layers (Brady and Weil, 2002).

Soil organic C occurs in a variety forms such as fresh litter, microbial biomass, humic substances which have different turnover times and are likely to differ in their sensitivity to disturbance factors. The effects of physical soil disturbance are most pronounce in the surface soil. Bauhus *et al.* (2002) showed that the highest concentrations of C was in the undisturbed areas in native eucalypt forest of South-eastern Australia. On average, C in the fine soil fraction (<2mm) accounted for only

55.1-78.4% of TOC, including litter layer of the sites. However, only the most severe soil disturbance, including removal of topsoil and/or mixing with subsoil, results in significantly reduced C concentrations. However, changes in bulk density reduce differences in C concentrations between the different disturbance treatments (Bauhus *et al.*, 2002). This suggests that the sensitivity of SOC to disturbance will depend on the way C is reported, namely C concentrations or amount of C per unit of soil volume (bulk density).

Richards *et al.* (2007) found that soil N stocks to 30 and 60 cm depth were highest for secondary rain forest in seasonally dry subtropical Australia (17 t ha^{-1}), followed by pasture and the 50-year-old hoop pine site, and while the lowest soil N stocks were found in 63-year-old hoop pine plantations. Soil C/N ratios at 30 cm depth were lowest under rainforest and highest under the 63-year-old hoop pine plantation. When total site C was compared, rainforest (372 t C ha^{-1}) had more C sequestered than old (50-63 years) hoop pine sites (331–309 t C ha^{-1}). Several studies have shown that changes in soil N cycling will affect C storage (Dalal and Mayer, 1986a; Brown and Lugo, 1990; Neff *et al.*, 2002). Lack of N availability can curtail the biomass productivity and conversion of litter and root biomass to humus (Lal, 2001). The increase in N availability may lead to increase in NPP and stabilization of humus (Paul and Clark, 1989; Johnson and Henderson, 1995).

2.8 Soil Bulk Density

Soil bulk density is influenced by natural and anthropogenic factors. Under natural conditions, bulk density may range from 0.1 to 0.5 g cm^{-3} for organic soils and 0.8 to 1.6 g cm^{-3} for non-volcanic mineral soils (Lal and Kimble, 2001). Important among natural factors are soil properties, particle size distribution, degree of aggregation, SOC content, exchangeable cations, flora and fauna, and climatic factors (Lal and Kimble, 2001).

Clay content and nature of clay strongly interact with SOC and other cations to form aggregates. Degree of aggregation and stability of aggregates strongly influence soil bulk density. High activity clays (2:1 minerals) tend to have higher bulk densities than soils low in clay SOC contents. Low activity clays (1:1 minerals) tend to have lower bulk densities and behave like low clay soils (Lal and Kimble, 2001).

2.9 Humic Acids

Soil organic matter consists of humic substances and nonhumic substances. Nonhumic substances are less complex and less resistant (sugars, amino acids, fats) to microbial attack than those of the humic group. Humic substances comprised about 60-80% of the SOM (Brady and Weil, 2002). Generally, humic substances are classified into three chemical groups based on solubility. These substances are fulvic acids (FA), humic acids (HA) and humin. All three groups of humic subtances are relatively stable in soils (Brady and Weil, 2002).

Humic acids are medium in molecule weight and colour, soluble in alkali but insoluble in acid, and intermediate in resistance to degradation. The resistance of humic substances to oxidation is important in maintaining SOM levels and in protecting associated N and other essential nutrients against rapid mineralization and loss from the soil (Brady and Weil, 2002). For example, the formation of polyphenol-protein complexes can protect the protein N from microbial attack. Without the annual addition of sufficient plant residues, continual microbial oxidation will result in reduced SOM levels.

Humic substances are mixtures of macromolecules with varied structures and chemical compositions that are affected by differences in parental biomaterials and environmental conditions (Kang *et al.*, 2003). In addition, chemical structures of HA change with depth, even with a single soil profile (Chen and Pawluk, 1995; Xing, 2001). Humic acids play important role in environmental processes governing the fate and transport of organic and inorganic contaminants in soil environments.

In addition, Kang *et al.* (2003) found that the last extracted HA and humin contained relatively lower contents of polar functional groups such as carboxylic and phenolic groups which are revealed by both elemental and spectroscopic data. Kang *et al.* (2003) found that there were significant chemical, structural, and molecular differences among the 10 sequentially extracted HA and humin, even from a single soil. Besides that, it was found that C content of the HA ranged from 52 to 58% and that of the humin was 54%. Ash contents were very low for the HA, but the humin had 35% ash because of the clay minerals. Steelink (1985) reported that major elements in humic are C and O. The C content of HA ranges from 53.8 to 58.7%; O content varies from 32.8 to 38.3%.

There are compositional differences among HA from different environments. Negre *et al.* (2002) found that forest soils are characterized by a high aromaticity and a low amount of polysaccharides and protein moieties, reflecting their high evolution level. However, the two HA from agricultural soils from the study were found to be poor in aromatic and carboxylic groups but rich in polysaccharides and protein moieties. The percentage of humus which occurs in the various humic fractions varies from one soil type to another. Stevenson (1982) observed the humus of forest soils is characterized by high content of FA while the humus of peat and grassland soils is high in HA.

Negre *et al.* (2002) found that the carboxylic group concentrations ranged between 310 and 400 cmole kg^{-1}. The highest values (400 cmole kg^{-1}) were detected in the two Histosols (natural soils in north Italy), which also exhibit high phenolic OH content (520 and 540 cmole kg^{-1}) and consequently high total acidity (920 and 940 cmole kg^{-1}). According to most literature, in only few cases HA have a phenolic content higher than 500 cmole kg^{-1}. In contrast, the less acid HA was found in paddy soil, north Italy (650 cmole kg^{-1} total acidity), because of low amount of both carboxylic and phenolic groups. This was because the anaerobic condition in the rice field prevented formation of highly oxidized groups such as carboxylic acid (Olk *et al.*, 1999, 2000).

According Stevenson (1982), total acidity of HA ranges from 560 to 890 cmole kg^{-1}. The acidity nature of these substances was due to the presence of both carboxylic-COOH and phenolic-OH groups. Higher values (1000 to 1100 cmole kg^{-1}) for carboxylic-COOH has been reported by Hatcher *et al.* (1981) in HA from Inceptisols. Schnitzer and Preston (1986) attributed this discrepancy to the inclusions of amides and esters in the analysis by NMR spectroscopy.

The E_4/E_6 value, which is the ratio of absorption intensities at 465 and 665 nm, is widely used to characterize HA. The E_4/E_6 ratio decreases with increasing condensation of aromatic humic constituents (Konova, 1966; Stevenson, 1982). The E_4/E_6 ratio is governed by the molecular size (Chen *et al.*, 1977). Mekkaoui *et al.* (2000) found that E_4/E_6 ratio as well as the TOC value were both constant with increasing time of irradiation, reflecting photostability of HA molecules after 24 hour of continuous irradiation. The E_4/E_6 ratio has been widely used to evaluate the condensation level of humic substances (Arshad *et al.*, 1988; Piccolo *et al.*, 1992; Trunbetskoj *et al.*, 1992).

CHAPTER 3

MATERIALS AND METHODS

3.1 Soil Sampling

Soil samples were collected from a 16 year old rehabilitated forest (plot A) (Figure 1) and a secondary forest (Nirwana forest) at University Putra Malaysia, Bintulu Campus. The abandoned shifting cultivation area was rehabilitated since 1991 by planting indigenous timber species to identify suitable species and appropriate techniques to rehabilitate the degraded forest area. The tree species in plot A1 of the rehabilitated forest are *Dryobalanops beccarii*, *Dryobalanops aromatica*, *Hopea becariana*, *Whiteodendron moultonianum*, *Shorea scaberrima*, *Koompasia mallacensis*, *Shorea venulosa*, *Syzygium sp.*, *Artocarpus integer*, *Shorea multiflora*, *Alstonia angustiloba*, *Sandoricum koetjape* and *Hopea Dracteata*. The method of rehabilitation used in the study area is dense planting technique (3 seedlings m^{-2}). However, the primary Nirvana forest site was disturbed since 1994; thereafter the forest is regenerating through natural processes. The size of each experimental plot was 1.0 ha. Fifteen samples were taken at random with a soil augur at 0-15 cm and 15-30 cm depths. Bulk densities at these depths were determined by the coring method.

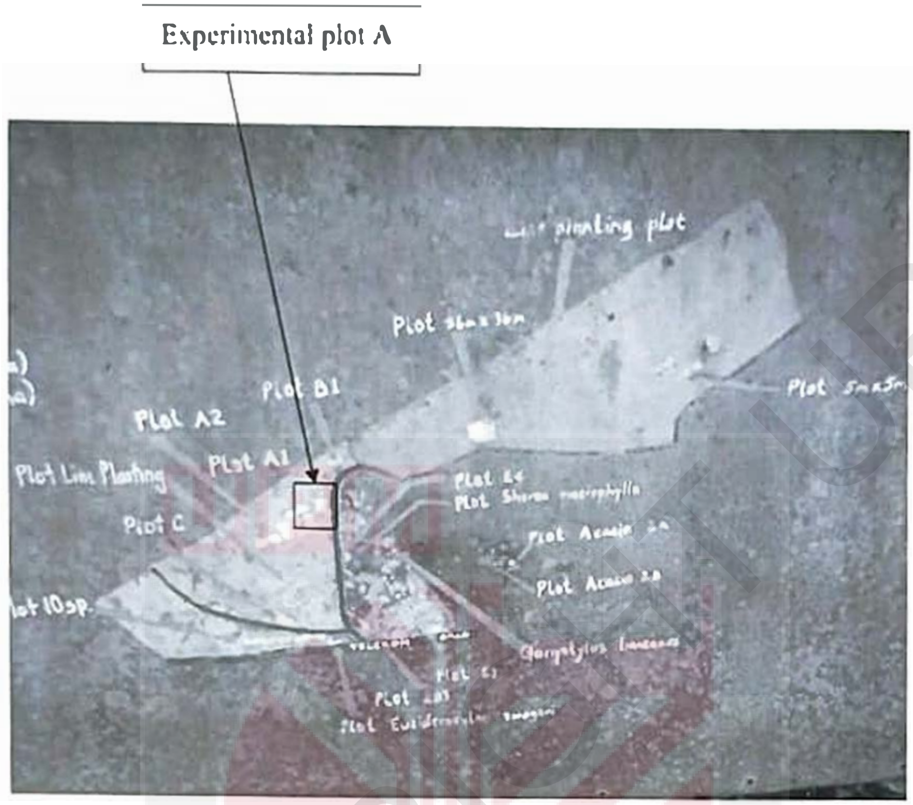

Figure 1: Map of rehabilitated forest at Universiti Putra Malaysia, Bintulu Campus indicating the experimental plot of this study

3.2 Soil Bulk Density

The bulk density method was used to quantify the total organic carbon (TOC), organic matter (OM) and humic acids (HA) at the stated sampling depths [(Ellert and Bethany, 1995) (Appendix D)].

3.3 Soil Preparation

Soil samples were air dried in the Soil Laboratory of Universiti Putra Malaysia, Bintulu Campus after which they were sieved to pass a 2 mm sieve and were kept in air tight plastic vials.

3.4 Determination of Soil Texture

The hydrometer method was used to determine soil texture in this research (Tan, 2005). This method determines the texture of the soil by measuring total sand (0.2-0.05 mm), silt (0.05-0.002 mm), and clay (<0.002 mm) contents.

Fifty grams of soil sample were placed in a blender cup. Then, the blender cup containing soil sample was filled with distilled water to within 10 cm of the top (rim) and 10 mL NaOH (4 M) solution. The cup was attached to a soil stirrer and the soil was stirred mechanically for 15 minutes. At the end of 15 minutes of stirring, the soil suspension was transferred into a measuring cylinder. The remaining soil residue was washed quantitatively in the cylinder by spraying with distilled water from a wash bottle. The volume in the cylinder was made up with water to the 1130 mL. To ensure thorough mixing of the suspension, it was stirred with a stirring rod so that all sediment disappeared from the bottom of the cylinder. Upon the removal of the stirring rod from the suspension, the temperature of the suspension was determined and recorded.

A hydrometer was placed carefully into the suspension and exactly after 40 seconds, the hydrometer reading was recorded. Afterwards, the hydrometer was removed and rinsed. The suspension was stirred one more time and the analysis of the 40 seconds reading was repeated. The average of these two readings represented the results. This result was equal the amount of silt and clay in grams of the soil sample. The suspension was thoroughly stirred again and third temperature and hydrometer reading were taken after two hours of settling time. This reading measured the amount of clay in grams. Since most hydrometers are calibrated at 68 °F (20 °C), all hydrometer readings were corrected if the temperature of the suspension was greater or less than 68 °F. The textural triangle was used to obtain the soil texture.

3.5 Soil Organic Matter and TOC Determination

The method described by Chefetz *et al.* (1996) was used to determine SOM and soil TOC. Ten grams of soil were weighed into crucible using a digital balance. The weight of the soil and crucible was determined. Afterwards, they were placed in a muffle furnace and ashed. Samples were initially ashed at 300 °C for 1 hour after which the temperature was raised to 750 °C for 5 hours. Samples were afterwards weighed upon cooling in a desiccator and simple mathematics was used to determine SOM. The calculated OM multiplied by 0.58 provides soil TOC (Chefetz *et al.*, 1996).

3.6 Total N Analysis

Total N was determined using micro-Kjeldahl method (Bremner and Lees, 1949). About 0.1 g of soil was weighed into 50 mL Kjeldahl digestion tube and treated with 5 mL concentrated sulphuric acid and one tablet of Kjeldahl catalyst (mixture of high selenium and sodium sulphate anhydrous) placed in the tube. The sample was shaken and allowed to equilibrate for 30 minutes after which it was digested on a digestion block in a fume chamber. The sample was initially heated at 180 °C for 1 hour and the temperature was raised to 320 °C for 5 hours and it was afterwards allowed to cool down. Afterwards, the sample was transferred into 50 mL volumetric flask, diluted to volume using distilled water. Ten mL of the filtrate was distilled with 10 mL of 40% NaOH and ammonium collected into 50 mL Erlenmeyer flask containing 10 mL of 2% boric acid-indicator mixture (bromocresol green-methyl red). Total N was determined by titrating the distillate with 0.01 M HCl.

Percentage of N in the soil was calculated as:

$$\% N = [(V-B) \times M \times R \times 14.01 / Wt \times 1000] \times 100$$

Where: V = Volume of 0.01 M HCl titrated for the sample (mL)

B = Digested blank titration volume (mL)

M = Molarity of HCl solution

14.01 = Atomic weight of N

R = Ratio between total volume of the digest and the digest volume used for distillation

Wt = Weight of air-dry soil or plant sample (g)

3.7 pH of Soil

To determine the soil pH in distilled water and pH in 1 M KCl, pH meter and pH buffer solutions were used. Five grams of soil sample were used in determining pH in distilled water and 1 M KCl. The pH was determined in a 1:2.5 of soil:distilled water suspension and/or 1 M KCl using a glass electrode (Peech, 1965).

3.8 Humic Acids Analysis

The extraction of HA was done using the method described by Stevenson (1994) with some modifications. Ten grams (dry weight basis) of soil samples (at natural moisture level) were placed in polyethylene centrifuge bottles, 100 mL NaOH (0.1 M) solution was added and the bottles were tightly closed with a rubber stopper (Gracia *et al.*, 1993). The samples were equilibrated at room temperature (about 25 °C) on a reciprocal mechanical shaker. The extraction (shaking) time used was 12 hours. At the end of extraction time, the side of the bottle was washed with distilled water, and the mixture centrifuged at 16000 G for 15 minutes. The dark coloured supernatant liquors containing the HA were decanted, filtered through glass-wool, and the pH of the solutions was adjusted to 1.0 with 6 M HCL. The HA were allowed to stand or equilibrate at room temperature.

The fractionation time used immediately after acidification was 12 hours. At the end of equilibration, the supernatant liquors (fulvic acids) were siphoned off from the acidified extract (Aiken *et al.*, 1985). The remainder of the suspensions was transferred to polyethylene bottles, and the HA were centrifuged off. The method described by Ahmed *et al.* (2004) was used with modifications to purify the HA. The HA were purified by being suspending them in 100 mL distilled water (excess distilled water can serve as Bronsted-Lowry acid), centrifuged at 16000 G for 10 minutes, and the supernatant decanted. The washed HA were oven dried at 50 °C to a constant weight. The yield of HA was expressed as percentage (%) of the weight of soil used.

3.9 Functional Groups of HA and Total Acidity Determination

Functional group analysis was conducted by the method described by Inbar *et al.* (1990). A 20 mg sample of HA was dissolved in 4 mL of 0.08 M NaOH and shaken for 30 minutes. The solution was titrated with 0.10 M HCl to pH 2.50 or 3.00. Carboxyl content was calculated based on the amount of acid required to titrate the suspension between pH 8 and the end point (approximately pH 3). Phenol content was calculated by assuming that 50% of the phenols dissociated at pH 10. Accordingly, the acid consumption between pH 8 and 10 should represent half of the phenol. Total acidity was calculated by summation of carboxyls and phenols.

3.10 E_4/E_6 Determination

Level of humification of HA was determined by E_4/E_6 method by spectroscopy (Stevenson, 1994). A 3 mg of HA was dissolved in 10 mL of 0.05 M $NaHCO_3$ and the sample shaken for 30 minutes. Afterwards, a 2.80 mL of the solution was transferred into a cuvette using micropipette. The E_4/E_6 determined at wavelengths of 465 and 665 nm by spectroscopy. The model of the spectrometer used was Lambda 25 UV/VIS.

3.11 Statistical Analysis

Independent T-test was used to detect significant difference between SOM, TOC and HA yield of rehabilitated and secondary forest soils. Statistical Analysis System (SAS) version 9.1 was used for the statistical analysis (SAS, 2001).

CHAPTER 4

RESULTS

4.1 pH of Rehabilitated and Secondary Forest Soils

The pH (1 M KCl) of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 3.505 and 3.599 respectively, while those of the secondary forest soil at the stated depths were 3.468 and 3.571, respectively (Table 1). On the other hand, the pH (water) of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 4.209 and 4.275 respectively, while those of the secondary forest soil at the stated depths were 4.147 and 4.238, respectively (Table 1).

The outcome of the statistical comparisons of means (Table 1) were: (i) Soil pH (1 M KCl) of rehabilitated forest at 0-15 cm and 15-30 cm – significant difference, (ii) Soil pH (1 M KCl) of secondary forest at 0-15 cm and 15-30 cm – significant difference, (iii) Soil pH (1 M KCl) of rehabilitated and secondary forests at 0-15 cm – no significant difference, (iv) Soil pH (1 M KCl) of rehabilitated and secondary forests at 15-30 cm – no significant difference, (v) Soil pH (water) of rehabilitated forest at 0-15 cm and 15-30 cm – no significant difference, (vi) Soil pH (water) of secondary forest at 0-15 cm and 15-30 cm – no significant difference, (vii) Soil pH (water) of rehabilitated and secondary forests at 0-15 cm – no significant difference, and (viii) Soil pH (water) of rehabilitated and secondary forests at 15-30 cm – no significant difference.

Table 1: pH of rehabilitated and secondary forest soils

Forest type	pH (1 M KCl)	pH (Water)
a) Rehabilitated forest		
(0-15 cm)	$3.505^{a} \pm 0.024$	$4.209^{a} \pm 0.042$
(15-30 cm)	$3.599^{b} \pm 0.025$	$4.275^{a} \pm 0.030$
b) Secondary forest		
(0-15 cm)	$3.468^{a} \pm 0.034$	$4.147^{a} \pm 0.044$
(15-30 cm)	$3.571^{b} \pm 0.018$	$4.238^{a} \pm 0.033$
c) Forest type (0-15 cm)		
Rehabilitated forest	$3.505^{a} \pm 0.024$	$4.209^{a} \pm 0.042$
Secondary forest	$3.468^{a} \pm 0.034$	$4.147^{a} \pm 0.044$
d) Forest type (15-30 cm)		
Rehabilitated forest	$3.599^{a} \pm 0.025$	$4.275^{a} \pm 0.030$
Secondary forest	$3.571^{a} \pm 0.018$	$4.238^{a} \pm 0.033$

Note: Means within column with different letters indicate significant difference between soil depths and forest types by independent t-test at $p \leq 0.05$.

4.2 Soil Texture and Bulk Densities of Rehabilitated and Secondary Forest Soils

The soil texture of the rehabilitated forest at 0-15 cm and 15-30 cm was clay loam. However, the soil texture of the secondary forest at both depths was sandy clay loam (Table 2). The bulk densities of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 1.175 g cm^{-3} and 1.230 g cm^{-3} respectively, whereas those of the secondary forest soil at the stated depths were 1.129 g cm^{-3} and 1.212 g cm^{-3}, respectively (Table 2).

The following statistical comparisons (Table 2) were made: (i) Bulk densities of rehabilitated forest soil at 0-15 cm and 15-30 cm – significant difference, (ii) Bulk densities of secondary forest soil at 0-15 cm and 15-30 cm – significant difference, (iii) Bulk densities of rehabilitated and secondary forest soils at 0-15 cm – no significant difference, and (iv) Bulk densities of rehabilitated and secondary forest soils at 15-30 cm – no significant difference.

Table 2: Soil texture and bulk densities of rehabilitated and secondary forest soils

Forest type	Texture	Bulk density (g cm^{-3})
a) Rehabilitated forest		
(0-15 cm)	Clay loam	$1.175^{a} \pm 0.012$
(15-30 cm)	Clay loam	$1.230^{b} \pm 0.011$
b) Secondary forest		
(0-15 cm)	Sandy clay loam	$1.129^{a} \pm 0.035$
(15-30 cm)	Sandy clay loam	$1.212^{b} \pm 0.008$
c) Forest type (0-15 cm)		
Rehabilitated forest		$1.175^{a} \pm 0.012$
Secondary forest		$1.129^{a} \pm 0.035$
d) Forest type (15-30 cm)		
Rehabilitated forest		$1.230^{a} \pm 0.011$
Secondary forest		$1.212^{a} \pm 0.008$

Note: Means within column with different letters indicate significant difference between soil depths and forest types by independent t-test at $p \leq 0.05$.

4.3 Soil Organic Matter (%) and Corresponding Quantities (Mg ha^{-1}) in Rehabilitated and Secondary Forest Soils

The percentages of SOM of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 6.908% and 6.869% respectively, while those of the secondary forest soil at the stated depths were 6.419% and 6.028%, respectively (Table 3). On the other hand, the SOM quantities of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 121.750 Mg ha^{-1} and 126.740 Mg ha^{-1} respectively, while those of the secondary forest soil at the stated depths were 108.700 Mg ha^{-1} and 109.590 Mg ha^{-1}, respectively (Table 3).

The statistical comparisons of means (Table 3) revealed the following: (i) Soil organic matter (%) of rehabilitated forest soil at 0-15 cm and 15-30 cm – no significant difference, (ii) Soil organic matter (%) of secondary forest soil at 0-15 cm and 15-30 cm – no significant difference, (iii) Soil organic matter (%) of rehabilitated and secondary forest soils at 0-15 cm – no significant difference, (iv) Soil organic matter (%) of rehabilitated and secondary forest soils at 15-30 cm – no significant difference, (v) Soil organic matter (Mg ha^{-1}) of rehabilitated forest soil at 0-15 cm and 15-30 cm – no significant difference, (vi) Soil organic matter (Mg ha^{-1}) of secondary forest soil at 0-15 cm and 15-30 cm – no significant difference, (vii) Soil organic matter (Mg ha^{-1}) of rehabilitated and secondary forest soils at 0-15 cm – no significant difference, and (viii) Soil organic matter (Mg ha^{-1}) of rehabilitated and secondary forest soil at 15-30 cm – no significant difference.

Table 3: Soil organic matter (%) and corresponding quantities (Mg ha^{-1}) in rehabilitated and secondary forest soils

Forest type	Soil Organic matter (%)	Organic matter quantity (Mg ha^{-1})
a) Rehabilitated forest		
(0-15 cm)	$6.908^a \pm 0.305$	$121.750^a \pm 5.374$
(15-30 cm)	$6.869^a \pm 0.335$	$126.740^a \pm 6.173$
b) Secondary forest		
(0-15 cm)	$6.419^a \pm 0.286$	$108.700^a \pm 4.843$
(15-30 cm)	$6.028^a \pm 0.315$	$109.590^a \pm 5.717$
c) Forest type (0-15 cm)		
Rehabilitated forest	$6.908^a \pm 0.305$	$121.750^a \pm 5.374$
Secondary forest	$6.419^a \pm 0.286$	$108.700^a \pm 4.843$
d) Forest type (15-30 cm)		
Rehabilitated forest	$6.869^a \pm 0.335$	$126.740^a \pm 6.173$
Secondary forest	$6.028^a \pm 0.315$	$109.590^a \pm 5.717$

Note: Means within column with different letters indicate significant difference between soil depths and forest types by independent t-test at $p \leq 0.05$.

4.4 Carbon Sequestration in Rehabilitated and Secondary Forest Soils

The total C of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 4.007% and 3.987% respectively, while those of the secondary forest soil at the stated depths were 3.723% and 3.496%, respectively (Table 4). The quantities of C (Mg ha^{-1}) of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 70.616 Mg ha^{-1} and 73.568 Mg ha^{-1} respectively, whereas those of the secondary forest soil at the stated depths were 63.048 Mg ha^{-1} and 63.558 Mg ha^{-1}, respectively (Table 4). The percentage of C in the HA of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 29.29% and 28.71% respectively, whereas those of the secondary forest soils at the stated depths were 33.06% and 28.71%, respectively (Table 4). The quantities of stable C of the rehabilitated forest soil at 0-15 cm and 15-30 cm were 6.436 Mg ha^{-1} and 5.050 Mg ha^{-1} respectively, while those of the secondary forest soil at the stated depths were 4.470 Mg ha^{-1} and 3.236 Mg ha^{-1}, respectively (Table 4).

The following statistical comparisons (Table 4) were made: (i) Total C (%) at 0-15 cm and 15-30 cm of rehabilitated forest soil – no significant difference, (ii) Total C (%) at 0-15 and 15-30 cm of secondary forest soil – no significant difference, (iii) Total C (%) at 0-15 cm of rehabilitated and secondary forest soils – no significant difference, and (iv) Total C (%) at 15-30 cm depth of rehabilitated and secondary forest soils – no significant decrease. (v) Quantities (Mg ha^{-1}) of C at 0-15 cm and 15-30 cm of rehabilitated forest soil – no significant difference, (vi) Quantities (Mg ha^{-1}) of C at 0-15 cm and 15-30 cm of secondary forest soil – no significant difference. (vii) Quantities

(Mg ha^{-1}) of C at 0-15 cm of rehabilitated and secondary forest soils – no significant difference, (viii) Quantities (Mg ha^{-1}) of C at 15-30 cm of rehabilitated and secondary forest soils – significant difference, (ix) Stable C (Mg ha^{-1}) in HA at 0-15 cm and 15-30 cm of rehabilitated forest soil – significant difference, (x) Stable C (Mg ha^{-1}) in HA at 0-15 cm and 15-30 cm of secondary forest soil – no significant difference, (xi) Stable C (Mg ha^{-1}) in HA at 0-15 cm of rehabilitated and secondary forest soils – significant difference, and (xii) Stable C (Mg ha^{-1}) in HA at 15-30 cm of rehabilitated and secondary forest soils – significant difference.

Table 4: Total carbon (%), quantity of carbon (Mg ha^{-1}), carbon (%) in HA, and stable carbon in HA in rehabilitated and secondary forest soils

Forest type	Total carbon (%)	Quantity of Carbon (Mg ha^{-1})	% Carbon in HA	Stable Carbon in HA (Mg ha^{-1})
a) Rehabilitated forest				
(0-15 cm)	$4.007^{a} \pm 0.177$	$70.616^{a} \pm 3.117$	29.29	$6.436^{a} \pm 0.483$
(15-30 cm)	$3.987^{a} \pm 0.194$	$73.568^{a} \pm 3.573$	28.71	$5.050^{b} \pm 0.423$
b) Secondary forest				
(0-15 cm)	$3.723^{a} \pm 0.166$	$63.048^{a} \pm 2.809$	33.06	$4.470^{a} \pm 0.484$
(15-30 cm)	$3.496^{a} \pm 0.182$	$63.558^{a} \pm 3.315$	28.71	$3.236^{a} \pm 0.520$
c) Forest type (0-15 cm)				
Rehabilitated forest	$3.977^{a} \pm 0.185$	$70.616^{a} \pm 3.117$	-	$6.436^{a} \pm 0.483$
Secondary forest	$3.723^{a} \pm 0.166$	$63.048^{a} \pm 2.809$	-	$4.470^{b} \pm 0.484$
d) Forest type (15-30 cm)				
Rehabilitated forest	$3.987^{a} \pm 0.194$	$73.568^{a} \pm 3.573$	-	$5.050^{a} \pm 0.423$
Secondary forest	$3.496^{a} \pm 0.182$	$63.558^{b} \pm 3.315$	-	$3.236^{b} \pm 0.520$

Note: Means within column with different letters indicate significant difference between soil depths and forest types by independent t-test at $p \leq 0.05$.

4.5 Total N and C/N Ratios of Rehabilitated and Secondary Forest Soils

The total N at 0-15 cm of the rehabilitated forest soil was 0.205%, while that at 15-30 cm was 0.140% (Table 5). In the case of the secondary forest soil, they were 0.163% and 0.098% at 0-15 cm and 15-30 cm, respectively (Table 5). The C/N ratios at 0-15 cm and 15-30 cm of the rehabilitated forest soil were 20.455 and 29.424, respectively (Table 5). The C/N ratios at 0-15 cm and 15-30 cm of the secondary forest soil were 25.229 and 38.729, respectively (Table 5).

The following statistical comparisons (Table 5) were made: (i) Total N at 0-15 cm and 15-30 cm of rehabilitated forest soil– significant difference, (ii) Total N at 0-15 cm and 15-30 cm of secondary forest soil– significant difference, (iii) Total N at 0-15 cm of rehabilitated and secondary forest soils– no significant difference, (iv) Total N at 15-30 cm of rehabilitated and secondary forest soil– significant difference, (v) C/N ratios at 0-15 cm and 15-30 cm of rehabilitated forest soil – significant difference, (vi) C/N ratios at 0-15 cm and 15-30 cm of secondary forest soil – significant difference, (vii) C/N ratios at 0-15 cm of rehabilitated and secondary forest soils – no significant difference, and (viii) C/N ratios at 15-30 cm of rehabilitated and secondary forest soils – significant difference.

Table 5: Total N and C/N ratios of rehabilitated and secondary forest soils

Forest type	Total N (%)	C/N ratio
a) Rehabilitated forest		
(0-15 cm)	$0.205^{a} \pm 0.014$	$20.455^{a} \pm 1.216$
(15-30 cm)	$0.140^{b} \pm 0.007$	$29.424^{b} \pm 1.914$
b) Secondary forest		
(0-15 cm)	$0.163^{a} \pm 0.015$	$25.229^{a} \pm 2.250$
(15-30 cm)	$0.098^{b} \pm 0.009$	$38.729^{b} \pm 2.987$
c) Forest type (0-15 cm)		
Rehabilitated forest	$0.205^{a} \pm 0.014$	$20.455^{a} \pm 1.216$
Secondary forest	$0.163^{a} \pm 0.015$	$25.229^{a} \pm 2.250$
d) Forest type (15-30 cm)		
Rehabilitated forest	$0.140^{a} \pm 0.007$	$29.424^{a} \pm 1.914$
Secondary forest	$0.098^{b} \pm 0.009$	$38.729^{b} \pm 2.987$

Note: Means within column with different letters indicate significant difference between soil depths and forest types by independent t-test at $p \leq 0.05$.

4.6 Humic Acids Yields (%) and Corresponding Quantities in Rehabilitated and Secondary Forest Soils

The yields of HA at 0-15 cm and 15-30 cm of the rehabilitated forest soil were 1.247% and 0.953% respectively, while those of the secondary forest soil at the stated depths were 0.787% and 0.620%, respectively (Table 6). The quantities of HA at 0-15 cm and 15-30 cm in the rehabilitated forest soil were 21.973 Mg ha^{-1} and 17.589 Mg ha^{-1} respectively, while those in the secondary forest soil at the stated depths were 13.322 Mg ha^{-1} and 11.272 Mg ha^{-1}, respectively (Table 6).

The following statistical comparisons (Table 6) were made: (i) Humic acids yields at 0-15 cm and 15-30 cm of rehabilitated forest soil– significant difference, (ii) Humic acids yields at 0-15 cm and 15-30 cm of secondary forest soil – no significant difference, (iii) Humic acids yields at 0-15 cm of rehabilitated and secondary forest soils – significant difference, (iv) Humic acids yields at 15-30 cm of rehabilitated and secondary forest soils – significant difference, (v) Quantities (Mg ha^{-1}) of HA at 0-15 cm and 15-30 cm of rehabilitated forest soil – no significant difference, (vi) Quantities (Mg ha^{-1}) of HA at 0-15 cm and 15-30 cm of secondary forest soil – no significant difference, (vii) Quantities (Mg ha^{-1}) of HA at 0-15 cm of rehabilitated and secondary forest soils – significant difference, (viii) Quantities (Mg ha^{-1}) of HA at 15-30 cm of rehabilitated and secondary forest soils –significant difference.

Table 6: Humic acids yields (%) and corresponding quantities (Mg ha^{-1}) in rehabilitated and secondary forest soils

Forest type	HA yields (%)	Quantities of HA (Mg ha^{-1})
a) Rehabilitated forest		
(0-15 cm)	$1.247^{a} \pm 0.094$	$21.973^{a} \pm 1.649$
(15-30 cm)	$0.953^{b} \pm 0.080$	$17.589^{a} \pm 1.472$
b) Secondary forest		
(0-15 cm)	$0.787^{a} \pm 0.089$	$13.322^{a} \pm 1.514$
(15-30 cm)	$0.620^{a} \pm 0.100$	$11.272^{a} \pm 1.811$
c) Forest type (0-15 cm)		
Rehabilitated forest	$1.247^{a} \pm 0.094$	$21.973^{a} \pm 1.649$
Secondary forest	$0.787^{b} \pm 0.089$	$13.322^{b} \pm 1.514$
d) Forest type (15-30 cm)		
Rehabilitated forest	$0.953^{a} \pm 0.080$	$17.589^{a} \pm 1.472$
Secondary forest	$0.620^{b} \pm 0.010$	$11.272^{b} \pm 1.811$

Note: Means within column with different letters indicate significant difference between soil depths and forest types by independent t-test at $p \leq 0.05$.

4.7 E_4/E_6 Ratios, Carboxylic-COOH, Phenolic-OH and Total Acidity of Rehabilitated and Secondary Forest Soils

The E_4/E_6 ratios at 0-15 cm and 15-30 cm of the rehabilitated forest soil were 6.382 and 6.599 respectively, while those of the secondary forest soil at the stated depths were 6.144 and 6.747, respectively (Table 7). The carboxylic-COOH contents at 0-15 cm and 15-30 cm of the rehabilitated forest soil were 363 and 500 respectively, while those of the secondary forest soil at the stated depths were 600 and 588, respectively (Table 7). The phenolic-OH contents at 0-15 cm and 15-30 cm of the rehabilitated forest soil were 300 and 300 respectively, while those that of secondary forest soil at the stated depths were 550 and 550, respectively (Table 7). The total acidity at 0-15 cm and 15-30 cm depths of the rehabilitated forest soil were 663 and 800 respectively, while those of the secondary forest soil at the stated depths were 1150 and 1137, respectively (Table 7).

Table 7: E_4/E_6 ratios, carboxylic-COOH, phenolic-OH and total acidity of rehabilitated and secondary forest soils

Forest type	E_4/E_6 ratios	Range	Carboxylic -COOH	Range	Phenolic -OH	Range	Total acidity	Range
a) Rehabilitated forest								
(0-15 cm)	6.382	3-5*	363	150-570**	300	210-570**	663	560-890**
(15-30 cm)	6.599		500		300		800	
b) Secondary forest								
(0-15 cm)	6.144		600		550		1150	
(15-30 cm)	6.747		588		550		1137	

* Tan (2003)
** Schnitzer (1972)

CHAPTER 5

DISCUSSION

5.1 pH of Rehabilitated and Secondary Forest Soils

The soil pH (1 M KCl) and pH (water) values of rehabilitated and secondary forests regardless of depth (Table 1) were typical of Ultisols (Baillie, 1971). The fact that the pH (1 M KCl) values at 15-30 cm were significantly higher than those of 0-15 cm of the two forests (Table 1) could be attributed to leaching of basic cations from 0-15 cm to 15-30 cm. This observation was not true for pH (water) which may be because the KCl used gives more acidity of the soils as a result of its effectiveness in displacing hydrogen ions. Lack of significant difference between the soil pH of the rehabilitated and secondary forests regardless of soil depth suggests that the forest type had no significant effect on the soil pH.

5.2 Soil Texture and Bulk Densities of Rehabilitated and Secondary Forest Soils

The soil texture of rehabilitated and secondary forests were clay loam and sandy clay loam, respectively (Table 2) suggesting that the soils of the two forests belong to Nyalau Series, a series which is characterized by sandy loam in top soil and sandy clay loam in subsoil (Baillie, 1971; Azani *et al.*, 2001). The soil bulk densities at 0-15 cm and 15-30 cm of the two forests were found to be within the range reported by Lal and Kimble (2001). Even though the soil texture of both forests were different, the soil bulk densities of these forests significantly increased down the soil profile. This observation also suggests that regardless of forest type, the soil gets compacted down the soil profile. Perhaps some of the clay may have been eluviated vertically and deposited in the subsoil. The absence of significant difference in the soil bulk densities of the rehabilitated and secondary forests irrespective of depth (Table 2) could be partly associated with no significant difference in the SOM of the two forests at both 0-15 cm and 15-30 cm.

5.3 Soil Organic Matter (%) and Corresponding Quantities (Mg ha^{-1}) in Rehabilitated and Secondary Forest Soils

The absence of significant difference in SOM (%) and corresponding quantities of SOM (Mg ha^{-1}) of the rehabilitated and secondary forests indicate that SOM in the rehabilitated forest has reached equilibrium compared with the level in the secondary forest. The quantities of SOM (Mg ha^{-1}) of the rehabilitated and secondary forests were relatively similar to the quantities reported by other authors (Anderson, 1991; Folster and Khanna, 1997; Neary *et al.*, 1999). Similar SOM values of both forests also demonstrate that probably the inevitable variations in vegetation had no significant effect on this variable.

5.4 Carbon Sequestration in Rehabilitated and Secondary Forest Soils

The similarity of the percentages of soil total C sequestered by the rehabilitated and secondary forests irrespective of soil depth (Table 4) is understandable because of the absence of significant difference in percent SOM at 0-15 cm and 15-30 cm of both forests soils. This finding is partly consistent with the observation that SOM is a major source and sink of atmospheric C in the global C cycle (Brady and Weil, 2002). Since the C in HA are more stable (Milori *et al.*, 2002), it is more realistic to quantify the amount of C sequestered in forest soils. The quantities (Mg ha^{-1}) of C were consistent with the percentage of total C of both forest soils except for C at 15-30 cm. This could be due to the way C is reported, that is C (%) or amount of C per unit of soil volume (Bauhus *et al.*, 2002).

5.5 Total N and C/N ratios of Rehabilitated and Secondary Forest Soils

The soil total N regardless of depth and type of forest were typical of Ultisol (Baillie, 1971). The soil total N of the rehabilitated and secondary forests significantly decreased down the soil profile and this observation was consistent with the general observation that soil N decreases with increasing soil depth (Baillie, 1971) because of decrease in organic N. The significant accumulation of N at 15-30 cm in the rehabilitated forest soil compared to that of the secondary forest could be attributed to the difference in soil texture. The soil texture of rehabilitated forest was clay loam while that of the secondary forest was sandy clay loam so it was possible that the N leached from 0-15 cm got accumulated in 15-30 cm of the rehabilitated forest while in the case of secondary forest, it may have been leached out of the soil profile because of the nature of the soil texture.

The increase in C/N ratio with increasing soil depth in both forests suggests that there was more humification at 0-15 cm than 15-30 cm. Although the degree of humification at 0-15 cm was observed to be statistically similar for both forests, the significant difference observed in the C/N ratios of the rehabilitated and secondary forest soils at 15-30 cm may not necessarily suggest differences in humification levels. The lower C/N ratio of the rehabilitated forest compared with that of the secondary forest could be due to the significant accumulation of N at 15-30 cm as discussed previously.

5.6 Humic Acids Yield (%) and Corresponding Quantities in Rehabilitated and Secondary Forest Soils

The HA yields and corresponding quantities of the rehabilitated and secondary forests irrespective of depths were significantly different (Table 6) probably because of lack of N for efficient conversion of biomass C into humus C in the secondary forest soils which was much required by the humification of biomass returned to soil (through litter and roots) (Lal, 2001). Humic acids yields (%) and corresponding quantities at 0-15 cm and 15-30 cm of secondary forest soils were not significantly different because the secondary forest soils had coarser soil texture such that organic residues on the surface layer could be incorporated into the subsurface horizon, and same amount of OM humified.

5.7 E_4/E_6 Ratios, Carboxylic-COOH, Phenolic-OH and Total Acidity of Rehabilitated and Secondary Forest Soils

Except for the total acidity of the secondary forest, the E_4/E_6, carboxylic-COOH, phenolic-OH, and total acidity of rehabilitated and secondary forest soils were found to be consistent with the ranges reported else where (Tan, 2003; Schnitzer, 1972). Since the E_4/E_6 values of the soils of both forests were relatively close to 7, they indicate prominence of aliphatic compounds of HA or relatively low molecular weights (Tan, 2003). Higher carboxylic group in HA of the secondary forest soils contributed to higher acidity, probably due to inclusion of amides and esters in the analysis by spectroscopy (Schnitzer and Preston, 1986).

CHAPTER 6

CONCLUSION

The SOM and amount of unstable C sequestered in the rehabilitated and secondary forest soils were similar but the stable C sequestered by HA was significantly higher in the rehabilitated forest soil compared to the secondary forest soil irrespective of depth. Hence, the finding suggest that the stability of C in HA realistically reflects C sequestration. This is partly because the quantity of stable C depends on the amount of HA.

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APPENDICES

APPENDIX A

Soil bulk densities (g cm^{-3}) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forests

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	1.205	1.216	1.198	1.195
2	1.239	1.246	0.996	1.237
3	1.088	1.347	1.269	1.251
4	1.208	1.220	1.205	1.210
5	1.107	1.172	1.164	1.195
6	1.207	1.230	1.219	1.218
7	1.221	1.225	1.182	1.179
8	1.122	1.270	1.159	1.216
9	1.186	1.207	1.183	1.253
10	1.180	1.239	1.134	1.190
11	1.159	1.247	0.998	1.173
12	1.108	1.188	0.845	1.224
13	1.184	1.230	-	-
14	1.186	1.203	-	-
15	1.227	1.210	-	-

APPENDIX B

Soil pH (KCl) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forests

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	3.63	3.72	3.28	3.57
2	3.59	3.67	3.47	3.61
3	3.47	3.83	3.74	3.57
4	3.46	3.46	3.63	3.65
5	3.36	3.48	3.43	3.62
6	3.37	3.47	3.29	3.43
7	3.34	3.53	3.46	3.57
8	3.51	3.57	3.41	3.53
9	3.58	3.66	3.47	3.56
10	3.59	3.60	3.51	3.60
11	3.51	3.59	3.38	3.55
12	3.60	3.61	3.54	3.61
13	3.56	3.59	3.29	3.42
14	3.54	3.62	3.55	3.67
15	3.47	3.59	3.57	3.61

APPENDIX C

Soil pH (water) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forests

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	4.41	4.42	3.95	4.15
2	4.23	4.29	4.07	4.24
3	4.09	4.47	4.48	4.15
4	4.10	4.15	4.11	4.17
5	3.96	4.12	4.39	4.31
6	4.02	4.07	3.90	4.08
7	4.02	4.16	4.11	4.27
8	4.18	4.25	4.16	4.23
9	4.39	4.37	4.08	4.21
10	4.32	4.31	4.01	4.14
11	4.10	4.23	4.10	4.20
12	4.45	4.41	4.19	4.30
13	4.36	4.28	4.00	4.15
14	4.36	4.35	4.25	4.36
15	4.14	4.25	4.40	4.61

APPENDIX D

Examples of how total organic carbon, organic matter and humic acids were quantified were as follows:

1) Rehabilitated forest (0-15 cm)

a) Bulk density = 1.175 g cm^{-3} = 1175 Kg m^{-3}

b) Weight of soil = 1175 x 10000 x 0.15

= 1762500 Kg ha^{-1} soil

c) Weight of OM = 0.069 x 1762500 Kg ha^{-1} OM

= 121612.5 Kg ha^{-1} OM

= 121.613 Mg ha^{-1} OM

d) Weight of C = 0.040 x 1762500 Kg ha^{-1} C

= 70500 Kg ha^{-1} C

= 70.500 Mg ha^{-1} C

e) Humic acids yield = 0.012 x 1762500 Kg ha^{-1} HA

= 21150 Kg ha^{-1} C

= 21.150 Mg ha^{-1} C

f) Stable carbon in humic acids = 21.150 x 0.293 Mg ha^{-1} C

= 6.197 Mg ha^{-1} C

2) Rehabilitated forest (15-30 cm)

a) Bulk density = 1.230 g cm^{-3} = 1230 Kg m^{-3}

b) Weight of soil = 1230 x 10000 x 0.15

= 1845000 Kg ha^{-1} soil

c) Weight of OM = 0.069 x 1845000 Kg ha^{-1} OM

= 127305 Kg ha^{-1} OM

= 127.305 Mg ha^{-1} OM

d) Weight of C = 0.040 x 1845000 Kg ha^{-1} C

= 73800 Kg ha^{-1} C

= 73.800 Mg ha^{-1} C

e) Humic acids yield = 0.010 x 1845000 Kg ha^{-1} HA

= 18450 Kg ha^{-1} HA

= 18.450 Mg ha^{-1} HA

f) Stable carbon in humic acids = 18.450 x 0.287 Mg ha^{-1} C

= 5.295 Mg ha^{-1} C

3) Secondary forest (0-15 cm)

a) Bulk density = 1.129 g cm^{-3} = 1129 Kg m^{-3}

b) Weight of soil = 1129 x 10000 x 0.15

= 1693500 Kg ha^{-1} soil

c) Weight of OM = 0.064 x 1693500 Kg ha^{-1} OM

= 108384 Kg ha^{-1} OM

= 108.384 Mg ha^{-1} OM

d) Weight of C = 0.037 x 1693500 Kg ha^{-1} C

= 62659.5 Kg ha^{-1} C

= 62.660 Mg ha^{-1} C

e) Humic acids yield = 0.008 x 1693500 Kg ha^{-1} HA

= 13548 Kg ha^{-1} HA

= 13.548 Mg ha^{-1} HA

f) Stable carbon in humic acids = 13.548 x 0.331 Mg ha^{-1} C

= 4.484 Mg ha^{-1} C

4) Secondary forest (15-30 cm)

a) Bulk density = 1.212 g cm^{-3} = 1212 Kg m^{-3}

b) Weight of soil = 1212 x 10000 x 0.15 Kg ha^{-1} soil

= 1818000 Kg ha^{-1} soil

c) Weight of OM = 0.060 x 1818000 Kg ha^{-1} OM

= 109080 Kg ha^{-1} OM

= 109.08 Mg ha^{-1} OM

d) Weight of C = 0.035 x 1818000 Kg ha^{-1} C

= 63630 Kg ha^{-1} C

= 63.630 Mg ha^{-1} C

e) Humic acids yield = 0.006 x 1818000 Kg ha^{-1} HA

= 10908 Kg ha^{-1} HA

= 10.908 Mg ha^{-1} HA

f) Stable carbon in humic acids = 10.908 x 0.287 Mg ha^{-1} C

= 3.131 Mg ha^{-1} C

APPENDIX E

Soil texture at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forests

Forest type	Sand (%)	Silt (%)	Clay (%)
a) Rehabilitated forest			
(0-15 cm)	38.6	34.6	26.8
(15-30 cm)	40.3	29.7	30.0
b) Secondary forest			
(0-15 cm)	47.0	29.0	24.0
(15-30 cm)	48.1	25.3	26.6

APPENDIX F

Soil organic matter (%) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forests

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	5.420	6.209	9.320	8.080
2	7.020	8.470	7.550	8.710
3	8.040	5.510	6.720	6.990
4	7.340	6.910	7.630	7.160
5	8.660	7.910	5.370	5.000
6	7.660	6.910	6.300	5.980
7	7.130	6.960	6.500	6.030
8	6.950	7.180	6.110	5.740
9	8.920	8.520	5.510	5.320
10	6.040	8.260	6.720	5.500
11	6.840	5.300	5.570	4.490
12	5.080	7.100	5.850	4.800
13	5.480	4.920	4.850	5.130
14	5.610	4.690	5.890	6.190
15	7.430	8.190	6.390	5.300

APPENDIX G

Soil organic matter (Mg ha^{-1}) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forests

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	95.528	114.556	157.834	146.894
2	123.728	156.272	127.859	158.348
3	141.705	101.660	113.803	127.078
4	129.368	127.490	129.214	130.169
5	152.633	145.940	90.941	90.900
6	135.008	127.490	106.691	108.716
7	125.666	128.412	110.078	109.625
8	122.494	132.471	103.473	104.353
9	157.215	157.194	93.312	96.718
10	106.455	152.397	113.803	99.990
11	120.555	97.785	94.328	81.628
12	89.535	130.995	99.070	87.264
13	96.585	90.774	82.135	93.263
14	98.876	86.531	99.747	112.534
15	130.954	151.106	108.215	96.354

APPENDIX H

Total carbon (%) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	3.144	3.648	5.406	4.687
2	4.072	4.913	4.379	5.050
3	4.663	3.196	3.898	4.054
4	4.257	4.008	4.425	4.153
5	5.023	4.588	3.115	2.900
6	4.443	4.008	3.654	3.468
7	4.135	4.037	3.770	3.497
8	4.031	4.164	3.544	3.329
9	5.174	4.942	3.196	3.086
10	3.503	4.791	3.898	3.190
11	3.967	3.074	3.231	2.604
12	2.946	4.118	3.393	2.784
13	3.178	2.854	2.813	2.975
14	3.254	2.720	3.416	3.590
15	4.309	4.750	3.706	3.074

APPENDIX I

Quantity of carbon (Mg ha^{-1}) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	55.413	67.306	91.551	85.210
2	71.769	90.645	74.158	91.809
3	82.185	58.966	66.013	73.702
4	75.030	73.948	74.937	75.502
5	88.530	84.649	52.753	52.722
6	78.308	73.948	61.880	63.048
7	72.879	74.483	63.845	63.575
8	71.046	76.826	60.018	60.521
9	91.192	91.180	54.124	56.103
10	61.740	88.394	66.013	57.994
11	69.918	56.715	54.717	47.341
12	51.923	75.997	57.460	50.613
13	56.012	52.656	47.638	54.086
14	57.352	50.184	57.850	65.266
15	75.946	87.638	62.761	55.885

APPENDIX J

Stable carbon in HA (Mg ha^{-1}) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	6.195	4.767	10.078	6.785
2	4.646	5.827	7.278	6.263
3	7.227	2.648	4.479	6.785
4	8.260	6.886	5.039	5.219
5	7.227	4.238	2.780	1.566
6	8.260	6.886	3.919	2.088
7	7.227	5.827	3.359	2.610
8	6.711	6.356	3.919	2.610
9	9.292	6.356	3.359	2.088
10	9.292	6.356	3.359	2.610
11	4.130	1.589	3.919	2.088
12	4.130	3.708	3.919	3.132
13	4.646	3.708	2.239	2.610
14	4.130	4.238	3.919	1.566
15	5.162	6.356	4.479	0.522

APPENDIX K

Total N (%) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	0.140	0.210	0.280	0.070
2	0.280	0.140	0.210	0.140
3	0.210	0.070	0.140	0.140
4	0.280	0.140	0.140	0.140
5	0.210	0.140	0.140	0.070
6	0.210	0.140	0.210	0.140
7	0.210	0.140	0.210	0.140
8	0.280	0.140	0.140	0.140
9	0.210	0.140	0.140	0.070
10	0.210	0.140	0.140	0.070
11	0.280	0.140	0.070	0.070
12	0.140	0.140	0.210	0.070
13	0.140	0.140	0.070	0.070
14	0.140	0.140	0.210	0.070
15	0.140	0.140	0.140	0.070

APPENDIX L

Carbon/nitrogen ratios at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	22.457	17.371	19.307	66.957
2	14.543	35.093	20.852	36.071
3	22.205	45.657	27.843	28.957
4	15.204	28.629	31.607	29.664
5	23.919	32.771	22.250	41.429
6	21.157	28.629	17.400	24.771
7	19.690	28.836	17.952	24.979
8	14.396	29.743	25.314	23.779
9	24.638	35.300	22.829	44.086
10	16.681	34.221	27.843	45.571
11	14.168	21.957	46.157	37.200
12	21.043	29.414	16.157	39.771
13	22.700	20.386	40.186	42.500
14	23.243	19.429	16.267	51.286
15	30.779	33.929	26.471	43.914

APPENDIX M

Humic acids yields (%) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	1.200	0.900	1.800	1.300
2	0.900	1.100	1.300	1.200
3	1.400	0.500	0.800	1.300
4	1.600	1.300	0.900	1.000
5	1.400	0.800	0.500	0.300
6	1.600	1.300	0.700	0.400
7	1.400	1.100	0.600	0.500
8	1.300	1.200	0.700	0.500
9	1.800	1.200	0.600	0.400
10	1.800	1.200	0.600	0.500
11	0.800	0.300	0.700	0.400
12	0.800	0.700	0.700	0.600
13	0.900	0.700	0.400	0.500
14	0.800	0.800	0.700	0.300
15	1.000	1.200	0.800	0.100

APPENDIX N

Quantities of humic acids (Mg ha^{-1}) at 0-15 cm and 15-30 cm depths of rehabilitated and secondary forest soils

Replicates	Rehabilitated forest (0-15 cm)	Rehabilitated forest (15-30 cm)	Secondary forest (0-15 cm)	Secondary forest (15-30 cm)
1	21.150	16.605	30.483	23.634
2	15.863	20.295	22.016	21.816
3	24.675	9.225	13.548	23.634
4	28.200	23.985	15.242	18.180
5	24.675	14.760	8.468	5.454
6	28.200	23.985	11.855	7.272
7	24.675	20.295	10.161	9.090
8	22.913	22.140	11.855	9.090
9	31.725	22.140	10.161	7.272
10	31.725	22.140	10.161	9.090
11	14.100	5.535	11.855	7.272
12	14.100	12.915	11.855	10.908
13	15.863	12.915	6.774	9.090
14	14.100	14.760	11.855	5.454
15	17.625	22.140	13.548	1.818

PUBLICATION OF THE PROJECT UNDERTAKING

This is to certify that I have no objection to publish the project entitled "**Organic Matter, Carbon, and Humic Acids in Rehabilitated and Secondary Forest Soils**" by the supervisor in a joint authorship. However, it has to be evaluated by the Faculty of Agriculture and Food Sciences, Universiti Putra Malaysia Bintulu Campus and published in form approved by the Faculty.

Lee Yit Leng

Date: 14/4/08