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SOIL CARBON DYNAMICS OF OIL PALM PLANTATIONS OF DIFFERENT AGES

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By

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Soil Carbon (C) studies in oil palm cultivation have generated much interest due to its large-scale planting and its large biomass production that could contribute to soil C sequestration. This three-part research explored the spatial and vertical distributions of Soil Organic Carbon (SOC), and its labile fraction in oil palm cultivation. In part-1, the spatial variability of SOC across five palm age groups, *i.e.* 1, 5, 10, 17 and 27 Year After Planting (YAP), was characterized. A total of 60 georeferenced topsoil samples (0-20 cm) were obtained for each operational zone: Weeded Circle (WC), Frond Heap (FH) and Avenue (AVE) in a cluster of four palms. Spatial characterization was done using classical and geo-spatial statistics. Results showed that all operational zones of the five palm age groups exhibited a definable spatial structure with moderate to strong spatial dependence, described by either spherical or exponential models. Operational zones of 5 and 27 YAP exhibited a shorter and a longer effective range, respectively, than the other palm age groups, indicating the distance between sampling locations with heterogeneous characteristics are closer for young oil palm plantations than mature oil palm plantations. Part-2 aimed at quantifying SOC dynamics of oil palm cultivation across palm ages, operational zones and soil depths (0-20, 20-40 and 40-60 cm), including a replanting area and secondary forest, each with four sampling clusters. Results showed that SOC contents and stocks of the study sites decreased down the soil profiles. The SOC contents and stocks of FH were the highest, followed by WC and AVE at 0-20 cm depth. Considering the percentage area of each operational zone, AVE possessed the highest SOC stock, followed by FH and WC. This indicates that percentage area of operational zones would affect the SOC stock of the oil palm plantation. The SOC stocks of all study sites were not statistically different at 0-20 and 20-40 cm, except for 17 YAP, which showed the lowest SOC stock. This was attributed to lower clay content and higher sand content, suggesting the essential role of soil texture in the accumulation of SOC stocks in oil palm plantations. Part-3 quantified the Labile C (C_L) using 333 mM potassium permanganate ($KMnO_4$) oxidation method, and established the Carbon Management Index (CMI) for oil palm cultivation. Both C_L and SOC content shown similar trends at different soil depths and operational zones. At

0-20 cm, the C_L contents and CMI values of 1, 5, 10 YAP and replanting were significantly lower than those of secondary forest, 17 and 27 YAP. Conversely, the CMI values increased from 1 to 27 YAP, indicating the increment of palm age and supply of organic materials could improve the CMI values. The CMI values of 10 and 5 YAP were statistically different from secondary forest at 20-40 and 40-60 cm, respectively. Overall, this research demonstrated an increase in SOC stocks with greater length of time under oil palm cultivation, and that spatial variability assessment will provide more precise quantification of SOC stocks by considering the operational zones in oil palm cultivation.

Abstrak tesis yang telah dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

DINAMIK KARBON TANAH DI LADANG KELAPA SAWIT YANG BERLAINAN UMUR

Oleh

LAW MEI CHING

Mei 2016

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Kajian karbon tanah di ladang kelapa sawit semakin banyak diberi perhatian disebabkan kelapa sawit telah ditanam secara berleluasa di Malaysia serta boleh menghasilkan biojisim yang tinggi untuk sekuestrasi karbon. Kajian ini telah dijalankan dalam 3 bahagian, dimana taburan ruang dan menegak karbon organik tanah, dan fraksi karbon labil tanah di dalam ladang kelapa sawit. Dalam bahagian pertama kajian ini, variasi ruang karbon organik tanah di antara ladang kelapa sawit yang berlainan umur, iaitu: 1, 5, 10, 17 dan 27 tahun selepas ditanam, telah ditentukan. Sejumlah 60 sampel tanah telah diambil pada kedalaman 0-20 cm daripada setiap zon operasi, iaitu bulatan dibuang rumpai, longgokan pelepah, dan zon lorong, di dalam kluster yang terdiri daripada empat pokok sawit. Lokasi pensampelan tanah telah ditanda dengan sistem kedudukan sejagat. Ciri-ciri variasi ruang telah ditentukan dengan statistik klasik dan geostatistik. Hasil kajian ini menunjukkan bahawa ketiga-tiga zon operasi bagi lima kumpulan umur kelapa sawit telah menunjukkan pemboleh ubah struktur ruang yang jelas dan mempunyai pergantungan ruang yang serdehana hingga kuat, dicirikan samada dengan model sfera atau eksponensial. Pokok sawit pada umur 5 dan 27 tahun selepas ditanam masing-masing telah menunjukkan jarak keberkesanan yang lebih pendek dan lebih panjang, jika dibandingkan dengan zon operasi daripada kumpulan umur kelapa sawit yang lain. Ini telah menunjukkan bahawan jarak antara lokasi sampel yang berciri heterogen pada pokok sawit yang muda adalah lebih dekat berbanding dengan pokok sawit yang lebih matang. Bahagian kedua dalam kajian ini adalah bertujuan untuk menentukan karbon organik tanah di dalam ladang kelapa sawit yang berlainan umur, zon operasi, serta kedalaman tanah (0-20, 20-40 dan 40-60 cm). Kawasan tanam semula serta hutan sekunder juga turut diambilkira dalam kajian ini. Sebanyak empat kluster sampel telah dipilih bagi setiap plot. Keputusan ekperimen ini menunjukkan bahawa apabila kedalaman tanah semakin meningkat, maka semakin berkurangan kandungan karbon organik tanah. Kandungan dan stok karbon organik tanah adalah paling tinggi di zon longgokan pelepah sawit, diikuti oleh zon bulatan dibuang rumpai, dan zon lorong pada kedalaman tanah 0-20 cm. Jika diambil kira jumlah peratusan keluasan tanah zon-zon operasi ini,

maka zon lorong mengandungi stok karbon organik tanah yang paling tinggi, diikuti oleh zon longgokan pelepah sawit, dan kemudian zon bulatan dibuang rumpai. Penelitian ini telah menunjukkan bahawa peratusan kawasan zon-zon operasi boleh mempengaruhi keputusan jumlah stok karbon organik tanah di ladang kelapa sawit. Stok karbon organik tanah pada semua plot kajian dengan pengecualian plot kelapa sawit 17 tahun selepas tanam, tidak menunjukkan sebarang perbezaan yang nyata secara statistik pada kedalaman tanah 0-20 dan 20-40 cm. Pada plot kelapa sawit 17 tahun selepas ditanam telah menunjukkan karbon organik tanah yang paling rendah pada semua kedalaman tanah disebabkan tekstur tanah plot tersebut mengandungi kandungan tanah liat yang rendah serta kandungan pasir yang tinggi. Jadi, bacaan dari eksperimen ini telah menandakan bahawa tekstur tanah boleh menjadi faktor yang penting dalam menentukan kandungan karbon organik tanah di dalam ladang kelapa sawit. Bahagian ketiga kajian ini adalah untuk menentukan karbon labil tanah dengan menggunakan kaedah pengoksidaan kalium permanganat ($KMnO_4$) pada 333 mM, dan selanjutnya membangunkan indeks pengurusan karbon. Dalam ujikaji ini, trend yang sama boleh diperihatikan di antara karbon labil serta karbon organik tanah pada kedalaman tanah dan zon operasi yang berlaninan. Pada kedalaman 0-20 cm, karbon labil serta indeks pengurusan karbon pada 1, 5, 10 tahun selepas ditanam adalah lebih rendah jika dibandingkan dengan hutan sekunder, 17 , dan 27 tahun selepas ditanam. Selain daripada itu, indeks pengurusan karbon juga meningkat daripada 1 sehingga 27 tahun selepas ditanam. Ini telah menunjukkan bahawa pengumpulan bahan organik yang semakin bertambah apabila umur pokok kelapa sawit semakin meningkat. Justerunya, indeks pengurusan karbon itu juga tetap meningkat. Di samping itu, indeks pengurusan karbon bagi 10 dan 5 tahun selepas ditanam masing-masing juga menunjukkan perbezaan yang nyata secara statistik dengan hutan sekunder pada kedalaman 20-40 dan 40-60 cm. Secara keseluruhanya, kajian ini telah mendemonstrasikan peningkatan stok karbon organik tanah adalah berkait rapat dengan umur kelapa sawit, serta penentuan variasi ruang karbon organik tanah dengan mengambilkira keluasan tanah zon-zon operasi akan meningkatkan ketepatan dalam penentuan stok karbon organik tanah di dalam ladang kelapa sawit.

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I certify that a Thesis Examination Committee has met on 20 May 2016 to conduct the final examination of Law Mei Ching on her thesis entitled "Soil Carbon Dynamics of Oil Palm Plantations of Different Ages" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
AVE	Avenue
BD	Bulk density
CC	Cover crop
C_L	Labile carbon
C_{NL}	Non-labile carbon
C_T	Total cabron
CEC	Cation exchange capasity
CEFIC	*Conseil Européen des Fédérations de l'Industrie Chimique* (European Chemical Industry Council)
CH_4	Methane
CMI	Carbon Management Index
CV	Coefficient of variation
dGPS	differential Global Positioning System
EC	Electrical conductivity
EFB	Empty fruit bunches
ER	Effective range
ESD	Extreme Studentized Deviate
FFB	Fresh fruit bunches
FH	Frond heap
GHG	Greenhouse gas
GLM	Generalized linear model
LULCC	Land use and land cover change
ME	Mean error
MSE	Mean square error
NGOs	Non-Governmental Organizations
NPP	Net primary productivity
p	Probability
Pg	Petagram
POXC	Permanganate oxidizable carbon
PSD	Particle size distribution
RSPO	Roundtable on Sustainable Palm Oil
SD	Standard deviation
SMSE	Standardized Mean Squared Error
SNK	Student-Newman-Keuls
SOC	Soil organic carbon
SOM	Soil organic matter
TH	Trunk heap
UNFCCC	United Nations Framework Convention on Climate Change

USDA	United States Department of Agriculture
WC	Weeded circle
YAP	Years after planting

CHAPTER 1

INTRODUCTION

1.1 Background

Oil palm (*Elaeis guineensis* Jacq.) is native to West Africa and is now mostly planted in large-scale plantations throughout the world's tropical regions. The Malaysian and Indonesian palm oil industries contributed about 86.19% of the world production of palm oil and 22.94% of the world's oils and fats production in 2010 (Ramli Abdullah, 2011). The increase in oil palm areas in Malaysia is either through the planting of fallow land or conversion from other tree crops, such as rubber, cocoa or coconut (Basiron, 2007). However, this Land Use and Land Cover Change (LULCC) has received a fair amount of attention from environmentalists and Non-Governmental Organizations (NGOs) because LULCC leads to Greenhouse Gas (GHG) emissions from vegetation and soils (Basiron, 2007). Pressure from the environmentalists and NGOs has compelled the Roundtable on Sustainable Palm Oil (RSPO) to set up the criteria for GHG emissions. Several studies have also been carried out using different approaches to assess the effects of oil palm cultivation on the exchanges of carbon dioxide (CO_2) and other GHG (Henson, 2009; Germer and Sauerborn, 2008; Melling *et al.*, 2005a, 2005b). Nevertheless, Carbon (C) sequestered in soils, particularly mineral soils, was not given adequate attention. Brinkmann Consultancy (2009) reported that sequestration and life cycle assessment of oil palm has not considered the Soil Organic C (SOC) of inland mineral soils in the calculation of the net C balance of oil palm cultivated land. This knowledge gap arose because there was insufficient long term data to demonstrate any major changes of SOC, and thus, the assumption of no change of SOC in mineral soils was made.

The area planted with oil palm in Malaysia reached 5.39 million ha in 2014, an increase of 3.1% compared to the 5.23 million ha recorded the previous year (Choo, 2015). With such a large area of oil palm plantations, the Malaysian palm oil industry was estimated to have generated 44.85 million t (dry weight) of oil palm biomass in 2014 (Appendix 1) (Loh, in press). These oil palm biomass included biomass from plantations, *i.e.* oil palm trunks, fronds; and biomass from palm oil mills, *i.e.* Empty Fruit Bunches (EFB), mesocarp fiber, and palm kernel shells. The oil palm trunks, fronds and EFB are usually retained in the plantations and left to decompose naturally for nutrient replacement or mulching purposes. Application of these biomass, which contain about 50% C (Moraidi *et al.*, 2012; Khalid *et al.*, 2000), in the plantations has potential to reduce GHG through improving soil C sequestration. However, studies describing the contribution of the oil palm biomass to the formation of soil organic matter are scanty. The study of Khalid *et al.* (2000) on decomposition processes of oil palm residues, for example, was only for a period of 18 months. Additionally, the study of Moraidi *et al.* (2013) on annual applications of EFB, Ecomat, and pruned fronds for four years over a period of 50 months, had resulted in increases in SOC content of topsoil (0-15 cm).

The roles of the crop residue and field management practices in the enhancement of soil C sequestration in agricultural land have been described by Lal (2004a). Lal (2004a) also stated that the SOC sequestration potential for the world's agricultural land, with the adoption of restorative land use and recommended management practices is 0.9 ± 0.3 Pg C year^{-1}. This may offset 25% to 30% of the annual increase atmospheric CO_2 (3.3 Pg C year^{-1}). Thus, the oil palm, which is grown on the same land continuously for 25 to 30 years per cropping cycle, with its ability in producing large amount of biomass production combined with the enormous scale of plantation, and adoption of zero burning approach during the establishment of new planting and replanting areas, has a high potential for soil C sequestration.

In order to quantify the SOC stocks in plantations, it is essential to understand the spatial variation of oil palm field according to the land management practices. The oil palm field encompasses three operational zones: Weeded Circle (WC), Frond Heap (FH) and Avenue (AVE). The AVE consists of the harvesting path and interrow. The heterogeneous above ground inputs across these operational zones suggest different equilibrium contents of SOC in each operational zone, during the lifespan of the plantation. Moreover, soil C inputs and outputs are influenced by climate, vegetation and soil physical characteristics, all of which are spatially variable, leading to substantial spatial variability in SOC (Conant and Paustian, 2002). However, information on SOC dynamics and spatial variability in this heterogeneous environment of an oil palm field are still limited. Besides, there is a gap of knowledge on the measurement and dynamics of the labile fraction of SOC in oil palm cultivation on tropical mineral soils. The labile SOC fraction in this study was based on the degree of oxidation of SOC by potassium permanganate ($KMnO_4$). The Carbon Management Index (CMI), which was developed from this method, is a procedure for monitoring the SOC dynamics in oil palm plantation. The CMI is an index that takes into account of changes in both labile (C_L) and total C (C_T), relative to a reference site, as a result of cultivation (Blair *et al.*, 1995).

1.2 Research Objectives

(i) To quantify the spatial variability of SOC in different palm ages and operational zones
(ii) To determine the SOC dynamics and C_L fractions of SOC in different palm ages, operational zones, and soil depths
(iii) To establish the CMI of oil palm plantations, relative to secondary forest (benchmark/reference site)

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