**UNIVERSITI PUTRA MALAYSIA**

# *STOCK, DISTRIBUTION, PRESERVATION AND STRUCTURE OF ORGANIC MATTER IN SOILS OF A CLIMO-BIOSEQUENCE FROM A PEDOGENIC PERSPECTIVE*

***AMIR HOSSEIN JAFARZADEH HAGHIGHI***

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By

**AMIR HOSSEIN JAFARZADEH HAGHIGHI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

**January 2016**

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# DEDICATION

I would like to dedicate my thesis to my beloved son, Sam, whose birth during the conduct of this research has given me sufficient strength and inspiration to work harder.

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

**STOCK, DISTRIBUTION, PRESERVATION AND STRUCTURE OF ORGANIC MATTER IN SOILS OF A CLIMO-BIOSEQUENCE FROM A PEDOGENIC PERSPECTIVE**

By

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Soil organic matter (SOM) represents the largest terrestrial pool of carbon (C). SOM characteristics such as stock, vertical distribution, preservation, and structural composition have been scarcely explored from pedogenic perspective. This study focused on a climo-biosequence in the Main Range of Peninsular Malaysia since it presents an opportunity to study the impacts of soil-forming factors, pedogenic processes, and soil properties on SOM characteristics. Soil samples from all genetic horizons of four representative soil profiles were subjected to routine physical, chemical, and mineralogical analyses. Particle-size fractionation and fulvic acid and humic acid extraction in combination with solid-state $^{13}C$ nuclear magnetic resonance spectroscopy, Fourier-transform infrared spectroscopy, and scanning electron microscopy were used as specific methods. Soil organic carbon stock to 1 m depth increased along the studied climo-biosequence, from 5.7 kg $m^{-2}$ in Udult to 8.9 kg $m^{-2}$ in Humult to 15.8 kg $m^{-2}$ in Orthod, reaching a maximum value of 49.6 kg $m^{-2}$ in Saprist. An increase in the proportion of fulvic acid with depth in soils where podzolization was the active pedogenic process showed the translocation of fulvic acid from the A-horizon toward the B-horizon. Close relationships between the content of organic carbon (OC) in the <53 µm fraction and indicators of Fe oxides and allophane-type aluminosilicates in the B-horizon indicated the importance of Fe oxides and poorly crystalline aluminosilicates for preservation of OC in the subsoil. Alkyl C (20.1-75.2%) and O-alkyl C (16.8-67.7%) dominated the bulk soils and particle-size fractions. The proportion of alkyl C in the bulk soils and particle-size fractions of A-horizon increased with increasing elevation, while O-alkyl C showed opposite trend. This study demonstrates that SOM characteristics such as stock, vertical distribution, preservation, and structural composition are controlled by soil-forming factors (i.e. climate and vegetation), pedogenic processes, soil properties (i.e. texture and mineralogy), and pedogenesis, respectively.

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

**KANDUNGAN, TABURAN, PEMELIHARAAN DAN STRUKTUR BAHAN ORGANIK DALAM TANAH KLIMO-BIOJUJUKAN DARI PERSPEKTIF PEDOGENIK**

Oleh

**AMIR HOSSEIN JAFARZADEH HAGHIGHI**

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Bahan organik tanah (SOM) merupakan simpanan terbesar karbon (C) di daratan. Ciri-ciri SOM seperti kandungannya, taburan menegak, pemeliharaan, dan komposisi strukturnya jarang diterokai dari perspektif pedogenik. Kajian ini tertumpu pada klimo-biojujukan di Banjaran Titiwangsa di Semenanjung Malaysia kerana ia menyediakan peluang untuk mengkaji kesan-kesan dari faktor pembentuk tanah, proses pedogenik, dan sifat tanah pada ciri-ciri SOM. Sampel tanah dari kesemua horizon genetik empat profil tanah telah dianalisis bagi sifat-sifat fizikal, kimia, dan mineralogi. Analisis khas seperti pemisahan saiz zarah dan pengekstrakan asid fulvik dan asid humik beserta dengan spektroskopi resonans magnet nuklear dari pepejal $^{13}C$, spektroskopi jelmaan Fourier inframera, dan imbasan mikroskop elektron telah digunakan. Kandungan karbon organik dalam tanah untuk kedalaman 1 m meningkat sepanjang kawasan klimo-biojujukan, iaitu 5.7 kg $m^{-2}$ dalam tanah Udult, 8.9 kg $m^{-2}$ dalam tanah Humult, sebanyak 15.8 kg $m^{-2}$ dalam tanah Orthod, dan mencapai nilai maksimum sebanyak 49.6 kg $m^{-2}$ dalam tanah Saprist. Peningkatan kadar asid fulvik didapati mengikut kedalaman tanah di mana podzolisasi yang merupakan proses pedogenik berlaku secara aktif menunjukkan translokasi asid fulvik dari horizon A ke arah horizon B. Perkaitan rapat antara kandungan karbon organik (OC) dalam bahagian zarah <53 μm dan petunjuk oksida Fe dan aluminosilikat jenis allophane di horizon B menunjukkan kepentingan oksida Fe dan aluminosilikat kurang berkristal dalam pemeliharaan OC di tanah horizon bawah. Alkil C (20.1-75.2%) dan O-alkil C (16.8-67.7%) mendominasi keseluruhan kandungan tanah dan pecahan zarah tanah. Peratusan alkil C dalam tanah dan pecahan zarah bagi horizon A meningkat dengan peningkatan aras ketinggian, manakala O-alkil C menunjukkan tren sebaliknya. Kajian ini menunjukkan bahawa ciri-ciri SOM seperti kandungan, taburan menegak, pemeliharaan, dan komposisi struktur SOM dikawal oleh faktor pembentuk tanah (seperti iklim dan tumbuh-tumbuhan), proses pedogenik, sifat tanah (seperti tekstur dan mineralogi), dan pedogenesis.



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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| ATR | attenuated total reflectance |
| C | carbon |
| CP | cross polarization |
| DEM | digital elevation model |
| DI | distilled water |
| DOC | dissolved organic carbon |
| DOM | dissolved organic matter |
| DR | diffuse reflectance |
| ECEC | effective cation exchange capacity |
| EDX | energy dispersive X-ray |
| FA | fulvic acid |
| FTIR | Fourier-transform infrared |
| GIS | geographic information system |
| GPS | global positioning system |
| HA | humic acid |
| HS | humic substances |
| ICP-OES | inductively coupled plasma optical emission spectrometry |
| IR | infrared |
| m asl | meters above sea level |
| Ma | million years ago |
| MAS | magic angle spinning |
| NMR | nuclear magnetic resonance |
| OC | organic carbon |
| OM | organic matter |
| PCA | principal component analysis |
| POM | particulate organic matter |
| QBSD | quadrant back scattering detector |
| RSD | relative standard deviation |
| SE | secondary electron detector |
| SEM | scanning electron microscope |
| SOM | soil organic matter |
| SRTM | shuttle radar topography mission |
| TC | total carbon |
| TR | transmission |
| WRB | world reference base for soil resources |
| XRD | X-ray diffraction |

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# CHAPTER 1

# INTRODUCTION

## 1.1 General overview

Soil containing 1500-2400 Pg carbon (C) (1 Pg C = $10^{15}$ g of C), more than three times the C in organic compounds in vegetation living biomass (450-650 Pg C) (Ciais et al., 2013), is considered as the largest terrestrial pool of organic carbon (OC) (Batjes, 1996). The global soil OC pool is dynamic on a decadal time scale and also is sensitive to climatic and human perturbation (Amundson, 2001). Yet, uncertainty remains regarding the long-term responses of soil organic matter (SOM) to these disturbances. Complex feedbacks among soil, climate, vegetation, and parent material at landscape scale results in such uncertainty (Wagai et al., 2008). Field SOM studies in the form of soil sequences would enable us to unravel this complexity. According to the state-factor model of Jenny (1941), a sequence is defined a group of soils in which one (or two) state factor is allowed to vary and the rest are held constant (Schaetzl and Anderson, 2005).

The Main Range of Peninsular Malaysia, running parallel to the long axis of the peninsula, provides conditions to examine a group of soils that all are formed on the fairly uniform parent material, of the same age, and topography that would form a climo-biosequence and described by the below equation. Only climate and vegetation are allowed to vary in climo-biosequences. This equation is called climo-biofunction.

$S = f_{cl,\,o}\,(\text{climate, organisms})_{r,\,p,\,t,\ldots}$

where S is the soil or a soil property and other variables are, respectively, climate, organisms, relief, parent material, and time. The dots are other soil-forming factors that are important locally but not universally (Phillips, 1998).

Factors are independent variables that define the state of the soil system. Each factor impacts the soil through the variety of pedogenic processes (Schaetzl and Anderson, 2005). Pedogenic processes are formed as a function of the five interacting factors. Pedogenic processes, in turn, interact to create inherent soil properties. Thus, changes in soil-forming factors result in changes in pedogenic processes (Bockheim and Gennadiyev, 2000) and subsequently changes in soil properties. The relation between soil-forming factors, pedogenic processes, and soil properties was depicted by Bockheim and Gennadiyev (2000) (Figure 1.1).

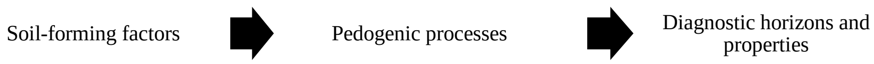


**Figure 1.1. Relationship between soil-forming factors, pedogenic processes, and soil properties [modified from Bockheim and Gennadiyev (2000)]**

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The dynamics of SOM as one of the principal soil component is affected by the soil-forming factors, pedogenic processes, and intrinsic soil properties. The fate of SOM from pedogenic perspective has been scarcely studied. Little is known about stock, vertical distribution, preservation, and structural composition of organic matter (OM) in soils of a climo-biosequence and how they are influenced by the soil-forming factors (i.e. climate and vegetation) and the subsequent pedogenic processes and soil properties.

Furthermore, inter-tropical mountain soils have received special attention in recent years because they are important in OM storage (Podwojewski et al., 2011) and vulnerable to climate change (Du et al., 2014). The Main Range of Peninsular Malaysia is a good example of such inter-tropical mountain soils with large C storage and accumulation of OM on the surface at high elevations. Forested highland soils in the Main Range are under threat of land use change involving deforestation and conversion to farmlands and tourist attractions due to their cool climate within tropical areas. Land use change along with global climate change may influence highland soils with high amounts of OM; therefore, large emission of carbon dioxide ($CO_2$) to the atmosphere would occur. For instance, based on the study of the long-term climatic data from Tanah Rata Station, Cameron Highlands, Leong (2006) reported steadily increase in temperature from mid-1970s to the present (warming trend of 0.7 °C per 100 years). Changes in SOM storage as a consequence of global changes (i.e climate change and land use/cover change) can affect water and nutrient supplies as well as the stability of slopes in the mountainous ecosystems which result in socio-economic vulnerabilities (Djukic et al., 2010). Thus, understanding SOM characteristics (i.e. stock, distribution, preservation, and structural composition) under the original condition in various elevation zones in the Main Range of Peninsular Malaysia may contribute to improve management practices that can mitigate the negative impact of global changes on the SOM. Characteristics of SOM in this mountainous area have not been fully understood because of the steep slopes and difficult accessibility. This study concentrated on a climo-biosequence in the Main Range of Peninsular Malaysia because it presents an opportunity to investigate the influence of soil-forming factors, pedogenic processes, and soil properties on SOM stock, distribution, preservation, and structural composition.

The following questions remain open:

1. Whether differences in C contents and structural characteristics of OM in soils along a climo-biosequence can be ascribed to single variable (i.e. climate or vegetation) or co-variation of these variables?
2. Whether changes in distribution and surface functionalities of the SOM fractions such as fulvic acid (FA) and humic acid (HA) with soil depth can be ascribed to the active pedogenic processes operating in soil?
3. Whether similar determinants of OC preservation are operative in topsoil and subsoil along a climo-biosequence and if preservation of OC in subsoil is the consequence of association with soil mineral matrix?
4. Whether structural changes of OM in particle-size fractions of soils can be ascribed to differences in climate and vegetation or pedogenesis as a function of the two variables?



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## 1.2 Objectives and hypotheses

The overall objective of this study was to understand the effect of soil-forming factors, pedogenic processes, and the resultant soil properties on the stock, vertical distribution, preservation, and structural composition of OM in soils of a climo-biosequence in the Main Range of Peninsular Malaysia. The specific objectives were as follows:

1. To investigate the impacts of climate and vegetation on C contents and structural characteristics of OM in the studied soils;
2. To investigate the vertical distribution and surface functionalities of FA and HA in soils of different pedogenesis in order to better understand the vertical translocation of OC in lights of pedogenic processes;
3. To evaluate the role of soil texture and mineralogy on preservation of OC in topsoil and subsoil of the studied soils; and
4. To determine changes in structural composition of OM in bulk and various particle-size fractions of the studied soils.

Through these objectives, the following hypotheses are formulated for soils of a climo-biosequence:

1. Climate and vegetation as the highest level of soil formation can affect the accumulation of OM on the soil surface;
2. The second level, pedogenic processes, affects the translocation of C, in particular vertically, through the soil system;
3. Soil properties such as texture and mineralogy as the lowest level of soil formation affect preservation of OC in the subsoil; and
4. Pedogenesis controls structural composition of SOM.



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