



**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***

**FP 2016 57**



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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.



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

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**January 2016**

**Chair : Professor Shamshuddin Jusop, PhD**  
**Faculty : Agriculture**

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  $^{13}\text{C}$  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  $5.7 \text{ kg m}^{-2}$  in Udult to  $8.9 \text{ kg m}^{-2}$  in Humult to  $15.8 \text{ kg m}^{-2}$  in Orthod, reaching a maximum value of  $49.6 \text{ kg m}^{-2}$  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  $<53 \mu\text{m}$  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.

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**

**Januari 2016**

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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-biojukkan 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  $^{13}\text{C}$ , spektroskopi jelmaan Fourier inframera, dan imbasan mikroskop elektron telah digunakan. Kandungan karbon organik dalam tanah untuk kedalaman 1 m meningkat sepanjang kawasan klimo-biojukkan, iaitu  $5.7 \text{ kg m}^{-2}$  dalam tanah Udult,  $8.9 \text{ kg m}^{-2}$  dalam tanah Humult, sebanyak  $15.8 \text{ kg m}^{-2}$  dalam tanah Orthod, dan mencapai nilai maksimum sebanyak  $49.6 \text{ kg m}^{-2}$  dalam tanah Saprism. 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  $<53 \mu\text{m}$  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.

## ACKNOWLEDGEMENTS

I thank Allah for graciously granting me the opportunity of doing PhD as well as giving me good health, strength, and inspiration to progress and finish my study. I wish to express my sincere thanks to my supervisor, Professor Dr Shamshuddin Jusop, for his guidance, sharing knowledge, encouragement, and punctual and efficient review of all my manuscripts during my PhD journey. This thesis would not have been possible without his supervision. My sincere gratitude goes to my supervisory committee members, Associate Professor Dr Hamdan Jol for his suggestions and comments particularly on soil sampling and profile description and Dr Norhazlin Zainuddin for her suggestion and invaluable comments on NMR and FTIR analyses. I would like to thank Universiti Putra Malaysia (UPM) for providing technical and financial support during the conduct of this study. This work was supported by the Research University Grant Scheme (RUGS) under Grant No. 01-02-12-1700RU (9327000) provided by UPM. I would also like to express my gratitude to Balu Perumal, Dr Sanath Kumaran, Dr S. Paramanathan, and Dr Roslan Ismail for many helpful comments, Dr Hadi Memarian for helping to produce the map of the study area using GIS, Dr Jeffrey Baldock at CSIRO Land and Water, Australia for providing helpful information on the method of particle-size fractionation, Siti Busyra Abu Hassan and Francis Voon Wai Thoo for their role in NMR analysis. Thanks to all lecturers and staffs at Department of Land Management, Faculty of Agriculture, UPM for their hospitality and friendly. Thanks are also extended to the staffs in NMR and FTIR laboratory, Department of chemistry, Faculty of Science and microscopy unit, Institute of Bioscience, UPM. I would like to thank all my colleagues, past and present, in mineralogy laboratory for sharing their knowledge and making the laboratory feasible place to work. My deepest appreciation goes to my parents and my sister for their love, continuous support and encouragement. I owe my wife, Firoozeh, a debt of thanks for her patience, understanding, and encouragement. She always gives me the reason to go on.



I certify that a Thesis Examination Committee has met on 12 January 2016 to conduct the final examination of Amir Hossein Jafarzadeh Haghghi on his thesis entitled "Stock, Distribution, Preservation and Structure of Organic Matter in Soils of a Climo-biosequence from a Pedogenic Perspective" 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

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

# CHAPTER 1

## INTRODUCTION

### 1.1 General overview

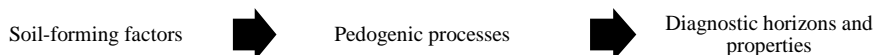
Soil containing 1500-2400 Pg carbon (C) (1 Pg C =  $10^{15}$  g of C), more than three times the C in organic compounds in vegetation living biomass (450-650 Pg C) (Ciais et al., 2013), is considered as the largest terrestrial pool of organic carbon (OC) (Batjes, 1996). The global soil OC pool is dynamic 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.

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

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)]**

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<sub>2</sub>) 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?



## 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.

## REFERENCES

- Agnelli, A., Celi, L., Corti, G., Del Innocenti, A., Ugolini, F.C., 2002. The changes with depth of humic and fulvic acids extracted from the fine earth and rock fragments of a forest soil. *Soil Sci.* 167, 524–538.
- Álvarez-Arteaga, G., Krasilnikov, P., García-Calderón, N.E., 2012. Vertical distribution and soil organic matter composition in a montane cloud forest, Oaxaca, Mexico. *Eur. J. For. Res.* 131, 1643–1651.
- Amelung, W., Flach, K.W., Zech, W., 1997. Climatic effects on soil organic matter composition in the Great Plains. *Soil Sci. Soc. Am. J.* 61, 115–123.
- Amelung, W., Zech, W., Zhang, X., Follerr, R.F., Tiessen, H., Knox, E., Flach, K.W., 1998. Carbon, nitrogen, and sulfur pools in particle-size fractions as influenced by climate. *Soil Sci. Soc. Am. J.* 62, 172–181.
- Amundson, R., 2001. The carbon budget in soils. *Annu. Rev. Earth Planet. Sci.* 29, 535–562.
- Artz, R.R.E., Chapman, S.J., Jean Robertson, A.H., Potts, J.M., Laggoun-Défarge, F., Gogo, S., Comont, L., Disnar, J., Francez, A., 2008. FTIR spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands. *Soil Biol. Biochem.* 40, 515–527.
- Baes, A.U., Bloom, P.R., 1989. Diffuse reflectance and transmission fourier transform infrared (DRIFT) spectroscopy of humic and fulvic acid. *Soil Sci. Soc. Am. J.* 53, 695–700.
- Baldock, J.A., Oades, J.M., Waters, A.G., Peng, X., Vassallo, A.M., Wilson, M.A., 1992. Aspects of the chemical structure of soil organic materials as revealed by solid-state <sup>13</sup>C NMR spectroscopy. *Biogeochemistry* 16, 1–42.
- Baldock, J.A., Oades, J.M., Nelson, P.N., Skene, T.M., Golchin, A., Clarke, P., 1997. Assessing the extent of decomposition of natural organic materials using solid-state <sup>13</sup>C NMR spectroscopy. *Aust. J. Soil Res.* 35, 1061–1083.
- Baldock, J.A., Nelson, P.N., 1999. Soil organic matter, in: Sumner, M.E. (Ed.), *Handbook of Soil Science*. CRC Press, Boca Raton, FL, pp. B25–B84.
- Baldock, J.A., Skjemstad, J.O., 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Org. Geochem.* 31, 697–710.
- Baldock, J.A., Broos, K., 2012. Soil organic matter, in: Huang, P.M., Li, Y., Sumner, M.E. (Eds.), *Handbook of Soil Sciences: Properties and Processes*. CRC Press, Boca Raton, FL, pp. 11:1–11:52.
- Baldock, J.A., Sanderman, J., Macdonald, L.M., Puccini, A., Hawke, B., Szarvas, S., McGowan, J., 2013. Quantifying the allocation of soil organic carbon to biologically significant fractions. *Soil Res.* 51, 561–576.

- Bardy, M., Fritsch, E., Derenne, S., Allard, T., do Nascimento, N.R., Bueno, G.T., 2008. Micromorphology and spectroscopic characteristics of organic matter in waterlogged podzols of the upper Amazon basin. *Geoderma* 145, 222–230.
- Barron, P.F., Wilson, M.A., Stephens, J.F., Cornell, B.A., Tate, K.R., 1980. Cross-polarization  $^{13}\text{C}$  NMR spectroscopy of whole soils. *Nature* 286, 585–587.
- Barron, P.F., Wilson, M.A., 1981. Humic soil and coal structure study with magic-angle spinning  $^{13}\text{C}$  CP-NMR. *Nature* 289, 275–276.
- Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci.* 47, 151–163.
- Bayer, C., Martin-Neto, L., Mielniczuk, J., Dieckow, J., Amado, T.J.C., 2006. C and N stocks and the role of molecular recalcitrance and organomineral interaction in stabilizing soil organic matter in a subtropical Acrisol managed under no-tillage. *Geoderma* 133, 258–268.
- Benke, M.B., Mermut, A.R., Shariatmadari, H., 1999. Retention of dissolved organic carbon from vinasse by a tropical soil, kaolinite, and Fe-oxides. *Geoderma* 91, 47–63.
- Bertsch, P.M., Bloom, P.R., 1996. Aluminum, in: Sparks, D.L. (Ed.), *Methods of Soil Analysis, Part 3. Chemical Methods*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 517–550.
- Beyer, L., Schulten, H.-R., Freund, R., Irmiler, U., 1993. Formation and properties of organic matter in a forest soil, as revealed by its biological activity, wet chemical analysis, CPMAS  $^{13}\text{C}$ -NMR spectroscopy and pyrolysis-field ionization mass spectrometry. *Soil Biol. Biochem.* 25, 587–596.
- Blake, G.R., Hartge, K.H., 1986. Bulk density, in: Klute, A. (Ed.), *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 363–375.
- Bockheim, J.G., Gennadiyev, A.N., 2000. The role of soil-forming processes in the definition of taxa in Soil Taxonomy and the World Soil Reference Base. *Geoderma* 95, 53–72.
- Bonifacio, E., Santoni, S., Celi, L., Zanini, E., 2006. Spodosol-Histosol evolution in the Krkonoše National Park (CZ). *Geoderma* 131, 237–250.
- Bonifacio, E., Catoni, M., Falsone, G., Said-Pullicino, D., Celi, L., 2013. Evolution of surface properties and organic matter stabilisation in podzolic B horizons as assessed by nitrogen and phosphate sorption. *Biol. Fertil. Soils.* 49, 505–516.
- Boudot, J., Hadj Brahim, A.B., Chone, T., 1988. Dependence of carbon and nitrogen mineralization rates upon amorphous metallic constituents and allophanes in highland soils. *Geoderma* 42, 245–260.

- Bracewell, J.M., Robertson, G.W., Tate, K.R., 1976. Pyrolysis-gas chromatography studies on a climosequence of soils in tussock grasslands, New Zealand. *Geoderma*, 15, 209–215.
- Brady, N.C., Weil, R.R., 2008. *The Nature and Properties of Soils*, 14<sup>th</sup> ed. Pearson Prentice Hall, Upper Saddle River, NJ.
- Bravard, S., Righi, D., 1991. Characterization of fulvic and humic acids from an oxisol-spodosol toposequence of Amazonia, Brazil. *Geoderma* 48, 151–162.
- Bremner, J.M., Mulvaney, C.S., 1986. Nitrogen-total, in: Page, A.L. (Ed.), *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 595–624.
- Brown, G., Brindley, G.W., 1980. X-ray diffraction procedures for clay minerals identification, in: Brindley, G.W., Brown, G. (Eds.), *Crystal Structures of Clay Minerals and Their X-Ray Identification*. Mineralogical Society, London, UK, pp. 305–359.
- Buol, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2011. *Soil Genesis and Classification*, 6<sup>th</sup> ed. Wiley-Blackwell, Ames, IA.
- Burgess, P.F., 1969. Ecological factors in hill and mountain forests of the States of Malaya. *Malay. Nat. J.* 22, 119–128.
- Burke, I.C., Yonker, C.M., Parton, W.J., Cole, C.V., Flach, K., Schimel, D.S., 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. *Soil Sci. Soc. Am. J.* 53, 800–805.
- Burnham, C.P. 1974a. Altitudinal changes in soils on granite in Malaysia, in: Nogina, N.A. (Ed.), *Transactions of the 10th International Congress of Soil Science*. Moscow, RU.
- Burnham, C.P., 1974b. The role of soil forming factors in controlling altitudinal zonation on granite in Malaysia, in: Flenley, J.R. (Ed.), *Altitudinal Zonation in Malesia*. Department of Geography, University of Hull, Hull, UK, pp. 59–74.
- Buschiazzo, D.E., Quiroga, A.R., Stahr, K., 1991. Patterns of organic matter accumulation in soils of the semiarid Argentinian Pampas. *J. Plant Nutr. Soil Sci.* 154, 437–441.
- Buurman, P., Jongmans, A.G., 2005. Podzolisation and soil organic matter dynamics. *Geoderma* 125, 71–83.
- Cambardella, C.A. and Elliot, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Sci. Soc. Am. J.* 56, 777–783.
- Capriel, P., Beck, T., Borchert, H., Gronholz, J., Zachmann, G., 1995. Hydrophobicity of the organic matter in arable soils. *Soil Biol. Biochem.* 27, 1453–1458.

- Carter, M.R., Angers, D.A., Gregorich, E.G., Bolinder, M.A., 2003. Characterizing organic matter retention for surface soils in eastern Canada using density and particle size fractions. *Can. J. Soil Sci.* 83, 11–23.
- Celi, L., Schnitzer, M., Michèle, N., 1997. Analysis of carboxyl groups in soil humic acids by a wet chemical method, fourier-transform infrared spectrophotometry, and solution-state carbon-13 nuclear magnetic resonance. A comparative study. *Soil Sci.* 162, 189–197.
- Cerli, C., Celi, L., Kaiser, K., Guggenberger, G., Johansson, M.-B., Cignetti, A., Zanini, E., 2008. Changes in humic substances along an age sequence of Norway spruce stands planted on former agricultural land. *Org. Geochem.* 39, 1269–1280.
- Chen, J., Chiu, C., 2003. Characterization of soil organic matter in different particle-size fractions in humid subalpine soils by CP/MAS  $^{13}\text{C}$  NMR. *Geoderma* 117, 129–141.
- Chen, J., Chung, T., Tian, G., Chiu, C., 2013. Characterization of soil organic matter in perhumid natural cypress forest: comparison of humification in different particle-size fractions. *Bot. Stud.* 54:56.
- Chenu, C., Plante, A. F., 2006. Clay-sized organo-mineral complexes in a cultivation chronosequence: revisiting the concept of the primary organo-mineral complex. *Eur. J. Soil Sci.* 57, 596–607.
- Child, C.W., Parfitt, R.L., Lee, R., 1983. Movement of aluminium as an inorganic complex in some podzolised soils, New Zealand. *Geoderma* 29, 139–155.
- Christensen, B.T., 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. *Adv. Soil Sci.* 20, 1–90.
- Christensen, B.T., 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. *Eur. J. Soil Sci.* 52, 345–353.
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S., Thornton, P., 2013. Carbon and other biogeochemical cycles, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, pp. 465–570.
- Cobbing, E.J., Pitfield, P.E.J., Darbyshire, D.P.F., Mallick, D.I.J., 1992. The granites of the south-east asian tin belt. *British Geological Survey, London, UK*.
- Conant, R.T., Ryan, M.G., gren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., Evans, S.E., Frey, S.D., Giardina, C.P., Hopkins, F.M., Hyvönen, R., Kirschbaum, M.U.F., Lavalley, J.M., Leifeld, J., Parton, W.J., Megan Steinweg, J., Wallenstein, M.D., Martin Wetterstedt, J., Bradford, M.A., 2011.

Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. *Glob. Chang. Biol.* 17, 3392–3404.

- Cui, J., Li, Z., Liu, Z., Ge, B., Fang, C., Zhou, C., Tang, B., 2014. Physical and chemical stabilization of soil organic carbon along a 500-year cultivated soil chronosequence originating from estuarine wetlands: temporal patterns and land use effects. *Agric. Ecosyst. Environ.* 196, 10–20.
- Dai, K.H., Johnson, C.E., 1999. Applicability of solid-state  $^{13}\text{C}$  CP/MAS NMR analysis in Spodosols: chemical removal of magnetic materials. *Geoderma* 93, 289–310.
- Dale, W.L., 1974. The rainfall of Malaya, part 1, in: Ooi, J.B., Chia, L.S. (Eds.), *The Climate of West Malaysia and Singapore*. Oxford University Press, Singapore, SG, pp. 132–144.
- Dalmolin, R.S.D., Gonçalves, C.N., Dick, D.P., Knicker, H., Klamt, E., Kögel-Knabner, I., 2006. Organic matter characteristics and distribution in Ferralsol profiles of a climosequence in southern Brazil. *Eur. J. Soil Sci.* 57, 644–654.
- De Coninck, F., 1980. Major mechanisms in formation of spodic horizons. *Geoderma* 24, 101–128.
- De Junet, A., Basile-Doelsch, I., Borschneck, D., Masion, A., Miche, H., Marol, C., Balesdent, J., 2012. Effects of hydrofluoric acid dissolution on organo-mineral associations in Cambisols and Andosols of Réunion. *Eur. J. Soil Sci.* 63, 659–673.
- Demyan, M.S., Rasche, F., Schulz, E., Breulmann, M., Müller, T., Cadisch, G., 2012. Use of specific peaks obtained by diffuse reflectance Fourier transform mid-infrared spectroscopy to study the composition of organic matter in a Haplic Chernozem. *Eur. J. Soil Sci.* 63, 189–199.
- Desjardins, T., Folgarait, P.J., Pando-Bahuon, A., Girardin, C., Lavelle, P., 2006. Soil organic matter dynamics along a rice chronosequence in north-eastern Argentina: evidence from natural  $^{13}\text{C}$  abundance and particle size fractionation. *Soil Biol. Biochem.* 38, 2753–2761.
- Dick, D.P., Gonçalves, C.N., Dalmolin, R.S.D., Knicker, H., Klamt, E., Kögel-Knabner, I., Simões, M.L., Martin-Neto, L., 2005. Characteristics of soil organic matter of different Brazilian Ferralsols under native vegetation as a function of soil depth. *Geoderma* 124, 319–333.
- Dieleman, W.I.J., Venter, M., Ramachandra, A., Krockenberger, A.K., Bird, M.I. 2013., Soil carbon stocks vary predictably with altitude in tropical forests: implications for soil carbon storage. *Geoderma* 204–205, 59–67.
- Djukic, I., Zehetner, F., Tatzber, M., Gerzabek, M.H., 2010. Soil organic-matter stocks and characteristics along an Alpine elevation gradient. *J. Plant Nutr. Soil Sci.* 173, 30–38.

- Du, B., Kang, H., Pumpanen, J., Zhu, P., Yin, S., Zou, Q., Wang, Z., Kong, F., Liu, C., 2014. Soil organic carbon stock and chemical composition along an altitude gradient in the Lushan Mountain, subtropical China. *Ecol. Res.* 29, 433–439.
- Duboc, O., Zehetner, F., Djukic, I., Tatzber, M., Berger, T.W., Gerzabek, M.H., 2012. Decomposition of European beech and Black pine foliar litter along an Alpine elevation gradient: mass loss and molecular characteristics. *Geoderma* 189-190, 522–531.
- Earl, W.L., Vanderhart, D.L., 1982. Measurement of  $^{13}\text{C}$  chemical shifts in solids. *J. Magn. Reson.* 48, 35–54.
- Egli, M., Alioth, L., Mirabella, A., Raimondi, S., Nater, M., René, V., 2007. Effect of climate and vegetation on soil organic carbon, humus fractions, allophanes, imogolite, kaolinite, and oxyhydroxides in volcanic soils of Etna (Sicily). *Soil Sci.* 172, 673–691.
- Egli, M., Sartori, G., Mirabella, A., Giaccari, D., 2010. The effects of exposure and climate on the weathering of late Pleistocene and Holocene Alpine soils. *Geomorphology* 114, 466–482.
- Ellerbrock, R.H., Gerke, H.H., 2013. Characterization of organic matter composition of soil and flow path surfaces based on physicochemical principles—a review. *Adv. Agron.* 121, 117–177.
- Ellert, B.H., Janzen, H.H., McConkey, B.G., 2001. Measuring and comparing soil carbon storage, in: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), *Assessment Methods for Soil Carbon*. Lewis Publishers, Boca Raton, FL, pp. 131–147.
- Eswaran, H., Van Den Berg, E., Reich, P., 1993. Organic carbon in soils of the world. *Soil Sci. Soc. Am. J.* 57, 192–194.
- Eusterhues, K., Rumpel, C., Kleber, M., Kögel-Knabner, I., 2003. Stabilisation of soil organic matter by interactions with minerals as revealed by mineral dissolution and oxidative degradation. *Org. Geochem.* 34, 1591–1600.
- Eusterhues, K., Rumpel, C., Kögel-Knabner, I., 2005. Organo-mineral associations in sandy acid forest soils: importance of specific surface area, iron oxides and micropores. *Eur. J. Soil Sci.* 56, 753–763.
- Falson, G., Celi, L., Caimi, A., Simonov, G., Bonifacio, E., 2012. The effect of clear cutting on podzolisation and soil carbon dynamics in boreal forests (Middle Taiga zone, Russia). *Geoderma* 177-178, 27–38.
- Farmer, V.C., Russell, J.D., Smith, B.F.L., 1983. Extraction of inorganic forms of translocated Al, Fe and Si from a podzol Bs horizon. *J. Soil Sci.* 34, 571–576.
- Faz Cano, A., Mermut, A.R., Ortiz, R., Benke, M.B., Chatson, B., 2002.  $^{13}\text{C}$  CP/MAS-NMR spectra of organic matter as influenced by vegetation, climate, and soil characteristics in soils from Murcia, Spain. *Can. J. Soil Sci.* 82, 403–411.

- Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79, 69–116.
- Garten Jr, C.T., Hanson, P.J., 2006. Measured forest soil C stocks and estimated turnover times along an elevation gradient. *Geoderma* 136, 342–352.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis, in: Klute, A. (Ed.), *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 383–409.
- Gerzabek, M.H., Antil, R.S., Kögel-Knabner, I., Knicker, H., Kirchmann, H., Haberhauer, G., 2006. How are soil use and management reflected by soil organic matter characteristics: a spectroscopic approach. *Eur. J. Soil Sci.* 57, 485–494.
- Ghani, A.A., 2009. Plutonism, in: Hutchison, C.S., Tan, D.N.K. (Eds.), *Geology of Peninsular Malaysia*. University of Malaya and Geological Society of Malaysia, Kuala Lumpur, MY, pp. 211–232.
- Gonçalves, C.N., Dalmolin, R.S.D., Dick, D.P., Knicker, H., Klamt, E., Kögel-Knabner, I., 2003. The effect of 10% HF treatment on the resolution of CPMAS <sup>13</sup>C NMR spectra and on the quality of organic matter in Ferralsols. *Geoderma* 116, 373–392.
- Gondar, D., Lopez, R., Fiol, S., Antelo, J.M., Arce, F., 2005. Characterization and acid-base properties of fulvic and humic acids isolated from two horizons of an ombrotrophic peat bog. *Geoderma* 126, 367–374.
- González-Pérez, M., Vidal Torrado, P., Colnago, L.A., Martin-Neto, L., Otero, X.L., Milori, D.M.B.P., Gomes, F.H., 2008. <sup>13</sup>C NMR and FTIR spectroscopy characterization of humic acids in spodosols under tropical rain forest in southeastern Brazil. *Geoderma* 146, 425–433.
- Grand, S., Lavkulich, L.M., 2011. Depth distribution and predictors of soil organic carbon in Podzols of a forested watershed in southwestern Canada. *Soil Sci.* 176, 164–174.
- Grieve, I.C., Proctor, J., Cousins, S.A., 1990. Soil variation with altitude on Volcan Barva, Costa Rica. *Catena* 17, 525–534.
- Haberhauer, G., Rafferty, B., Strebl, F., Gerzabek, M.H., 1998. Comparison of the composition of forest soil litter derived from three different sites at various decompositional stages using FTIR spectroscopy. *Geoderma* 83, 331–342.
- Haberhauer, G., Gerzabek, M.H., 1999. Drift and transmission FT-IR spectroscopy of forest soils: an approach to determine decomposition processes of forest litter. *Vib. Spectrosc.* 19, 413–417.
- Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil.* 191, 77–87.



- Hobbie, S.E., Schimel, J.P., Trumbore, S.E., Randerson, J.R., 2000. Controls over carbon storage and turnover in high-latitude soils. *Glob. Chang. Biol.* 6, 196–210.
- Holmgren, G.G., 1967. A rapid citrate dithionite extractable iron procedure. *Soil Sci. Soc. Am. J.* 31, 210–211.
- IUSS Working Group WRB, 2006. World Reference Base for Soil Resources 2006. World Soil Resources Reports No. 103. FAO, Rome, IT.
- Jenny, H., 1941. *Factors of Soil Formation: A System of Quantitative Pedology*. McGraw-Hill Book Company, Inc., New York, NY.
- Jenny, H., 1980. *The Soil Resources: Origin and Behavior*. Springer-Verlag, New York, NY.
- Jeyanny, V., Husni, M.H.A., Wan Rasidah, K., Kumar, B.S., Arifin, A., Hisham, M.K., 2014. Carbon stocks in different carbon pools of a tropical lowland forest and a montane forest with varying topography. *J. Trop. For. Sci.* 26, 560–571.
- Jien, S., Wu, S., Chen, Z., Chen, T., Chiu, C., 2010. Characteristics and pedogenesis of podzolic forest soils along a toposequence near a subalpine lake in northern Taiwan. *Bot. Stud.* 51, 223–236.
- Jindaluang, W., Kheoruenromne, I., Suddhiprakarn, A., Singh, B.P., Singh, B., 2013. Influence of soil texture and mineralogy on organic matter content and composition in physically separated fractions soils of Thailand. *Geoderma* 195–196, 207–219.
- Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* 10, 423–436.
- Johnston, C.T., Aochi, Y.O., 1996. Fourier transform infrared and Raman spectroscopy, in: Sparks, D.L. (Ed.), *Methods of Soil Analysis, Part 3. Chemical Methods*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 269–323.
- Jolivet, C., Arrouays, D., Lévêque, J., Andreux, F., Chenu, C., 2003. Organic carbon dynamics in soil particle-size separates of sandy Spodosols when forest is cleared for maize cropping. *Eur. J. Soil Sci.* 54, 257–268.
- Kaiser, K., Zech, W., 2000. Dissolved organic matter sorption by mineral constituents of subsoil clay fractions. *J. Plant Nutr. Soil Sci.* 163, 531–535.
- Kaiser, K., Eusterhues, K., Rumpel, C., Guggenberger, G., Kögel-Knabner, I., 2002. Stabilization of organic matter by soil minerals—investigations of density and particle-size fractions from two acid forest soils. *J. Plant Nutr. Soil Sci.* 165, 451–459.
- Kaiser, M., Ellerbrock, R. H. and Sommer, M. 2009. Separation of coarse organic particles from bulk surface soil samples by electrostatic attraction. *Soil Sci. Soc. Am. J.* 73, 2118–2130.

- Kirschbaum, M.U.F., 2000. Will changes in soil organic carbon act as a positive or negative feedback on global warming. *Biogeochemistry* 48, 21-51.
- Kleber, M., Mikutta, R., Torn, M.S., Jahn, R., 2005. Poorly crystalline mineral phases protect organic matter in acid subsoil horizons. *Eur. J. Soil Sci.* 56, 717-725.
- Kleber, M., Johnson, M.G., 2010. Advances in understanding the molecular structure of soil organic matter: implications for interaction in the environment. *Adv. Agron.* 106, 77–142.
- Kögel-Knabner, I., 1997. <sup>13</sup>C and <sup>15</sup>N NMR spectroscopy as a tool in soil organic matter studies. *Geoderma* 80, 243–270.
- Kögel-Knabner, I., Zech, W., Hatcher, P.G., 1988. Chemical composition of the organic matter in forest soils: the humus layer. *J. Plant Nutr. Soil Sci.* 151, 331–340.
- Kögel-Knabner, I., 2000. Analytical approaches for characterizing soil organic matter. *Org. Geochem.* 31, 609–625.
- Kögel-Knabner, I., 2002. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. *Soil Biol. Biochem.* 34, 139–162.
- Kögel-Knabner, I., Guggenberger, G., Kleber, M., Kandeler, E., Kalbitz, K., Scheu, S., Eusterhues, K., Leinweber, P., 2008. Organo-mineral associations in temperate soils: integrating biology, mineralogy, and organic matter chemistry. *J. Plant Nutr. Soil Sci.* 171, 61–82.
- Kononova, M.M., 1966. *Soil Organic Matter*. Pergamon press, Oxford, UK.
- Kumaran, S., 2008. Hydrometeorology of tropical montane rainforest of Gunung Brinchang, Pahang Darul Makmur, Malaysia. PhD Thesis. Universiti Putra Malaysia.
- Ladd, J.N., Amato, M., Oades, J.M., 1985. Decomposition of plant material in Australian soils. III. Residual organic and microbial biomass C and N from isotope-labelled legume material and soil organic matter, decomposing under field conditions. *Aust. J. Soil Res.* 23, 603–611.
- Leifeld, J., 2006. Application of diffuse reflectance FT-IR spectroscopy and partial least-squares regression to predict NMR properties of soil organic matter. *Eur. J. Soil Sci.* 57, 846–857.
- Lemenih, M., Itanna, F., 2004. Soil carbon stocks and turnovers in various vegetation types and arable lands along an elevation gradient in southern Ethiopia. *Geoderma* 123, 177–188.
- Leong, C.P., 2006. Global warming: has there been a change in the climate of Cameron Highlands, in: Chan, N.W. (Ed.), *Cameron Highlands: Issues & Challenges in*

Sustainable Development. School of Humanities, Universiti Sains Malaysia, Penang, MY, pp. 26–34.

- Li, P., Wang, Q., Endo, T., Zhao, X., Kakubari, Y., 2010. Soil organic carbon stock is closely related to aboveground vegetation properties in cold-temperate mountainous forests. *Geoderma* 154, 407–415.
- Longbottom, T.L., Townsend-Small, A., Owen, L.A., Murari, M.K., 2014. Climatic and topographic controls on soil organic matter storage and dynamics in the Indian Himalaya: potential carbon cycle–climate change feedbacks. *Catena* 119, 125–135.
- Lorenz, K., Lal, R., Jiménez, J.J., 2009. Soil organic carbon stabilization in dry tropical forests of Costa Rica. *Geoderma* 152, 95–103.
- Lundström, U.S., van Breemen, N., Bain, D., 2000a. The podzolization process. A review. *Geoderma* 94, 91–107.
- Lundström, U.S., van Breemen, N., Bain, D.C., van Hees, P.A.W., Giesler, R., Gustafsson, J.P., Ilvesniemi, H., Karlton, E., Melkerud, P.-A., Olsson, M., Riise, G., Wahlberg, O., Bergelin, A., Bishop, K., Finlay, R., Jongmans, A.G., Magnusson, T., Mannerkoski, H., Nordgren, A., Nyberg, L., Starr, M., Tau Strand, L., 2000b. Advances in understanding the podzolization process resulting from a multidisciplinary study of three coniferous forest soils in the Nordic Countries. *Geoderma* 94, 335–353.
- MacCarthy, P., Rice, J.A. 1985. Spectroscopic methods (other than NMR) for determining functionality of humic substances, in: Aiken, G.R., McKnight, D.M., Wershaw, R.L., MacCarthy, P. (Eds). *Humic Substances in Soil, Sediment, and Water: Geochemistry, Isolation, and Characterization*. Wiley-Interscience Publication, New York, NY, pp. 527–561.
- Mahieu, N., Powlson, D.S., Randall, E.W., 1999. Statistical analysis of published carbon-13 CPMAS NMR spectra of soil organic matter. *Soil Sci. Soc. Am. J.* 63, 307–319.
- Mathers, N.J., Mao, X.A., Xu, Z.H., Saffigna, P.G., Berners-Price, S.J., Perera, M.C.S., 2000. Recent advances in the application of  $^{13}\text{C}$  and  $^{15}\text{N}$  NMR spectroscopy to soil organic matter studies. *Aust. J. Soil Res.* 38, 769–787.
- Maynard, D.G., Curran, M.P., 2008. Bulk density measurement in forest soils, in: Carter, M.R., Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. CRC Press, Boca Raton, FL, pp. 863–869.
- McKeague, J.A., Day, J.H., 1966. Dithionite- and oxalate-extractable Fe and Al as aids in differentiating various classes of soils. *Can. J. Soil Sci.* 46, 13–22.
- McKeague, J.A., 1967. An evaluation of 0.1 M pyrophosphate and pyrophosphate-dithionite in comparison with oxalate as extractants of the accumulation products in Podzols and some other soils. *Can. J. Soil Sci.* 47, 95–99.

- Metcalf, I., 2000. The Bentong-Raub suture zone. *J. Asian. Earth Sci.* 18, 691-712.
- Mikutta, R., Kleber, M., Torn, M.S., Jahn, R., 2006. Stabilization of soil organic matter: association with minerals or chemical recalcitrance? *Biogeochemistry* 77, 25–56.
- Mizota, C., van Reeuwijk, L.P., 1989. Clay mineralogy and chemistry of soils formed in volcanic material in diverse climatic regions, *Soil Monograph 2. International Soil Reference and Information*, Wageningen, NL.
- Muñoz, C., Monreal, C.M., Schnitzer, M., Zagal, E., 2008. Influence of *Acacia caven* (Mol) coverage on carbon distribution and its chemical composition in soil organic carbon fractions in a Mediterranean-type climate region. *Geoderma* 144, 352–360.
- Munsell Color Company, 2000. *Munsell Soil Color Charts*. Munsell Color, New Windsor, NY.
- Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter, in: Page, A.L. (Ed.), *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 539–577.
- Niemeyer, J., Chen, Y., Bollag, J.-M., 1992., Characterization of humic acids, composts, and peat by diffuse reflectance Fourier-transform infrared spectroscopy. *Soil Sci. Soc. Am. J.* 56, 135-140.
- Norris, C.E., Quideau, S.A., Bhatti, J.S., Wasylshen, R.E., 2011. Soil carbon stabilization in jack pine stands along the Boreal Forest Transect Case Study. *Glob. Chang. Biol.* 17, 480–494.
- Oades, J.M., 1988. The retention of organic matter in soils. *Biogeochemistry* 5, 35–70.
- Paramanathan, S., 1977. *Soil genesis on igneous and metamorphic rocks in Malaysia*. Doctoral thesis. State University of Ghent.
- Parfitt, R.L., Childs, C.W., 1988. Estimation of forms of Fe and Al: a review , and analysis of contrasting soils by dissolution and moessbauer methods. *Aust. J. Soil Res.* 26, 121–144.
- Parikh, S.J., Goyne, K.W., Margenot, A.J., Mukome, F.N.D., Calderón, F.J., 2014. Soil Chemical Insights Provided through Vibrational Spectroscopy. *Adv. Agron.* 126, 1-148.
- Phillips, J.D., 1998. On the relations between complex systems and the factorial model of soil formation (with Discussion). *Geoderma* 86, 1–21.
- Piccolo, A., 2002. The supramolecular structure of humic substances: a novel understanding of humus chemistry and implications in soil science. *Adv. Agron.* 75, 57–134.

- Podwojewski, P., Poulencard, J., Nguyet, M.L., de Rouw, A., Nguyen, V.T., Pham, Q.H., Tran, D.T., 2011. Climate and vegetation determine soil organic matter status in an alpine inner-tropical soil catena in the Fan Si Pan Mountain, Vietnam. *Catena* 87, 226–239.
- Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. *Nature* 298, 156–159.
- Powlson, D., Smith, P., De Nobili, M., 2013. Soil organic matter, in: Gregory, P.J., Nortcliff, S. (Eds.), *Soil Conditions and Plant Growth*. Wiley-Blackwell, Oxford, UK, pp. 86–131.
- Preston, C., 1996. Applications of NMR to soil organic matter analysis: history and prospects. *Soil Sci.* 161, 144–166.
- Pronk, G.J., Heister, K., Kögel-Knabner, I., 2011. Iron oxides as major available interface component in loamy arable topsoils. *Soil Sci. Soc. Am. J.* 75, 2158–2168.
- Quideau, S.A., Anderson, M.A., Graham, R.C., Chadwick, O.A., Trumbore, S.E., 2000. Soil organic matter processes: characterization by  $^{13}\text{C}$  NMR and  $^{14}\text{C}$  measurements. *For. Ecol. Manage.* 138, 19–27.
- Quideau, S.A., Chadwick, O.A., Benesi, A., Graham, R.C., Anderson, M. A., 2001. A direct link between forest vegetation type and soil organic matter composition. *Geoderma* 104, 41–60.
- Rumpel, C., Kögel-Knabner, I., Bruhn, F., 2002. Vertical distribution, age, and chemical composition of organic carbon in two forest soils of different pedogenesis. *Org. Geochem.* 33, 1131–1142.
- Rumpel, C., Eusterhues, K., Kögel-Knabner, I., 2004. Location and chemical composition of stabilized organic carbon in topsoil and subsoil horizons of two acid forest soils. *Soil Biol. Biochem.* 36, 177–190.
- Sai, L.J., Mokhtar, S., 1989. Soil correlation of steepland soils in Cameron Highlands. Unpublished report. Land Management Branch, Department of Agriculture Malaysia: Peninsular Malaysia.
- Salomé, C., Nunan, N., Pouteau, V., Lerch, T.Z., Chenu, C., 2010. Carbon dynamics in topsoil and in subsoil may be controlled by different regulatory mechanisms. *Glob. Chang. Biol.* 16, 416–426.
- Sanderman, J., Baldock, J., Hawke, B., Macdonald, L., Massis-puccini, A., Szarvas, S., 2011. National Soil Carbon Research Programme: Field and Laboratory Methodologies. CSIRO Land and Water, Urrbrae, AU.
- Sauer, D., Saccone, L., Conley, D.J., Herrmann, L., Sommer, M., 2006. Review of methodologies for extracting plant-available and amorphous Si from soils and aquatic sediments. *Biogeochemistry* 80, 89–108.

- Sauer, D., Sponagel, H., Sommer, M., Giani, L., Jahn, R., Stahr, K., 2007. Podzol: soil of the year 2007. A review on its genesis, occurrence, and functions. *J. Plant Nutr. Soil Sci.* 170, 581–597.
- Schaetzl, R., Anderson, S., 2005. *Soils: Genesis and Geomorphology*. Cambridge University Press, New York, NY.
- Schawe, M., Glatzel, S., Gerold, G., 2007. Soil development along an altitudinal transect in a Bolivian tropical montane rainforest: podzolization vs. hydromorphy. *Catena* 69, 83–90.
- Schmidt, M.W.I., Knicker, H., Hatcher, P.G., Kögel-Knabner, I., 1997. Improvement of  $^{13}\text{C}$  and  $^{15}\text{N}$  CPMAS NMR spectra of bulk soils, particle size fractions and organic material by treatment with 10% hydrofluoric acid. *Eur. J. Soil Sci.* 48, 319–328.
- Schmidt, M.W.I., Gleixner, G., 2005. Carbon and nitrogen isotope composition of bulk soils, particle-size fractions and organic material after treatment with hydrofluoric acid. *Eur. J. Soil Sci.* 56, 407–416.
- Schnitzer, M., Khan, S.U., 1972. *Humic Substances in The Environment*. Marcel Dekker, New York, NY.
- Schnitzer, M., 1978. Humic substances: chemistry and reactions, in: Schnitzer, M., Khan, S.U. (Eds.), *Soil Organic Matter*. Elsevier Science Publishers B.V., Amsterdam, NL, pp. 1–64.
- Schnitzer, M., 1982. Organic matter characterization, in: Page, A.L. (Ed.), *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 581–594.
- Schnitzer, M., Monreal, C.M., 2011. *Quo vadis* soil organic matter research? A biological link to the chemistry of humification. *Adv. Agron.* 113, 143–217.
- Schöning, I., 2005. Organic matter stocks in temperate forest soils: composition, radiocarbon age and spatial variability. Technische Universität München.
- Schöning, I., Kögel-Knabner, I., 2006. Chemical composition of young and old carbon pools throughout Cambisol and Luvisol profiles under forests. *Soil Biol. Biochem.* 38, 2411–2424.
- Schwertmann, U., Taylor, R.M., 1989. Iron oxide, in: Dixon, J.B., Weed, S.B. (Eds.), *Minerals in Soil Environments*. Soil Science Society of America, Madison, WI, pp. 379–438.
- Senesi, N., D’Orazio, V., Ricca, G., 2003. Humic acids in the first generation of EUROSOILS. *Geoderma* 116, 325–344.
- Shamshuddin, J., Che Fauziah, I., 2010. *Weathered Tropical Soils: The Ultisols & Oxisols*. Universiti Putra Malaysia Press, Serdang, MY.

- Simonson, R.W., 1959. Outline of a generalized theory of soil genesis. *Soil Sci. Soc. Am. J.* 23, 152–156.
- Simpson, A.J., McNally, D.J., Simpson, M.J., 2011. NMR spectroscopy in environmental research: from molecular interactions to global processes. *Prog. Nucl. Magn. Reson. Spectrosc.* 58, 97–175.
- Simpson, M.J., Preston, C., 2008. Soil organic matter analysis by solid-state  $^{13}\text{C}$  nuclear magnetic resonance spectroscopy, in: Carter, M.R., Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. CRC Press, Boca Raton, FL, pp. 681–692.
- Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil.* 241, 155–176.
- Skjemstad, J.O., Clarke, P., Taylor, J.A., Oades, J.M., Newman, R.H., 1994. The removal of magnetic materials from surface soils. A solid state  $^{13}\text{C}$  CP/MAS NMR study. *Aust. J. Soil Res.* 32, 1215–1229.
- Skjemstad, J.O., Spouncer, L.R., Cowie, B., Swift, R.S., 2004. Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. *Aust. J. Soil Res.* 42, 79–88.
- Soil Survey Division Staff, 1993. *Soil Survey Manual*. Soil Conservation Service. USDA handbook 18, Washington, DC.
- Soil Survey Staff, 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2<sup>nd</sup> ed. USDA and Natural Resources Conservation Service, Washington, DC.
- Soil Survey Staff, 2010. *Keys to Soil Taxonomy*, 11<sup>th</sup> ed. USDA and Natural Resources Conservation Service, Washington, DC.
- Sollins, P., Homann, P., Caldwell, B.A., 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. *Geoderma* 74, 65–105.
- Spain, A.V., 1990. Influence of environmental conditions and some soil chemical properties on the carbon and nitrogen contents of some tropical Australian rainforest soils. *Aust. J. Soil Res.* 28, 825–839.
- Spielvogel, S., Prietzel, J., Kögel-Knabner, I., 2008. Soil organic matter stabilization in acidic forest soils is preferential and soil type-specific. *Eur. J. Soil Sci.* 59, 674–692.
- Stevenson, F.J., Goh, K.M., 1971. Infrared spectra of humic acids and related substances. *Geochim. Cosmochim. Acta.* 35, 471–483.
- Stevenson, F.J., 1994. *Humus Chemistry: Genesis, Composition, Reactions*. Wiley, New York, NY.

- Stewart, J.W.B., Cole, C.V., 1989. Influences of elemental interactions and pedogenic processes in organic matter dynamics. *Plant Soil*. 115, 199–209.
- Swift, R.S. 1996. Organic matter characterization, in: Sparks, D.L. (Ed.), *Methods of Soil Analysis, Part 3. Chemical Methods*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 1011–1071.
- Tan, K.H., Lobartini, J.C., Himmelsbach, D.S., Asmussen, L.E., 1991. Composition of humic acids extracted under air and nitrogen atmosphere. *Commun. Soil Sci. Plant Anal.* 22, 861–877.
- Tan, K.H., 2003. *Humic Matter in Soil and the Environment: Principles and Controversies*. Marcel Dekker, Inc., New York, NY.
- Tatzber, M., Stemmer, M., Spiegel, H., Katzlberger, C., Haberhauer, G., Mentler, A., Gerzabek, M.H., 2007. FTIR-spectroscopic characterization of humic acids and humin fractions obtained by advanced NaOH, Na<sub>4</sub>P<sub>2</sub>O<sub>7</sub>, and Na<sub>2</sub>CO<sub>3</sub> extraction procedures. *J. Plant Nutr. Soil Sci.* 170, 522–529.
- Tatzber, M., Mutsch, F., Mentler, A., Leitgeb, E., Englisch, M., Zehetner, F., Djukic, I., Gerzabek, M.H., 2011. Mid-infrared spectroscopy for topsoil layer identification according to litter type and decompositional stage demonstrated on a large sample set of Austrian forest soils. *Geoderma* 166, 162–170.
- Thaymuang, W., Kheoruenromne, I., Suddhipraharn, A., Sparks, D.L., 2013. The role of mineralogy in organic matter stabilization in tropical soils. *Soil Sci.* 178, 308–315.
- Thomas, G.W., 1982. Exchangeable cations, in: Page, A.L. (Ed.), *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*. American Society of Agronomy, Inc and Soil Science Society of America, Inc, Madison, WI, pp. 159–164.
- Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371, 783–785.
- Townsend, A.R., Vitousek, P.M., Trumbore, S.E., 1995. Soil organic matter dynamics along gradients in temperature and land use on the island of Hawaii. *Ecology* 76, 721–733.
- Tsai, C.C., Chen, Z.S., Kao, C.I., Ottner, F., Kao, S.J., Zehetner, F., 2010. Pedogenic development of volcanic ash soils along a climosequence in Northern Taiwan. *Geoderma* 156, 48–59.
- Tsui, C., Tsai, C., Chen, Z., 2013. Soil organic carbon stocks in relation to elevation gradients in volcanic ash soils of Taiwan. *Geoderma* 209-210, 119–127.
- Ussiri, D.A.N., Johnson, C.E., 2003. Characterization of organic matter in a northern hardwood forest soil by <sup>13</sup>C NMR spectroscopy and chemical methods. *Geoderma* 111, 123–149.



- van Reeuwijk, L.P., 2002. Procedures for Soil Analysis. International Soil Reference and Information, Wageningen, NL.
- von Lützw, M., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions—a review. *Eur. J. Soil Sci.* 57, 426–445.
- von Lützw, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., 2007. SOM fractionation methods: relevance to functional pools and to stabilization mechanisms. *Soil Biol. Biochem.* 39, 2183–2207.
- Wagai, R., Mayer, L.M., Kitayama, K., Knicker, H., 2008. Climate and parent material controls on organic matter storage in surface soils: a three-pool, density-separation approach. *Geoderma* 147, 23–33.
- Wang, Q., Zhang, P., Liu, M., Deng, Z., 2014. Mineral-associated organic carbon and black carbon in restored wetlands. *Soil Biol. Biochem.* 75, 300–309.
- Wattel-Koekkoek, E.J.W., van Genuchten, P.P.L., Buurman, P., van Lagen, B., 2001. Amount and composition of clay-associated soil organic matter in a range of kaolinitic and smectitic soils. *Geoderma* 99, 27–49.
- Whitmore, T.C., Burnham, C.P., 1969. The altitudinal sequence of forests and soils on granite near Kuala Lumpur. *Malay. Nat. J.* 22, 99–118.
- Wilson, M.A., Pugmire, R.J., Zilm, K.W., Goh, K.M., Heng, S., Grant, D.M., 1981. Cross-polarization  $^{13}\text{C}$ -NMR spectroscopy with magic angle spinning characterizes organic matter in whole soils. *Nature* 294, 648–650.
- Wilson, M.A., 1987. *NMR Techniques and Applications in Geochemistry and Soil Chemistry*. Pergamon press, Oxford, UK.
- Zinn, Y.L., Lal, R., Bigham, J.M., Resck, D.V.S., 2007. Edaphic controls on soil organic carbon retention in the Brazilian Cerrado: texture and mineralogy. *Soil Sci. Soc. Am. J.* 71, 1204–1214.