Asian Journal of Agriculture and Food Sciences (ISSN: 2321 – 1571)
Volume 03 – Issue 05, October 2015

Carbon Contents and Structural Characteristics of Organic Matter in Soils of a Climo-biosequence in the Main Range of Peninsular Malaysia

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ABSTRACT— ***Climate and vegetation are known to be the most important soil forming factors in determining carbon (C) contents and structural characteristics of organic matter (OM) in soils. Four representative soil profiles along a climo-biosequence in the Main Range of Peninsular Malaysia were investigated to determine the impacts of climate and vegetation on C contents and structural characteristics of OM. Soil samples from all genetic horizons were subjected to physical and chemical analyses. Structural characteristics of soil samples from selected horizons were analyzed by Fourier-transform infrared (FTIR) spectroscopy. Soil organic carbon content to 1 m depth increased along the studied climo-biosequence, from 5.7 kg m^{-2} in Udult under hill dipterocarp forest to 8.9 kg m^{-2} in Humult under upper dipterocarp forest to 15.8 kg m^{-2} in Orthod under myrtaceous forest, reaching a maximum value of 49.6 kg m^{-2} in Saprist under ericaceous forest. FTIR spectra for the surface organic horizons showed an increase of aliphatic band (2920 cm^{-1}) with increasing elevation from upper dipterocarp forest to ericaceous forest. The increase in aliphatic band with increasing elevation likely resulted from a selective preservation of aliphatic structures derived from original plants with high content of waxes. This study demonstrates that differences in C contents along the studied climo-biosequence are related to co-variation of climate and vegetation; however, vegetation, not climate, is the major driver of differences in structural characteristics of OM.***

Keywords— climate, climo-biosequence, FTIR spectroscopy, organic matter, vegetation

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1. INTRODUCTION

Soil organic matter (SOM) represents the largest terrestrial pool of carbon (C). Both quality and quantity of SOM reflect and control the primary productivity [1]. Dynamic equilibrium between primary productivity and decomposition process determines the amount of SOM [2], which is controlled by soil forming factors such as climate (i.e. temperature and precipitation) and vegetation (i.e. quality and quantity of litter fall) as well as soil properties such as texture and mineralogy [3]. Of the soil forming factors, climate as independent factor in the state-factor model of Jenny [4] represents one of the most important factors determining SOM content [5]. The effects of climate on soil properties have been studied using climosequences if all state-factors except climate are relatively constant [6]; however, in empirical field studies, it is difficult to isolate climosequences from climo-biosequences due to changes in vegetation with regional climate. Examining soils within a mountain range is considered as a common form of climosequence and/or climo-biosequence [7].

Tropical mountain soils have received more attention of late because they are important in organic matter (OM) storage and considered as potential sinks for greenhouse gases [8,9]. Generally, decrease in temperature with rising elevation and concomitant reduction in OM decomposition would increase C content [7]. Townsend et al. [10], Garten and Hanson [11], and Tsai et al. [12] reported this trend. In addition, the chemical structure of SOM can change along climatic and bioclimatic gradients [1,5,13,14,15,16]. The decomposition of plant residues is mainly associated with the decline in polysaccharides and accumulation of aliphatic structures [17]. In this regard, one can predict the increase in the content of polysaccharides with increasing elevation. For example, Faz Cano et al. [15] and Dalmolin et al. [5] found the increase in O-alkyl C proportion with increasing elevation.

The Main Range of Peninsular Malaysia runs parallel to the long axis of the peninsula from Thailand's borders in the north toward Tampin, Negeri Sembilan in the south [18]. The Main Range is composed of fairly uniform parent material which provides gradients of soil forming factors such as climate and vegetation which form various soil types with different potential to store OM [19]. Increase in OM accumulation with increasing elevation in the Main Range was reported by Whitmore and Burnham [20], Burnham [21], and Paramananthan [19] . Despite the attempts made to characterize the soils along an elevation gradient in the Main Range, there is still a dearth of information on OM characteristics and the impacts of environmental controls, particularly climate and vegetation, on it. Climate and vegetation have been considered as two discrete variables in the context of the conceptual models of pedogenesis. The research question is whether differences in C contents and structural characteristics of OM in soils of a climo-biosequence can be ascribed to single variable or co-variation of these variables. To answer this question, the present study was conducted to investigate the impacts of climate and vegetation on C contents and structural characteristics of OM in soils of a climo-biosequence in the Main Range of Peninsular Malaysia.

2. MATERIALS AND METHODS

2.1 Study Area

A sequence of four soil profiles along an elevation gradient in the Main Range of Peninsular Malaysia was investigated (Figure 1). Variation in climate and vegetation along the respective elevation gradient makes major differences among the study sites. Therefore, within the context of state-factor model of Jenny [4], attempts were made to fix all independent factors except climate and vegetation. Thus, it is assumed that variation in pedogenesis results from climate and vegetation and the effects of other factors are negligible.

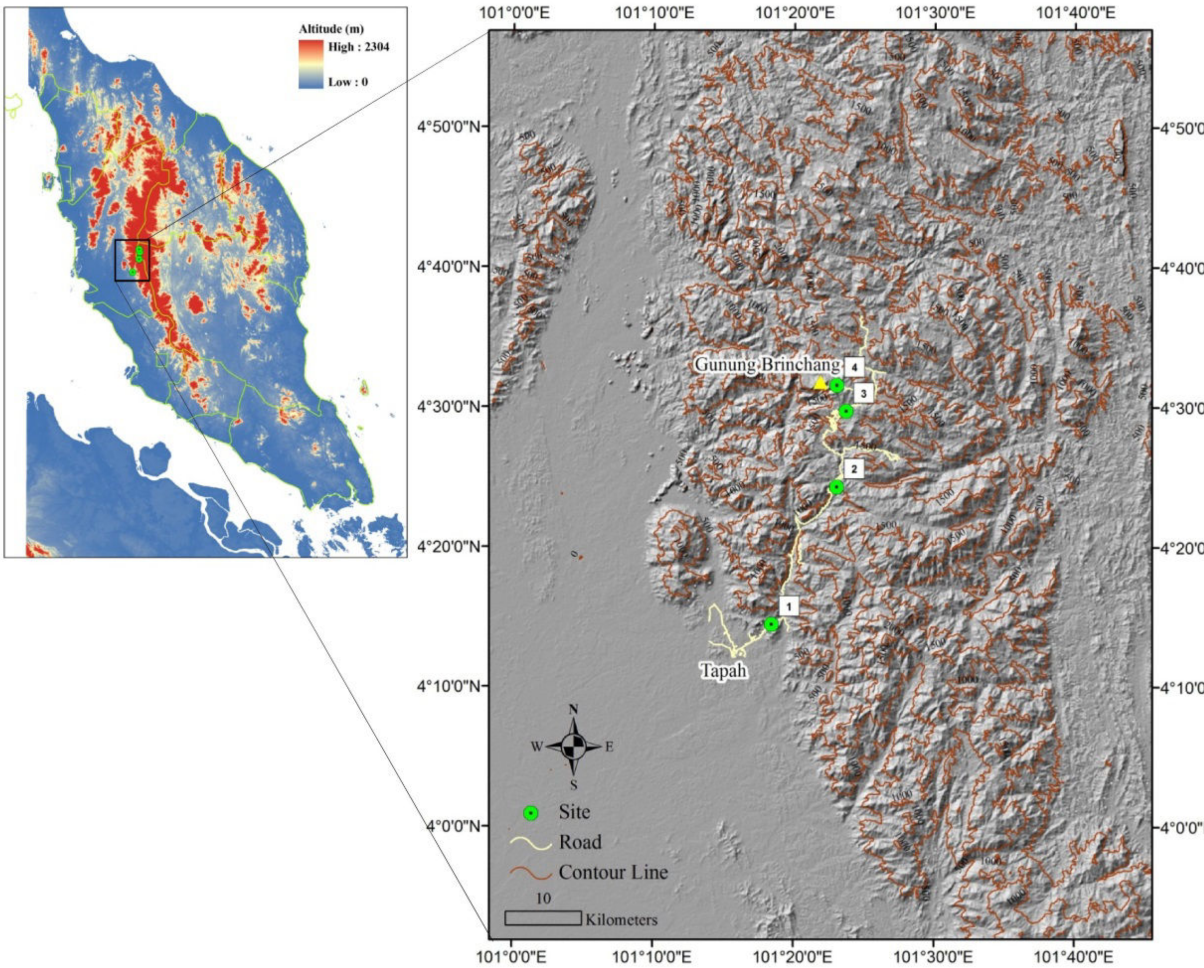

Figure 1: Location of the investigated sites (1-4) along an elevation gradient in the Main Range of Peninsular Malaysia from near Tapah to Gunung Brinchang, Cameron Highlands. The map was prepared using GIS (data source for contour lines and hillshade: SRTM DEM with 90 m resolution; road: topographic map (1:50000); points: GPS surveying)

Climatic data of the study area were collected from two meteorological stations: (1) Hospital Tapah (04°12'N, 101°16'E) located at 35.1 m asl; and (2) Cameron Highlands (04°28'N, 101°22'E) located at 1545 m asl. Based on 10 years (2003–012) of records, the mean annual rainfall was 3282 mm at Hospital Tapah and 2977 mm at Cameron Highlands. The amount of rainfall does not necessarily increase with elevation in the Main Range of Peninsular Malaysia [22,23]. However, horizontal precipitation due to fog occurrence and duration as additional water input increase with elevation [23]. According to Kumaran [23], fog was persistent at elevations above 1900 m asl in the study area. All the study sites were located on the western slopes (windward), which receive slightly higher precipitation (rainfall and fog) due to their close proximity to the coastlines. The mean annual temperature decreased from 26.9 °C recorded at Hospital Tapah (monthly minimum=22.7, monthly maximum=33.6) to 18.0 °C recorded at Cameron Highlands (monthly minimum=15.4, monthly maximum=22.5) (the lapse rate of 5.9°C/1000 m).

As a function of climatic factors, four distinct vegetation zones occur with increasing elevation, progressing from hill dipterocarp forest (<750 m asl) through upper dipterocarp forest (750-1200 m asl), oak-laurel and myrtaceous forest (1200-1800 m asl), and ericaceous forest at high elevations (>1800 m asl) [18]. All the soils formed on granitoid parent material [19]. The underlying granitoid bedrock in the study area belongs to the Main Range Province [24] and is of Triassic age (200-230 Ma) [24,25]. All soil sampling sites were located on similar geomorphic positions and characterized by steep slopes (20-30%). The geomorphic age was assumed to be similar.

2.2 Soil Sampling

Three major elevation zones were identified due to variation in environmental conditions (climatic conditions and vegetation) including foothill, lower montane, and upper montane zones (Figure 2). Several soil pits were dug and studied in the major elevation zones. Four soil profiles (P1-P4) were selected and assumed to be representatives of the elevation zones in the study area (Table 1). Two soil pits were dug in the lower montane zone due to vegetation change (Figure 2). All the study sites were selected in the primary forests with no accelerated soil erosion and human perturbation. The coordinate and elevation of soil profiles were recorded using global positioning system (GPS) (Garmin GPSmap 76CS x). Soil profile description and soil sampling were carried out based on standard procedures [26]. Munsell Soil Color Charts [27] was used to determine soil color. Soil color was determined in the moist condition, which is considered as a standard condition for humid regions [26]. Undisturbed soil cores were collected from the genetic horizons in order to determine bulk density [28]. Bulk density of some surface organic horizons with partially decomposed materials that were not cohesive enough to fill the core sampler completely was measured by excavation method [29]. Soils were classified according to Keys to Soil Taxonomy [30].

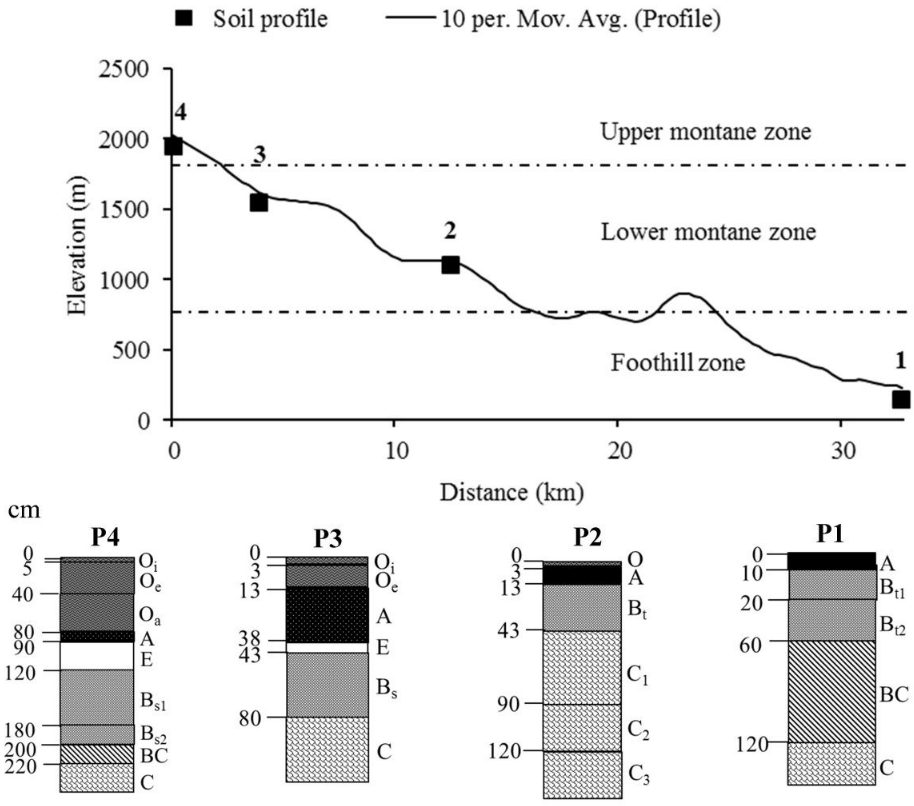

Figure 2: Soil profiles along a climo-biosequence in the Main Range of Peninsular Malaysia

Table 1: General description of the study sites

Site/soil profile	Elevation (m asl)	Soil moisture-temperature regimes[a]	Forest formation[b]	Vegetation[c]	Non-vascular epiphytes[b]	Geological formation[a]
1	155	Udic-Isohyperthermic	Lowland rainforest	*Shorea leprosula; Intsia palembanica; Artucarpus elasticus; Orania sylvicola*	Occasional	Quartz monzonite (Adamellite)
2	1129	Perudic-Isohyperthermic	Lower montane rainforest	*Shorea platyclados; Livistona speciosa; Duabanga grandiflora; Cyathea contaminans*	Occasional to abundant	Granite
3	1567	Perudic-Isothermic	Lower montane rainforest	genus of *Syzygium*	Occasional to abundant	Granite
4	1946	Perudic-Isomesic	Upper montane rainforest	Ericaceous genera (e.g. *Rhododendron*); *Holttumochloa magica*	Often abundant	Granite

[a] From Paramananthan [19]
[b] From Kumaran [23]
[c] From B. Perumal, Malaysian Nature Society, personal communication

2.3 Soil Analysis

Bulk soil samples from all genetic horizons were air-dried, gently ground, and passed through 2 mm sieve prior to the physical and chemical analyses. Particle-size distribution was determined by the pipette method [31]. Soil pH was measured using a glass electrode in a supernatant suspension of 1:2.5 soil/water and KCl ratio [32]. For pH measurement of the organic horizons, a 1:10 soil/solution ratio was used. Total C was determined by dry combustion method using LECO TruMac series. The absence of inorganic C was confirmed by 4 mol L^{-1} hydrochloric acid (HCl) [33]; therefore, the concentration of total C was equal to organic carbon (OC). Kjeldahl method was used for determination of total Nitrogen (N) [34]. Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined by leaching method with 1 mol L^{-1} ammonium acetate (NH_4OAc) at pH 7 and collected soil leachates were subjected to analysis by Atomic Absorption Spectrophotometer (Perkin Elmer Analyst 400) [35]. Exchangeable aluminum was extracted by 1 mol L^{-1} potasium chloride (KCl) [36]. The Al concentration in the extract was determined by ICP-OES (Perkin Elmer Optima 8300). Effective cation exchange capacity (ECEC) was calculated by adding exchangeable Al to the sum of NH_4OAc exchangeable bases. Base saturation was calculated by dividing the sum of NH_4OAc exchangeable bases by the ECEC and Al saturation was calculated by dividing exchangeable Al by the ECEC. The OC stock for individual soil horizon was calculated as follows:

$$SOC = C \times BD \times d \times \frac{\mathrm{kg}}{10^6\,\mathrm{mg}} \times \frac{10^4\,\mathrm{cm}^2}{\mathrm{m}^2}$$

where SOC is OC stock (kg m^{-2}) in individual soil horizons of thickness d (cm), C is the measured concentration of carbon in each soil horizon (mg g^{-1}), and BD is the bulk density (g cm^{-3}) of the respective soil horizon corrected for coarse fractions (>2 mm). SOC stocks for the upper 100 cm of soil profiles were calculated by summing up C stocks for the individual soil horizons.

2.4 FTIR Spectroscopy

Infrared absorption characteristics of OM in soil samples from O, A, and B-horizons were analyzed by Fourier-transform infrared (FTIR) spectroscopy. Soil samples were finely ground (<250 µm) and heated at 60 °C for 48 hours to reduce the influence of water content on interpretation of the spectra. FTIR measurements were performed with a Perkin Elmer Spectrum 100 spectrometer. Attenuated total reflectance (ATR) method was applied to record spectra over the range of 4000 to 400 cm^{-1}. The recording was carried out with a resolution of 4 cm^{-1} and 16 scans per sample. Peak analysis, including baseline subtraction and peak integration, was done using OriginPro 9.1 (Originlab Corporation, Northampton, USA). Nine bands between 3400 and 950 cm^{-1} were evaluated. The same starting and ending points were used for the integration of individual bands. The relations between FTIR bands and OC concentration were evaluated by the correlation coefficient which was performed using OriginPro 9.1 software (Originlab Corporation, Northampton, USA).

3. RESULTS AND DISCUSSION

3.1 Soil Morphology and Classification

The main morphological characteristics of the investigated soil profiles are presented in Table 2. All the soils were well drained. At low elevations (<750 m asl: P1) under hill dipterocarp forest, the soil was classified as Udult. The observed diagnostic horizon was argillic horizon. Argillic horizon in P1 was identified in the field by the increase in clay content and the presence of clay film on the surface of peds and pores. Soil color in the B-horizon became less red in hue and low in value with increasing elevation. The maximum redness was observed in P1 (B_{t1}:7.5YR; B_{t2}:5YR; Table 2).

At the middle elevations (750-1200 m asl: P2) under upper dipterocarp forest, the soil was classified as Humult. Thin O-horizon (3 cm) derived from leaf litter was formed on the soil surface. The thickness of the argillic horizon decreased with increasing elevation from 50 cm in P1 to 30 cm in P2. There was no evidence of the presence of argillic horizon at the elevations above 1200 m asl. At the middle elevations (1200-1800 m asl: P3), the soil was classified as Orthod. This podzolized soil had a horizon sequence of O_i-O_e-A-E-B_s-C. Above 1200 m asl, OM began to accumulate; P3 had 13 cm O-horizon under myrtaceous forest. The spodic horizon was overlaid by weakly developed albic horizon. The matrix color of pale brown in hue with low chroma (10YR 6/3) indicated the presence of albic horizon and the pedogenic process of eluviation. At the highest elevation (>1800 m asl: P4) under ericaceous forest, the soil was classified as Saprist. Thick organic layer (80 cm) on the surface was observed at the highest site. The representative sequence of O-horizons was O_i-O_e-O_a. This high mountain organic soil occurred not directly on the bedrock or fragments of bedrock, but rather on the mineral soil horizons (Table 2 and Figure 2). The bottom tier included thick albic horizon (30 cm), followed by spodic horizon.

Table 2: Selected morphological characteristics of the studied soil profiles and classification of the soils according to Keys to Soil

Horizon	Depth (cm)	Matrix Colour	Field Texture[a]	Structure[b]	Consistence[c]	Remarks
P1: Fine, kaolinitic, isohyperthermic Typic Paleudult						
A	0-10	10YR 4/6	SCL	3fgr	FR	Many roots and faunal channels
B_{t1}	10-30	7.5YR 6/8	C	3fsbk	FI	Presence of clay films
B_{t2}	30-60	5YR 6/8	C	3fsbk	FI	Presence of clay films
BC	60-120	2.5YR 5/8	CL	1msbk	FR	
C	>120	2.5YR 5/8	SCL	m	FR	
P2: Fine, kaolinitic, isohyperthermic Typic Haplohumult						
O	0-3					
A	3-13	10YR 4/6-4/4	CL	3fgr	FR	Common fine roots
B_t	13-43	10YR 5/8	C	3fsbk	FI	Presence of clay films
C_1	43-90	5YR 6/8	L	1msbk	FR	
C_2	90-120	7.5YR 6/8	L	1msbk	FR	
C_3	>120	7.5YR 5/8	L	m	VFR	
P3: Coarse-loamy, isotic, active, isothermic Typic Haplorthod						
O_i	0-3	10YR6/4				
O_e	3-13	5YR2.5/2				
A	13-38	10YR 5/3	LCOS	1vfsbk	VFR	
E	38-43	10YR 6/3	SCL	2fsbk	FI	
B_s	43-80	10 YR 7/8	L	2msbk	FR	Patches of 10YR4/4 and 10YR2/2
C	>80	5 YR 6/8	L	m	FR	
P4: Loamy, mixed, dysic, isomesic Terric Haplosaprist						
O_i	0-5	7.5YR3/2				
O_e	5-40	5YR2.5/2				
O_a	40-80	5YR2.5/1				
A	80-90	10YR 3/3	SL	1fgr	FR	
E	90-120	10 YR 6/3	SL	1fsbk	FI	
B_{s1}	120-180	10 YR 6/8	SIL	2msbk	FR	Patches of 5YR2.5/1 and 5YR3/4
B_{s2}	180-200	10 YR 4/4	L	2msbk	FR	Patches of 5YR2.5/1
BC	200-220	7.5 YR 6/8	L	1msbk	FR	
C	>220	10 YR 7/3	SL	sg	L	

[a] LCOS: loamy coarse sand, SL: sandy loam, SCL: sandy clay loam, SIL: silt loam, L: loam, CL: clay loam, C: clay.
[b] 1: weak, 2: moderate, 3: strong- vf: very fine, f: fine, m: medium- sg: single grain, m: massive, sbk: subangular blocky, gr: granular.
[c] L: loose, VFR: very friable, FR: friable, FI: firm.

3.2 Soil Physical and Chemical Characteristics

Generally, the soil reaction was acidic throughout all the profiles. In the mineral horizons, the pH in H_2O ranged from 4.00 to 5.99 (average of 4.74) and 2.96 to 5.32 (average of 3.89) for the pH in KCl (Table 3). The values of pH in KCl were lower than pH in H_2O; however, the trends in both within the soil profiles were identical. Differences between the values of the two pH measurements were linked to the salt concentration. The concentrated KCl can displace Al ions on the exchange sites. The Al ions can hydrolyze and lower the pH [37]. The pH in the A-horizons slightly decreased with increasing elevation from P1 to P4. Organic horizons compared with the mineral ones showed higher concentrations of basic cations (Table 3). Effective cation exchange capacity (ECEC) was low (<12 cmol$_c$ kg^{-1}) in all soil horizons. Base saturation in the A-horizon of P1 was 36.5%; it decreased to 15.2, 9.3, and 2.3% in P2, P3, and P4, respectively. Results showed a decreasing trend of base saturation with increasing elevation. This decreasing trend could be due to increasing precipitation (rain and fog) with increasing elevation which, in turn, resulted in strong leaching of bases and relative enrichment of Al. Therefore, soils at high elevation contained higher values of Al saturation. For example, in P4, more than 90% of the exchange sites in the topsoil were occupied by Al. In the study area, clay content diminished with increasing elevation (Table 3). The amount of clay ranged from more than 40% in the low elevation soils (accumulated in the B-horizons of P1 and P2) to less than 25% in the high elevation soils. Bulk density in the A-horizons were low in all soils (<1 g cm^{-3}) (Table 3). The spodic B-horizon at the highest site (P4) had the lowest value of bulk density (0.34 g cm^{-3}) among all mineral horizons along the studied climo-biosequence. High content of OC in the spodic B-horizon of P4 contributed to the low value of bulk density in this horizon.

Table 3: Selected physical and chemical properties of the studied soil profiles

Horizon	pH (H_2O)	pH (KCl)	BD^a	Clay	Silt	Sand	C	N	C/N	C-stock	Sum of bases	Al^{3+}	ECEC	BS	Al-sat
			g cm^{-3}	%			g kg^{-1}			kg m^{-2}	cmol$_c$kg^{-1}			%	
							P1								
A	4.54	3.76	0.59	28.4	17.9	53.5	22.0	2.5	8.8	5.7	0.69	1.20	1.89	36.5	63.5
B$_{t1}$	4.85	3.90	1.07	41.1	15.6	43.2	8.5	1.2	7.1		0.22	1.38	1.60	13.8	86.3
B$_{t2}$	4.87	3.96	1.06	43.3	20.1	36.4	6.8	0.8	8.5		0.31	1.24	1.55	20.0	80.0
BC	5.10	3.99	1.34	33.1	23.8	42.8	2.6	0.3	8.7		0.26	0.90	1.16	22.4	77.6
C	5.19	4.04	1.22	23.8	25.6	50.4	1.8	0.4	4.5		0.27	0.85	1.12	24.1	75.9
							P2								
O	4.84	3.71	0.10	n.d^b	n.d	n.d	427.9	13.6	31.5	8.9	7.69	1.40	9.09	84.6	15.4
A	4.56	3.60	0.48	36.2	26.1	37.6	33.3	2.9	11.5		0.58	3.23	3.81	15.2	84.8
B$_t$	4.45	3.73	0.96	43.5	22.8	33.6	13.2	1.1	12.0		0.42	3.41	3.83	11.0	89.0
C$_1$	4.62	3.82	0.98	17.9	37.7	44.3	7.3	0.7	10.4		0.17	2.21	2.38	7.1	92.9
C$_2$	4.79	3.85	0.95	17.7	37.7	44.4	1.7	0.2	8.5		0.36	2.24	2.60	13.8	86.2
C$_3$	4.77	3.87	0.99	13.7	39.5	46.7	2.0	0.3	6.7		0.20	2.48	2.68	7.5	92.5
							P3								
O$_i$	4.41	3.04	0.13	n.d	n.d	n.d	432.0	21.9	19.7	15.8	10.04	1.24	11.28	89.0	11.0
O$_e$	4.21	2.96	0.18	n.d	n.d	n.d	195.8	10.5	18.6		3.77	3.70	7.47	50.5	49.5
A	4.00	2.96	0.86	5.10	16.1	78.6	13.3	1.0	13.3		0.15	1.46	1.61	9.3	90.7
E	4.09	3.32	1.14	24.9	21.2	53.7	13.1	0.8	16.4		0.11	8.79	8.90	1.2	98.8
B$_s$	4.22	3.78	0.79	20.1	35.0	44.7	29.2	1.5	19.5		0.10	6.63	6.73	1.5	98.5
C	4.67	4.04	1.40	11.8	36.6	51.4	2.5	0.3	8.3		0.08	4.89	4.97	1.6	98.4
							P4								
O$_i$	4.16	2.72	0.13	n.d	n.d	n.d	495.0	14.0	35.4	49.6	5.69	0.25	5.94	95.8	4.2
O$_e$	3.95	2.28	0.14	n.d	n.d	n.d	505.3	13.8	36.6		3.41	1.25	4.66	73.2	26.8
O$_a$	4.24	2.88	0.15	n.d	n.d	n.d	266.0	4.1	64.9		2.04	2.38	4.42	46.2	53.8
A	4.13	3.24	1.09	10.9	11.5	77.3	43.2	1.6	27.0		0.09	3.76	3.85	2.3	97.7
E	4.59	3.79	1.23	15.3	17.9	66.7	8.8	0.7	12.6		0.10	3.36	3.46	2.9	97.1
B$_{s1}$	5.99	5.32	0.34	12.2	54.2	32.7	63.9	1.5	42.6		0.13	0.04	0.17	76.5	23.5
B$_{s2}$	5.47	4.74	0.47	20.5	36.7	42.4	26.5	1.1	24.1		0.13	0.23	0.36	36.1	63.9
BC	4.97	4.01	n.d	18.2	31.4	50.3	3.9	0.2	19.5		0.09	2.68	2.77	3.2	96.8
C	5.02	4.02	n.d	4.90	25.2	69.6	1.8	0.1	18.0		0.10	2.71	2.81	3.6	96.4

[a] The bulk density of O-horizon of P2 and O$_i$ and O$_e$ horizons of P3 was measured by excavation method

[b] not determined

3.3 Soil Organic Carbon Concentration and Stock

P1 had no organic horizon and consisted of mineral horizons with OC concentration decreasing consistently with depth (Table 3). P1 had OC stock value of 5.7 kg m^{-2} and low C:N ratio (<10). At low elevations (<750 m asl), high temperature provided adequate energy for biological activities; therefore, rapid decomposition of OM could occur. Thus, Udults at low elevations were linked to low storage of C. In this area, SOC storage was below the global estimate for tropical Ultisols (8.3 kg m^{-2}) as stated by Eswaran et al. [38]. At middle elevation (P2), leaf litter accumulated on the surface. Thin forest litter layer at P2 had OC concentration of 427.9 g kg^{-1} and C:N ratio of 31.5. P2 showed similar vertical distribution pattern of C concentration as that of P1. SOC stock value to 1 m depth of Humults at middle elevations was similar to Acrisols reported by Podwojewski et al. [8] for the Fan Si Pan Mountain in Vietnam.

The OC concentration of the O$_i$ horizon was 432.0 g kg^{-1} for P3, dropping to 195.8 g kg^{-1} in the O$_e$ horizon (Table 3). In contrast to cumulative distribution pattern observed in the P1 and P2, OC concentrations in the P3 and P4 decreased with depth and subsequently increased in the spodic horizons (eluviation-illuviation pattern). Calculated SOC stock for Spodosols in the Main Range (15.8 kg m^{-2}; Table 3) was lower than that of its counterparts in Vietnam (1975 m asl) [8] and Mexico (2050 m asl) [39], in which SOC stocks were >20 kg m^{-2}. In the podzolized soil profile (P3), the organic compartment contained 32.9% of the total C stock in 1 m depth, while at the highest site (P4) more than 80% of SOC stock in 1 m depth corresponded to organic layers stock (Figure 3). At high elevations (P4), thick organic layers caused large value of C storage (49.6 kg m^{-2}). Organic horizons in P4 contained wide C:N ratio, reflecting low nitrogen concentration of ericaceous and mosses litters.

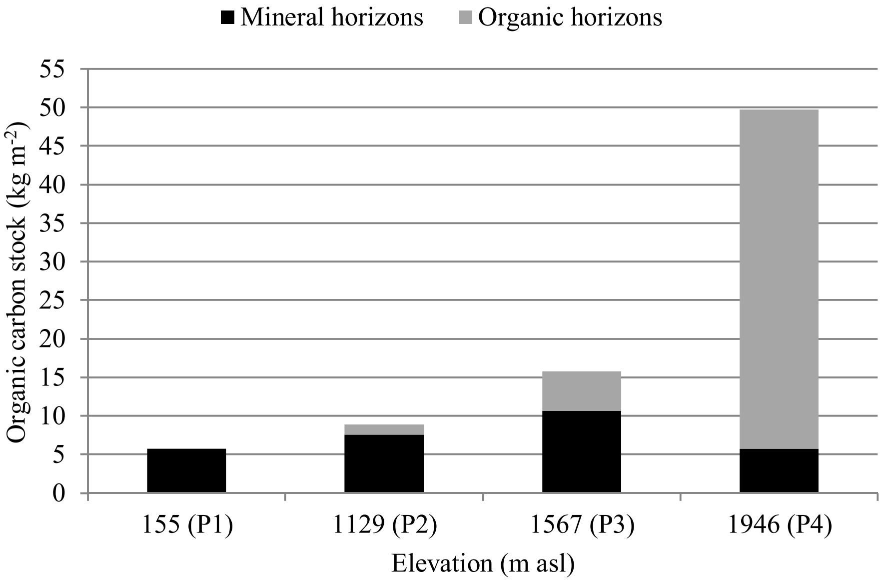

Figure 3: Organic carbon stock distribution in the mineral and organic horizons within 1 m depth of four soil profiles along the studied climo-biosequence

Increase in SOC content along the studied climo-biosequence in the Main Range was consistent with other studies conducted elsewhere in the tropics [8,9,10,40]. The observed increasing trend of SOC content along the studied climo-biosequence resulted from the complex combination of several factors including temperature and litter quality. Decrease in temperature with rising elevation slowed down the decomposition of SOM by way of reducing microbial and faunal activities [7]. The mean annual temperature of tropical upper montane forests is low and bears a resemblance to temperate forests; however, the seasonal fluctuation is small and similar to that of tropical lowland forests [41]. Therefore, decomposition of SOM in tropical upper montane zone is expected to be slow at a constant rate throughout the year. Additionally, decrease in the decomposition could be related to litter quality. Poor degradability of litters from mosses could retard the process of decomposition in areas of high elevation. In the study area, mosses biomass are abundant in the forests of the upper montane zone (>1800 m asl) [23]. Hobbie et al. [42] stated three reasons for the slow decomposition of litters from *Sphagnum* spp.: (1) low nutrient concentration; (2) recalcitrant nature; and (3) capable to produce compounds with antimicrobial characteristics. In the study area, climate and vegetation varied with elevation; thus, SOM distribution and accumulation responded to elevation and can be explained as co-variation of these variables instead of single variable.

3.4 FTIR Spectroscopy and Structural Characteristics of Soil Organic Matter

Infrared spectroscopy is of considerable value in qualitative and quantitative studies of SOM structures. Soil samples from O, A, and B-horizons were analyzed by FTIR spectroscopy. There were distinct changes in the abundance of IR bands with soil depth in all soil profiles. The resulting infrared spectra of soils from four soil profiles are shown in Figure 4. The main IR absorption bands and their corresponding assignments for the soil samples are summarized in Table 4.

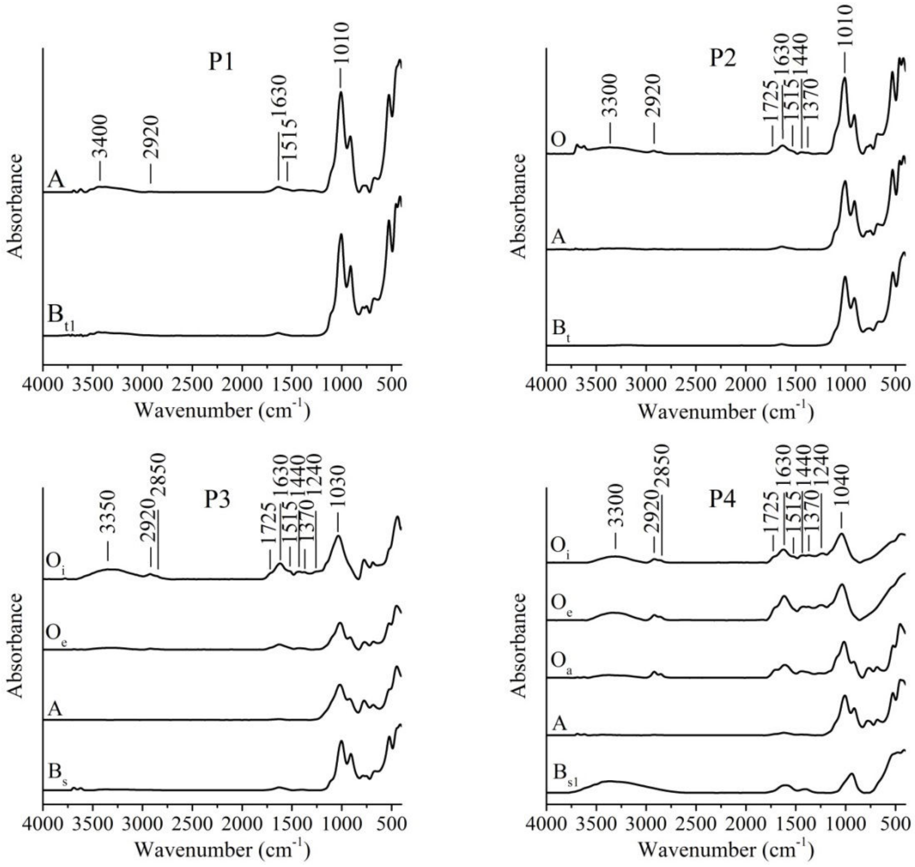

Figure 4: FTIR spectra of soil samples from selected horizons of P1-P4 along the studied climo-biosequence. Spectra were stacked by Y offsets

Table 4: Main IR absorption bands and assignments for the soil samples

Band (cm^{-1})	Base points for the integrated bands (cm^{-1})	Assignment
2920	2800-3000	Asymmetric and symmetric stretching vibrations, respectively, of aliphatic C-H bonds in methyl and/or methylene[a,b]
1725	1700-1790	C=O stretching vibration of carboxyl groups, ketones and aldehydes[c]
1630	1570-1700	C=O stretching vibration of carboxylates and Amides, aromatic C=C stretching vibration[b,d]
1515	1480-1570	Aromatic C=C stretching vibration[b]
1440	1400-1480	C-H bending vibration of aliphatic[b]
1370	1330-1400	C–O stretching vibration of phenolic OH[c], C-H bending vibration[e], COO^- antisymmetric stretching vibration[f], $CO\text{-}CH_3$[g]
1240	1200-1290	C-O stretching vibration and O-H bending vibration of COOH[b], C–O stretching vibration of aryl ethers and phenols[c]
1040	950-1170	C-O stretching vibration of polysaccharides, Si-O vibration of minerals[d]

[a] Ellerbrock and Gerke [43]
[b] MacCarthy and Rice [44]
[c] Senesi et al. [45]
[d] Haberhauer et al. [46]
[e] Tatzber et al. [47]
[f] Stevenson [48]
[g] Duboc et al. [49]

Generally, the spectra of soils at the four sites exhibited similar peak patterns. Aliphatic (either C-H stretching vibrations at 2920 and 2850 cm^{-1} or C-H bending vibration at 1440 cm^{-1}), aromatic (band 1630 cm^{-1}), carboxyl group (ill-resolved C=O stretching vibration at 1725 cm^{-1}), and polysaccharide (C-O stretching vibration at 1040 cm^{-1}) formed the backbone structures of the spectra. Other bands located in the fingerprint area (1000-1500 cm^{-1}) were assigned to couple vibrations. Bands in this region showed the complex nature of analyzed samples as stated by Haberhauer et al. [46]. Organic horizons showed higher number of absorption bands, especially in the fingerprint area as compared with mineral layers. This is in accordance with the results of humus and mineral layers reported by Tatzber et al. [47]. Decreasing trend in the intensity of the bands in the fingerprint area from O_i to A was evident. Similar pattern was reported for Irish and Austrian forest litter by Haberhauer et al. [46]. In the mineral horizons, low concentration of organic materials and the presence of mineral absorbance could weaken the signals of SOM. IR spectra of mineral horizons were dominated by mineral characteristics of hydroxyl and Si-O. The bands between 1000 and 1050 cm^{-1}, which indicated the presence of polysaccharides in the organic horizons, could also be assigned to Si-O vibration of minerals in the A and B-horizons.

The aliphatic bands were more pronounced in the organic horizons of P3 and P4. The intensities of aliphatic stretching vibration (band 2920 cm^{-1}) and aliphatic bending vibration (band 1440 cm^{-1}) increased with depth, from O_i to O_a in P4 (Table 5). The increase in aliphatic bands with depth may be associated with the increase in the decomposition of plant materials and the process of humification. Similar trend was observed by Rumpel et al. [50] for Podzol and Cambisol under spruce and beech forest, respectively using ^{13}C NMR spectroscopy. This is in contrast to Haberhauer et al. [46] who reported no significant changes in aliphatic stretching vibration (band 2920 cm^{-1}) for the Irish and Austrian forest litter and Djukic et al. [16] who reported decrease of this band with depth in the soils along an Alpine elevation gradient in Austria. The band at wave number 2920 cm^{-1} was strongly correlated with the bands at 1440, 1630, and 1725 cm^{-1} (Table 6).

Table 5: Areas of nine FTIR bands and their relative intensities

Horizon	**Bands (cm^{-1}) and relative intensities (%)**								
	1040	**1240**	**1370**	**1440**	**1515**	**1630**	**1725**	**2920**	**3400**
					P1				
A	69.73 (83.3)	0.37 (0.4)	0.5 (0.6)	0	0.61 (0.7)	2.98 (3.6)	0	0.22 (0.3)	9.28 (11.1)
B_{t1}	56.93 (88.4)	0	0	0	0	1.73 (2.7)	0	0	5.73 (8.9)
					P2				
O	81.42 (77.4)	0.19 (0.2)	0.42 (0.4)	0.94 (0.9)	2.05 (1.9)	8.42 (8.0)	1.45 (1.4)	1.65 (1.6)	8.63 (8.2)
A	63.86 (91.2)	0	0	0	0.58 (0.8)	2.75 (3.9)	0	0	2.81 (4.0)
B_t	58.76 (98.1)	0	0	0	0	1.13 (1.9)	0	0	0
					P3				
O_i	85.15 (54.9)	3.73 (2.4)	1.2 (0.8)	2.29 (1.5)	4.82 (3.1)	18.49 (11.9)	3.19 (2.1)	4.22 (2.7)	31.98 (20.6)
O_e	48.23 (73.3)	0.44 (0.7)	0.53 (0.9)	0.78 (1.2)	0	6.37 (10.4)	1.21 (1.8)	1.33 (2.0)	6.36 (9.7)
A	59.77 (98.3)	0	0	0	0	1.04 (1.7)	0	0	0
B_s	57.43 (89.0)	0	0.31 (0.5)	0	0	3.94 (6.1)	0	0	2.82 (4.4)
					P4				
O_i	55.2 (46.0)	1.65 (1.4)	1.49 (1.2)	2.22 (1.9)	3.36 (2.8)	18.68 (15.6)	4.51 (3.8)	6.24 (5.2)	26.61 (22.2)
O_e	62.65 (40.4)	2.8 (1.8)	1.88 (1.2)	3.55 (2.3)	0	33.54 (21.6)	8.11 (5.2)	9.13 (5.9)	33.6 (21.6)
O_a	70.77 (58.2)	0.44 (0.4)	1.37 (1.1)	2.78 (2.3)	0	18.88 (15.5)	5.43 (4.5)	9.63 (7.9)	12.25 (10.1)
A	67.42 (89.7)	0	0	0.43 (0.6)	0	3.86 (5.1)	0.91 (1.2)	0.68 (0.9)	1.84 (2.4)
B_{s1}	23.17 (25.1)	0	1.71 (1.9)	0	0	11.4 (12.4)	0	0	55.98 (60.7)

Increase in the area of the bands at 1240, 1370, 1630 cm^{-1} of the O_e in P4 was due to the relative enrichment of aromatic compounds (Table 5). As the hemic soil materials were at the intermediate degree of decomposition, the aromatic compounds were not yet exposed to microbial attack. Therefore, relative accumulation of these compounds is expected. Marked changes in the IR bands along the studied climo-biosequence were observed (Table 5). FTIR spectra for the surface organic horizons (O-horizon in P2 and O_i horizons in P3 and P4) showed an increase of aliphatic band (2920 cm^{-1}), carboxylic (1725 cm^{-1}), carboxylate, and aromatic C=C (1630 cm^{-1}) and concomitant decrease of polysaccharides from upper dipterocarp forest at middle elevations to ericaceous forest at high elevation (Table 5). Although it was expected that the most labile compound such as polysaccharides and polysaccharide like materials to increase with cooler and moisture climate, the content of polysaccharides at the highest site (P4) was lower than those at the other sites.

An increase in the aliphatic band along the climo-biosequence in the current study is in contrast to Amelung et al. [1] who found positive correlation between alkyl C and mean annual temperature. An accumulation of the aliphatic compounds at the O_i horizon of the soils at high elevations likely resulted from selective preservation of aliphatic structures derived from original plant materials, not in situ synthesis by microorganisms [51]. The higher content of aliphatic compounds and the lower content of polysaccharides in the soils at high elevation sites could be explained by the dominance of plant with high waxes, such as ericaceous and mosses. The strong correlation between the bands at wavenumber 2920 and 1725 cm^{-1} could indicate the presence of waxy materials as explained by Duboc et al. [49]. This also explains the positive correlation coefficient (r = 0.77, P=0.0012) found between the concentration of OC and aliphatic band (2920 cm^{-1}) (Table 6). An increase in the proportion of aliphatic structures in the soils at high elevations due to input of waxes was also reported by Djukic et al. [16] for a climosequence in Austria. The changes in functional groups and the related compounds along the studied climo-biosequence could be more attributed to changes in vegetation composition (substrate quality) than climatic conditions.

Table 6: Coefficient of correlation between FTIR band areas for the selected horizons (O, A, and B) of the four soil profiles and OC concentration (n = 14). A 2-tailed test of significance was used

Band (cm^{-1})	1040	1240	1370	1440	1515	1630	1725	2920	3400	OC
1040	1.00									
1240	0.38	1.00								
1370	-0.20	0.63^{*}	1.00							
1440	0.34	0.78^{**}	0.75^{**}	1.00						
1515	0.48	0.69^{**}	0.31	0.40	1.00					
1630	0.11	0.78^{**}	0.89^{***}	0.94^{***}	0.34	1.00				
1725	0.25	0.71^{**}	0.75^{**}	0.98^{***}	0.26	0.95^{***}	1.00			
2920	0.27	0.63^{*}	0.75^{**}	0.97^{***}	0.26	0.90^{***}	0.97^{***}	1.00		
3400	-0.39	0.52	0.87^{***}	0.43	0.33	0.66^{**}	0.42	0.37	1.00	
OC	0.36	0.77^{**}	0.69^{*}	0.87^{***}	0.65^{*}	0.84^{***}	0.82^{***}	0.77^{**}	0.47	1.00

*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level; *** Correlation is significant at the 0.001 level

4. CONCLUSION

The following conclusions were obtained from this study:

1. Differences in C contents along the studied climo-biosequence are related to the co-variation of climate and vegetation instead of climate alone by influencing the process of decomposition;
2. Vegetation, not climate, is the major driver of differences in structural characteristics of OM along the studied climo-biosequence. With increasing elevation and subsequent changes in vegetation composition from more labile to recalcitrant compounds, the influence of substrate quality over climatic condition becomes more prominent;
3. The impacts of climatic factors and vegetation composition on the C contents and structural characteristics of OM in soils are more pronounced in the surface horizons (particularly O-horizon). With increasing depth, the role of other factors such as pedogenic processes and soil properties become evident; and
4. Our results confirmed that FTIR spectroscopy of soil samples can be a rapid, low-cost, and informative means of measurement for studying SOM in order to monitor structural changes induced by environmental factors (i.e. climate and vegetation). This methodology has limitation for mineral horizons; therefore, the use of subtractive FTIR spectroscopy could be helpful to improve FTIR markers of OM in soil samples, but more research is needed to evaluate this method.

5. ACKNOWLEDGMENT

The authors would like to thank Universiti Putra Malaysia 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. We would also like to express our gratitude to Balu Perumal, Dr Sanath Kumaran, and Dr S. Paramananthan for many helpful comments and Dr Hadi Memarian for helping to produce the map of the study area using GIS.

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