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SPATIAL VARIABILITY OF SELECTED FOREST SOIL PROPERTIES RELATED TO CARBON MANAGEMENT IN TROPICAL LOWLAND AND MONTANE FORESTS

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JEYANNY V, BALASUNDRAM SK, HUSNI MHA, WAN RASIDAH K & ARIFIN A. 2013. Spatial variability of selected forest soil properties related to carbon management in tropical lowland and montane forests. A better understanding of spatial variability of forest soil properties related to carbon (C) sequestration will improve management strategies towards conserving forest areas that project higher C stocks. This study was aimed at determining spatial variability of soil C, C:N (nitrogen) and forest floor depth in tropical lowland and montane forests at varying topographic positions. Quadrants of 10 m × 10 m were established for soil (0–15 cm depth) and forest floor sampling along three slope positions. This amounted to 120 quadrants at the montane forest and 60, in the lowland forest. Soil and forest floor samples were geo-referenced using global positioning system. Univariate statistics, including normality check, non-spatial outlier detection and data transformation were performed on test variables, followed by variography and kriging analyses to quantify spatial variability. Results showed that spatial structure of test variables differed across topographic positions and within the lowland forest. Surface maps showed distinct spatial clustering and displayed acceptable accuracy of interpolated values. Soil C stocks were highest in the summit, followed by toeslope, sideslope and Jengka Virgin Jungle Reserve. Site specific management for carbon sequestration monitoring in tropical forest should be based on topographic delineation.

Keywords: Soil carbon, spatial variability, tropical forest, topography, management zoning

JEYANNY V, BALASUNDRAM SK, HUSNI MHA, WAN RASIDAH K & ARIFIN A. 2013. Variasi ruang ciri-ciri terpilih tanah hutan berkaitan pengurusan karbon di hutan tropika tanah pamah dan tanah tinggi. Pemahaman mengenai ciri variasi ruang tanah hutan berkaitan pengsekuestran karbon dapat memperbaiki strategi pengurusan ke arah pemuliharaan kawasan hutan sasaran yang berpotensi menyimpan stok karbon yang tinggi. Objektif penyelidikan ini adalah untuk menentukan variasi ruang karbon tanah, C:N (nitrogen) dan ketebalan lapisan organik di hutan tropika di tanah pamah dan tanah tinggi pada kedudukan topografi berlainan. Kuadrat bersaiz 10 m × 10 m telah ditubuhkan untuk pensampelan tanah (kedalaman 0 cm hingga 15 cm) dan lapisan organik di tiga kedudukan cerun. Jumlah kuadrat di hutan tanah tinggi ialah 120 manakala jumlah kuadrat di hutan tanah pamah ialah 60. Lokasi pensampelan tanah dan lapisan organik ditanda menggunakan sistem kedudukan sejagat. Analisis statistik univariat, pengesanan taburan data normal, pengesanan *outlier* dan transformasi data dijalankan atas pemboleh ubah diikuti analisis variografi dan kriging untuk penentuan variasi ruang. Hasil analisis menunjukkan pemboleh ubah struktur ruang berbeza di setiap kedudukan cerun berlainan di hutan tanah tinggi dan di hutan tanah pamah. Peta permukaan menunjukkan kelompok ruang yang berbeza dan memaparkan nilai interpolasi yang tepat. Stok karbon tanah paling tinggi di puncak bukit diikuti oleh kaki bukit, tengah bukit dan di hutan simpan dara di tanah pamah Jengka. Pengurusan khusus tapak berlandaskan kedudukan topografi berlainan perlu untuk pemantauan pengsekuestran stok karbon di hutan tropika.

INTRODUCTION

Carbon (C) storage in tropical forests has received various reviews throughout the decade. In the current scenario, climate change has taken centre stage due to atmospheric release of fossil C via anthropogenic activities mostly during the past 150 years. Atmospheric carbon dioxide is expected to reach 650–700 µmol mol^{-1} by 2075, increasing global air temperature (Houghton et al. 1995, Saxe et al. 1998). According to current projections, tropical rainforests will be warmer by 2–4 °C by the year 2100 (Corlett 2011).

The majority of C is stored in forest biomes and the total global C pools in soils are estimated to be between 1500 and 2000 Gtons (Usuga et al. 2010). Tropical soils constitute 26% of the soil organic C in the world (Batjes 1996). Malaysia, as one of the tropical countries within the Asian region, has the potential to sequester C via its forest ecosystems. At present, total forest cover in Malaysia, excluding rubber stands, is 60% (Food and Agriculture Organization 2010). However, valuable quantitative information on C sequestration in forest soils is still lacking in Malaysia, especially in the Land Use and Land Use Change and Forestry (LULUCF) sector where assessment of soil C by forest types is still unavailable (Anonymous 2009b). With a projected temperature increase of 1–3.6 °C (Anonymous 2009a), quantification of spatial variability in soil organic C and its related properties has become necessary for assessment of C stocks in Malaysia.

Soil formation factors (parent material, topography, climate, vegetation and time) are linked to soil organic C accumulation (Brady & Weil 2008). The highest amount of soil organic C in Malaysia was found in the highlands at elevations ranging from 300 to 1200 m above sea level (asl), followed by croplands at 20 to 100 m asl (Lim 2002). Belowground C stocks in a lowland forest, i.e. a 50-ha long-term ecology plot at Pasoh Forest Reserve, is 117 Mg ha^{-1} (Turner 2010). Carbon stocks in soils have also been associated with C to nitrogen (N) ratio. C:N influences the decomposition rate of organic matter, which controls the mineralisation or immobilisation of soil N. C:N is significantly influenced by altitude, parent material and their interactions (Wagai et al. 2008). C:N values are higher in uplands compared with lowlands (Silveira et al. 2009) and vary with different slope aspects and vegetation types (Yimer et al. 2006).

At present, various tools for the quantification and mapping of C stocks have emerged to replace conventional techniques. These include the global positioning system (GPS), satellite imagery and geospatial statistics for monitoring of carbon sequestration. Geospatial statistics (geostatistics) is a set of tools that has been successfully used in tropical soil studies to characterise and map the spatial variation of soil properties (Couto et al. 1997). Common geostatistical procedures include classification and modelling of spatial structure, spatial interpolation to predict values at unsampled locations and optimisation of spatial sampling (Nogueira et al. 2002, Balasundram et al. 2008). A geographical information system (GIS) integrated with geostatistics and remote sensing imagery will be able to produce efficient spatial/temporal maps for visualisation and for calculation and projection of spatial differences (Zhang & McGrath 2004), which will greatly reduce costs and human resources.

Developing spatialised maps for C stocks, C:N and forest floor depth for varying topography will allow forest managers to strategise field management zoning in order to avoid areas having significant potential in sequestering C. Spatial variability maps will facilitate decision making on which areas to conserve and which can be harvested for timber. This information will be essential for Malaysia when reporting on the LULUCF sector. Sufficient information from spatial variability maps will facilitate the provision of mechanism to define forest landscape maps that can be used in Reduced Emission from Deforestation and Forest Degradation (REDD) projects, which outline monetary values for C stocks. REDD+ goes beyond to include the role of conservation, sustainable management of forests and enhancement of forest C stocks, which can be implemented by Malaysia if necessary efforts are taken to quantify C stocks in various forest systems. Thus, this study was directed to quantify the spatial variability of soil C, C:N and forest floor depth at varying topographic positions in a tropical montane forest and in a lowland forest. This study will be useful in quantifying C stocks related to C management.

MATERIALS AND METHODS

Study site

This work was carried out at two different areas in Pahang, Malaysia, each representing a montane forest and a lowland forest. The first site is located at Sungai Kial Forest Reserve (FR), Tringkap, Cameron Highlands, Pahang (4° 31' N, 101° 26' E) with steep to very steep topography ranging from 22° to 40°. This 1.2-ha site was divided into summit (22° to 40°), sideslope (31° to 34°) and toeslope (29° to 36°), measuring 0.4 ha each, which will reflect the actual processes and effects of a catena on selected forest properties (Thwaites 2000). Site elevation varies between 1400 and 1600 m asl and is classified as montane forest. Soil type in this area is Ringlet series (*Typic Tropohumult*) comprising clay loam texture, with mean annual rainfall of 3325 mm and mean annual temperature of 17.8 °C. This area consists of vegetation derived from Myrtaceae, Fagaceae and Moraceae.

The second site is located at a secondary lowland forest known as Jengka Virgin Jungle Reserve (Jengka VJR), Jengka 18, Pahang (3° 35' N, 102° 34' E) ranging from undulating (2° to 6°) to rolling (6° to 12°) and moderately hilly (17°–18°) areas within 0.6 ha. Site elevation is classified as lowland forest and varies between 50 and 90 m asl. Soil type in this area is Durian series (*Plinthaquic Paleudult*) comprising silty clay loam texture with mean annual rainfall and temperature of 2123 mm and 27.8 °C respectively. The forest is dominated by Euphorbiaceae, Dipterocarpaceae and Annonaceae.

Sampling design

At the montane forest, boundary of the plot was first marked and determined using a GPS receiver. A transect running from north-east towards south-west was established from the boundary of each slope type. Grids (10 m × 10 m) were laid out systematically along the transect using 0.5-m length PVC poles as identification markers for each slope type. Each slope position had 40 quadrants and a total of 120 quadrants were established in the montane forest. However, only 60 quadrants were established in the lowland forest as topographic variability was minimal. Sampling intervals were spaced at approximately 10 m apart. A 25 cm × 25 cm frame was placed at the middle of the quadrant as sampling point. The forest floor was characterised by litter layer and the partially decomposing organic material above the mineral soil. The forest floor depth comprising litter and organic material was recorded using standard metric ruler. Forest floor samples were obtained for further analysis after discarding twigs and materials which measured more than 25 mm (McKenzie et al. 2000). Three replicates of forest floor litter were bulked for each sampling point and the location was georeferenced with the GPS device. At the same point, soil samples and representative bulk density samples were collected at 0–15 cm depth using a marked Jarett auger. Samples were collected in triplicates to obtain one composite sample per quadrant. A total of 120 and 60 composite samples were obtained at regular intervals for the montane and lowland forests respectively.

Soil examination and testing

Soil investigation was carried out by digging soil pits at both areas according to Soil Survey Staff (1993) methods. Bulk density samples and disturbed samples were collected based on horizon designations. Samples were analysed for basic properties, namely, N, C, P (phosphorus), K (potassium), Ca (calcium), Mg (magnesium), electrical conductivity (EC), cation exchange capacity (CEC), pH and soil texture. Soil samples were analysed for total C by dry combustion method using a C analyser and soil N was determined using Kjedahl digestion (MS 1980). Available P was determined by Bray and Kurtz Method II (Olsen & Sommers 1982). Exchangeable K, Ca and Mg were extracted using 1 M ammonium acetate (NH_4OAc) calibrated at pH 7 followed by atomic absorption spectrometry and CEC was determined using the leaching method (Thomas 1982). Replicates of bulk density samples were collected randomly at each slope position and depth. Soil characteristics are given in Table 1.

Laboratory analysis

Soil samples were air dried, ground and sieved to pass through a 1-mm sieve and then analysed for C, N and S (sulphur) using a CNS analyser. Only total C, C:N and forest floor depth were explored further using geostatistics as S did not fulfil the spatial variability assessment at the sampling scale. Soil C densities were calculated by multiplying the percentage of soil organic C in fine soil by bulk density at the measured soil depth [(%C/100) × bulk density (g cm^{-3}) × depth (cm)] and converted to carbon t ha^{-1}.

Geospatial data analysis

The C, C:N and forest floor depth data were subjected to exploratory data analysis involving descriptive statistics, normality check and non-spatial outlier detection in Statistix version 8.1. Non-normal data were transformed using

Table 1 Soil physio-chemical properties of the soil profile at study sites

Site/soil type	Horizon	pH	BD	EC	CEC	C	N	P	K	Ca	Mg	Fe	Cu	Zn	Mn
	(cm)		(g cm^{-3})	(μs cm^{-1})	(cmol$_c$ kg^{-1})	(%)	(%)	(μg g^{-1})							
Sungai Kial FR	0–5	3.5	0.33	476.00	26.36	40.22	0.06	66.01	439.00	161.70	217.00	210.45	1.42	12.81	29.45
Typic Tropohumult	5–17	4.0	0.63	356.00	25.29	9.20	0.66	31.85	20.90	2.40	5.90	232.15	0.90	1.47	0.60
(Ringlet series)	17–33	4.0	0.66	136.10	25.71	4.03	0.38	39.13	19.50	0.80	3.20	678.00	0.75	1.00	0.10
	33–48	4.3	1.23	27.80	16.93	1.65	0.17	39.20	11.30	0.00	2.20	156.90	0.69	1.18	0.65
	48–79	4.4	1.32	14.47	12.00	0.35	0.09	40.46	6.00	0.00	1.40	440.00	0.64	1.14	0.35
	79–130	4.4	1.71	12.88	22.79	0.11	0.06	39.06	5.00	0.70	6.40	39.35	0.61	0.79	0.15
Jengka VJR	0–11	3.9	1.52	114.80	15.79	2.20	0.32	35.49	382.00	47.90	98.00	198.65	2.59	0.65	0.30
Plinthaquic Paleudult	11–34	4.1	1.68	60.00	10.21	0.89	0.24	32.83	21.80	0.50	7.80	817.50	3.27	0.54	1.60
(Durian series)	34–79	4.4	1.73	15.90	14.36	0.36	0.22	39.06	19.80	0.40	2.40	501.00	2.82	0.06	0.40
	79–89	4.5	1.87	14.35	15.71	0.31	0.24	30.03	39.40	7.20	17.00	709.50	3.04	0.52	1.95
	89–135	4.3	1.96	26.60	13.50	0.76	0.23	38.15	31.60	0.20	3.80	1165.00	3.91	0.42	2.50

pH (water); BD = soil bulk density, EC = electrical conductivity, CEC = cation exchange capacity appropriate functions to normalise the data. Normality checks were performed using the Shapiro–Wilk test. Grubbs test was used for detecting outliers. Spatial analyses for variables were carried out using variography and interpolation techniques (Balasundram et al. 2008). Variography characterises and models spatial variance of data using semivariogram. Semivariogram attributes (i.e. nugget, sill and effective range) were used to perform point kriging. Kriging uses the modelled variance to estimate values between samples. In kriging, the value of a measurement at an unsampled location is predicted based on neighbourhood values. Variography and kriging were computed using GS+ 7.0 (2004). Measured and kriged values were mapped using Surfer 8.06. Spatial dependence of the data was computed using the nugget to sill ratio according to Cambardella et al. (1994) (Table 2).

Table 2 Classification of spatial dependence

Ratio	Inference
Nugget:sill < 0.25	Strong spatial dependence
0.25 < nugget:sill < 0.75	Moderate spatial dependence
Nugget:sill > 0.75	Weak spatial dependence

Kriged values were cross validated (Isaaks & Srivastava 1989, Law et al. 2009) to assess accuracy of the interpolated values using the following procedure.

Firstly, the interpolated mean error (ME) should be close to zero and was calculated as follows:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}[\bar{z}(x_i) - z(x_i)] \qquad (1)$$

where n = number of sample points, $\bar{z}$ = predicted value of the variable at point x_i and $z(x_i)$ = measured value of the variable at point x_i.

Secondly, the mean squared error (MSE) should be less than the sample variance. The MSE was given as:

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}[\bar{z}(x_i) - z(x_i)]^2 \qquad (2)$$

Thirdly, the ratio of the theoretical and calculated variance, i.e. the standardised mean squared error (SMSE), should be approximately close to one. The SMSE was given as:

$$\mathrm{SMSE} = \frac{\frac{1}{n-1}\sum_{i=1}^{n}[\bar{z}(x_i) - z(x_i)]^2}{\sigma^2} \qquad (3)$$

where σ^2 = theoretical variance.

RESULTS AND DISCUSSION

C, C:N and forest floor depths at different sites

Carbon, C:N and forest floor depth data were analysed using one-way ANOVA and are presented in Table 3. Total C concentration was significantly different along different topographic differences and between study plots. It was found that total C in the summit of Sungai Kial FR was 11-folds higher than that in Jengka VJR. Calculation of C stocks showed that values at the summit, sideslope, toeslope and Jengka VJR were 126, 40, 98 and 23 Mg C ha^{-1} respectively at 0–15 cm depth. This indicated that the concentration of total C was strongly influenced by topographic variability. Studies have indicated that soil C concentrations in mountainous terrain increase with altitude (Nakashizuka et al. 1992, Garten & Hanson 2006). The vegetation diversity along a toposequence reflects changing balances of soil C inputs and losses due to abiotic and biotic factors. Changes in litter quality, decomposition, temperature, soil moisture and vegetation species composition alter the availability of C (Garten & Hanson 2006, Arnold et al. 2009). Soil profile at Sungai Kial FR showed that the 0–5 cm horizon had more than 40% C (Table 1). This could be due to the presence of well decomposed (sapric) organic material. Thus, there was a high possibility that the 0–15 cm soil horizon yielded higher C concentrations due to the mixed material of organic and mineral components. This value is similar to that reported for Brinchang, Cameron Highlands, Malaysia which has an altitude of 1912 m asl (Jeyanny et al. 2011). However, with the projected temperature increase in Malaysia (Anonymous 2009a), tropical montane forest may become vulnerable to soil C stock depletion due to global warming.

The C:N values at sideslope, toeslope at Sungai Kial FR and Jengka VJR were 17, 23 and

86% lower than that of the summit of Sungai Kial FR (Table 3). High C:N in the summit area was also reported to slow down decomposition processes, causing accumulation of organic matter and immobility of nutrients (Satrio et al. 2009). The high C:N value in the summit of Sungai Kial FR was due to profound presence of histic epipedon with high organic matter which translated to higher labile C stocks (Marland et al. 2004) in Sungai Kial FR (Table 1). Similarly, increased C:N values had been reported at Mount Kinabalu, Sabah, Malaysia for slopes above 700 m asl (Wagai et al. 2008). On the contrary, C:N at the surface horizons of Mount Haleakala in Hawaii decreased at upslope from 600 to 1400 m asl (Hugget & Cheeseman 2002) due to higher N (≥ 1%), latitude, aspect, volcanic parent material and altitude (Duchaufour 1982).

The toeslope recorded the highest forest floor depth compared with the rest of the areas (Table 3). Values for Jengka VJR was the lowest, almost six-folds compared with toeslope. This vast disparity is usually due to the natural function of climate, vegetation and time. Contrary to reports that the greatest forest floor accumulation is at the highest elevation of boreal montane forests of spruce, fir and birch species (Gosz et al. 1976), the highest accumulation in tropical forests occur at the toeslope. This is attributable to the concave slopes which permit transport and deposition in montane forest. Higher precipitation in montane forest compared with lowlands also facilitates the downward movement of waste material through mass wasting as well as surface and subsurface water actions (Hugget & Cheeseman 2002).

Classical statistical analysis

Based on the Shapiro–Wilk test, variables at the summit showed normal distribution except for forest floor depth (Table 4). Both C and C:N were negatively skewed and kurtotic. The coefficient of skewness for C and C:N indicated a longer tail to the left. Kurtosis characterises relative peakness or flatness of a distribution compared with normal distribution. Skewness and kurtosis of the forest floor depth were positive. Coefficient of variation ranged from 14 to 32%, inferring minimal variability for test variables at the summit region of Sungai Kial FR.

Only forest floor depth was subjected to data transformation using the square root transformation so as to conform to a normal distribution at the sideslope. Meanwhile, C and C:N were normally distributed. C was positively skewed but the other two variables were negatively skewed. Sample distribution curve of C was relatively flat (negative kurtosis) while C:N and forest floor depth displayed relatively peaked distributions (positive kurtosis). Coefficient of variation for variables tested ranged from 9 to 16%.

In the toeslope area, natural log (ln) C, square root C:N and square root forest floor depth transformation were performed to normalise sample distribution. Both C and C:N were negatively skewed but forest floor was positively skewed. All test variables showed relatively flat distributions at the toeslope. Coefficient of variation were between 13 and 26%.

Carbon, C:N and forest floor depth for Jengka VJR were not normally distributed. Square root transformation for C was done to normalise the distribution. Other test variables which were not normally distributed remained non-normal even after transformation. Coefficient of skewness values for variables tested were positive, indicating a longer tail to the right. Kurtosis for C was negative but positive for the rest of the variables. Coefficient of variation for C, C:N and

Table 3 Total C, C:N and forest floor depth of Sungai Kial FR and Jengka VJR

Site	Total C (%)	C:N	Forest floor depth (cm)
Sungai Kial FR			
Summit	11.22 a (0.60)	120.02 a (2.96)	7.54 b (0.34)
Sideslope	6.73 b (0.16)	99.21 b (1.53)	4.56 c (0.23)
Toeslope	5.31 c (0.35)	92.50 c (3.88)	11.32 a (0.87)
Jengka VJR	1.05 d (0.03)	16.74 d (0.05)	1.85 d (0.19)

Mean values followed by different superscripts are significantly different (Student–Newmann–Keul test at $p \leq 0.05$), values in parentheses represent standard errors

Table 4 Descriptive statistics for selected soil properties at Sungai Kial FR and Jengka VJR

Site/variable	n[a]	Mean	Median	CV (%)	Skewness[b]	Kurtosis[c]	Normality
Sungai Kial FR							
Summit							
Total C (%)	40	11.12	10.99	32.72	-0.06	-1.01	0.32 ns
C:N	40	119.80	125.00	14.86	-0.36	-0.42	0.23 ns
FF depth (cm)	40	7.49	7.35	27.70	0.85	0.70	0.02 **
Sideslope							
Total C (%)	39	6.73	6.62	14.51	0.49	-0.05	0.37 ns
C:N	39	99.10	99.00	9.43	-0.33	0.36	0.57 ns
FF depth (cm)	39	2.10	2.10	16.57	-0.48	0.77	0.06 ns
Toeslope							
Total C (%)	39	1.59	1.53	25.83	-0.02	-1.07	0.11 ns
C:N	39	9.50	9.60	13.11	-0.20	-1.11	0.06 ns
FF depth (cm)	40	3.30	3.30	26.55	0.11	-1.10	0.07 ns
Jengka VJR							
Total C (%)	59	1.02	1.00	13.31	0.49	-0.27	0.14 ns
C:N	59	17.46	16.50	39.97	3.91	21.11	0.01 **
FF depth (cm)	60	1.83	2.25	80.22	0.05	1.80	0.01 **

FF = Forest floor, CV = coefficient of variation; [a]non-spatial outliers were removed from data set, non-spatial outliers were detected using the extreme studentised deviate test; [b]significant if the absolute value of skewness or kurtosis was ≥ two times its standard error, standard error of skewness = $(6/n)^{0.5}$, standard error of kurtosis = $(24/n)^{0.5}$; [c]estimated using the Shapiro–Wilk test, if the test statistic W was significant ($p < 0.05$), thus the distribution was normal; ns = not significant ($p > 0.05$), ** = siginificant difference ($p \leq 0.01$)

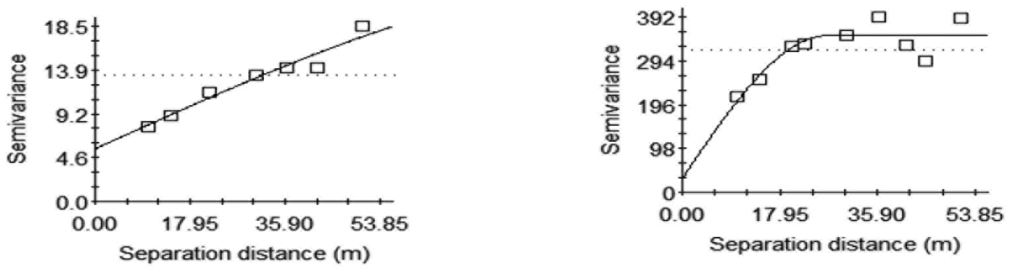
forest floor were 13, 39 and 80% respectively. The range for coefficient of variation of C was within normal values as reported by Liu et al. (2006).

Spatial structure and attributes

The semivariograms corresponding to summit, sideslope and toeslope at Sungai Kial FR and Jengka VJR were constructed based on active lag distances of 53, 79, 86 and 52 m respectively (Figure 1). The lag class interval, which defined how pairs of points would be grouped into lag classes, were manually configured. The lag class intervals for summit, sideslope, toeslope and Jengka VJR were 6.5–7.5, 8.0–10.3, 6.7–13.7 and 4.9–9.3 respectively. All variables exhibited definable spatial structures for all areas except for forest floor depth in the summit which had a linear isotropic model. Spatial autocorrelation only occurred across the entire range sampled and it was impossible to predict spatial continuity beyond the sampled area for forest floor depth. Thus, semivariance analysis for the forest floor depth in the summit was not explored.

Carbon and C:N at the summit were best explained by a spherical model (Figures 1a and b). Nugget to sill ratios suggested strong spatial dependence, i.e. 0.23 and 0.09 for C and C:N respectively. Effective range values were moderate, i.e. less than 107.3 m. Sampling points which are separated at distances greater than the effective range will no longer demonstrate spatial correlation (Balasundram et al. 2008).

Carbon and C:N at the sideslope was explained by a Gaussian model but not for forest floor depth (Figures 1c–e). Gaussian model demonstrates that the variables display a great continuity in the first lag with a slow increase in semivariance (Aznar et al. 2010). All three properties showed moderate to strong spatial dependence values ranging from 0.24 to 0.30. Forest floor depth had the shortest effective range at 8 m, followed by C:N (108 m) and C (125 m). At the toeslope, C was best described by an exponential model

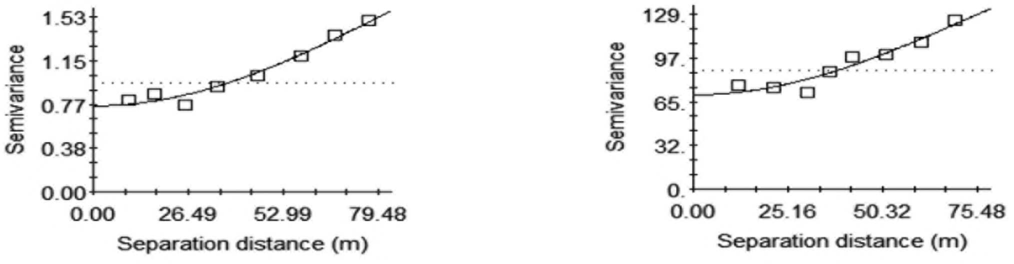


(a) Total C (%), summit

Model: spherical; spatial dependence: strong; nugget : 5.56; sill: 23.64; effective range:107.3 m

(b) C:N, summit

Model: spherical; spatial dependence: strong; nugget: 31.0; sill: 350.2; effective range: 26.7 m

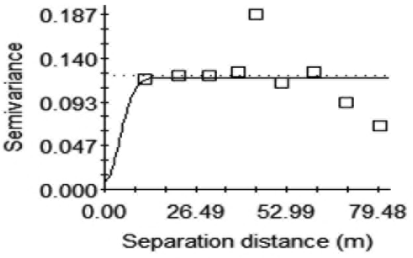


(c) Total C (%), sideslope

Model: Gaussian; spatial dependence: strong; nugget: 0.75; sill: 3.11; effective range: 125.2 m

(d) C:N, sideslope

Model: Gaussian; spatial dependence: moderate; nugget: 69.7; sill: 225.5; effective range: 108.8 m



(e) Forest floor depth (cm), sideslope

Model: Gaussian; spatial dependence: strong; nugget: 0.01; sill: 0.12; effective range: 8.6 m

Figure 1 Spatial structure and attributes of selected soil variables at the summit and sideslope of Sungai Kial FR

with strong spatial dependence, i.e. nugget to sill ratio of 0.12 (Figures 2a–c). Both C:N and forest floor depth fitted a spherical model where 99% of the total variation in both variables were explainable. Effective range at the toeslope was short (< 18.2 m).

In Jengka VJR, C, C:N and forest floor depth were described by exponential models (Figures 2d and f). Spatial dependence values for C and forest floor depth were strong, with nugget to sill ratios of 0.05 and 0.18 respectively. However, C:N had a moderate spatial dependence, i.e. nugget to sill ratio of 0.46 (Figures 2a–c). Thus, the explainable proportion of total variation in C, forest floor and C:N were 99.5, 99.8 and 99.5% respectively, while the remaining variation was due to random sources. The majority of the properties for Jengka VJR had shorter effective range.

Overall, this study showed short to moderate effective range, for C which was less than 125.2 m for all areas. In other studies, soil C was found to exhibit relatively longer effective range (Kravchenko et al. 2006, Law et al. 2009). Longer effective range for soil C was common as large spatial variations in C was evident (Zhang & McGrath 2004). Since effective range is also known as correlation length, greater separation distance from the reported effective range will not exhibit spatial correlation (Boyd et al. 2005, Balasundram et al. 2007). Thus, spatial correlation for C was assumed negligible beyond 125.2 m for all areas.

Forest floor depth is highly variable due to topography, vegetation distribution, soil temperature, moisture and decomposition rates. Thus, a short effective range was found in this study at all areas, especially at the sideslope

(a) Total C (%), toeslope

Model: exponential; spatial dependence: strong; nugget: 0.02; sill: 0.17; effective range: 8.1 m

(d) Total C (%), Jengka VJR

Model: exponential; spatial dependence: strong; nugget: 0.001; sill: 0.02; effective range: 8.9 m

(b) C:N, toeslope

Model: spherical; spatial dependence: strong; nugget: 0.06; sill: 1.61; effective range: 18.8 m

(e) C:N, Jengka VJR

Model: exponential; spatial dependence; moderate; nugget: 12.34; sill: 26.86; effective range: 79.7 m

(c) Forest floor depth (cm), toeslope

Model: spherical; spatial dependence: strong; nugget: 0.001; sill: 0.73; effective range: 18.2 m

(f) Forest floor depth (cm), Jengka VJR

Model: exponential; spatial dependence: moderate; nugget: 0.57; sill: 3.15; effective range: 44.6 m

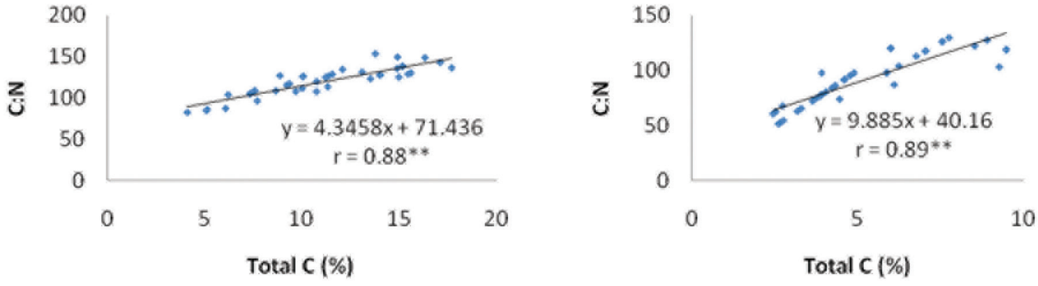
Figure 2 Spatial structure and attributes of selected soil variables at the toeslope of Sungai Kial FR and Jengka VJR which registered an effective range of 8.6 m. Based on the short effective range obtained, we recommend that sampling intervals for forest floor depth should not be more than 10 m apart for geospatial analysis. Generally, we also observed that variograms of the toeslope at Sungai Kial FR and Jengka VJR had sill values close to the sample variance, implying that a fixed variance was present (Rossi et al. 2009).

Spatial variability

The distribution and pattern of both measured and kriged values for each variable were represented as surface maps. All variables except forest floor depth at summit exhibited spatial clustering of test values across the study plots. The surface maps demonstrated a linear association between C:N and C for the summit, toeslope and Jengka VJR. These sites also showed significant correlations between C:N and C (Figure 3). Pearson correlation coefficient of determination (r) values for the summit, toeslope and Jengka VJR were 0.88, 0.89 and 0.99 respectively. Correlation between C:N and C is expected due to their close interactions in decomposition rates (Satrio et al. 2009) and slope variability (Hugget & Cheeseman 2002). C:N can serve as possible indicator for forest managers to illustrate C stocks in tropical montane and lowland forests.

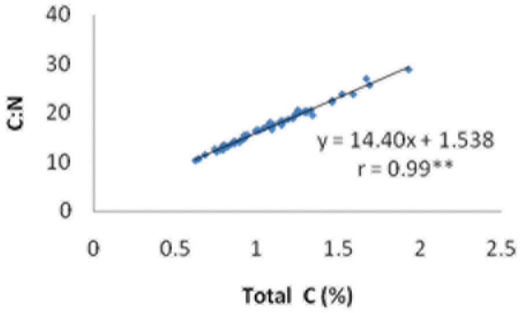
Cross validation of all three variables showed that the interpolation accuracy criteria were satisfied on all counts (Table 5). Reliable interpolation of these variables using the kriging technique potentially reduced sampling cost of estimating total C and C:N and at various topographic positions. Sampling intervals should be 0.25 to 0.5 of the effective range (Mulla & McBratney 1999). For instance, a reduced number of samples can be collected to detect spatial variability of total C in summit since the sampling interval in our study (i.e. 10 m) can be increased further to either 27 or 53 m apart based on the effective range (107 m) given. This will lessen initial inputs such as manpower, time and expenditure needed to develop spatial variability maps and promote cost savings.

At the summit, high values of total C were detected in the northern region which slowly reduced towards the central region and increased



(a) Total C (%) against C:N at the summit

(b) Total C (%) against C:N at the toeslope



(c) Total C (%) against C:N at Jengka VJR

Figure 3 Correlation between C:N and C; **significant at $p \leq 0.01$

Table 5 Cross validation statistics of kriged values at Sungai Kial FR and Jengka VJR

Site	Variable	Model	Sample variance	ME	MSE	SMSE
Sungai Kial FR						
Summit	Total C (%)	S	13.25	0.00	9.36	0.72
	C:N	S	319.00	0.09	235.53	0.76
	FF depth (cm)	G	——————not determined—————			
Sideslope	Total C (%)	G	0.954	-0.01	0.953	1.02
	C:N	G	87.39	-0.07	85.23	1.001
	FF depth (cm)	G	0.12	-0.02	0.13	1.11
Toeslope	Total C (%)	E	0.16	0.02	0.16	0.99
	C:N	S	1.57	0.06	1.19	0.79
	FF depth (cm)	S	0.76	-0.05	0.48	0.65
Jengka VJR	Total C (%)	E	0.02	0.00	0.01	0.92
	C:N	E	17.88	-0.10	17.71	1.01
	FF depth (cm)	E	2.16	0.01	1.35	0.64

FF = Forest floor; S = spherical, E = exponential, G = Gaussian, ME = mean error; MSE = mean squared error, SMSE = standardised mean squared error

moderately towards the south-east (Figure 4a). A similar trend was found for C:N at the summit, except that test values for the south-eastern region were slightly higher in comparison with the northern region (Figure 4b).

Values of total C and C:N were elevated in the south-east region of the sideslope in Sungai Kial FR. Low levels of total C and C:N were found in the western region, which were 5 to 6% and 91 to 94% respectively. Higher amount of forest floor accumulation was found in the northern region of the sideslope. However, pockets of high values were distributed thoroughout the study area (Figures 4c–e).

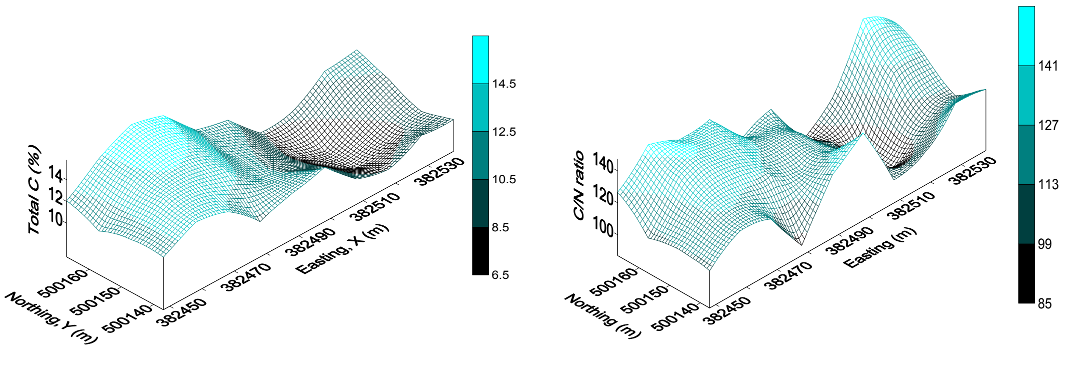
At the toeslope, distribution of total C was quite erratic, showing clustered peaks at the northern and eastern boundary with values above 8.5% while pockets of low C values were evident in the western boundary. A similar distribution trend was found for C:N. Higher values of forest floor depth were concentrated in the central region of the study area (more than 23 cm) as opposed to the western boundary (Figures 5a–c).

At Jengka VJR, higher total C and C:N were observed in the north-eastern region, i.e. higher than 1 and 16% respectively. Results confirmed the positive linear relationship between these two variables. The forest floor depth, however, showed deeper forest floor accumulation in the south-western region as compared with the northern region, which had lower amounts of forest floor accumulation (Figures 5d and f).

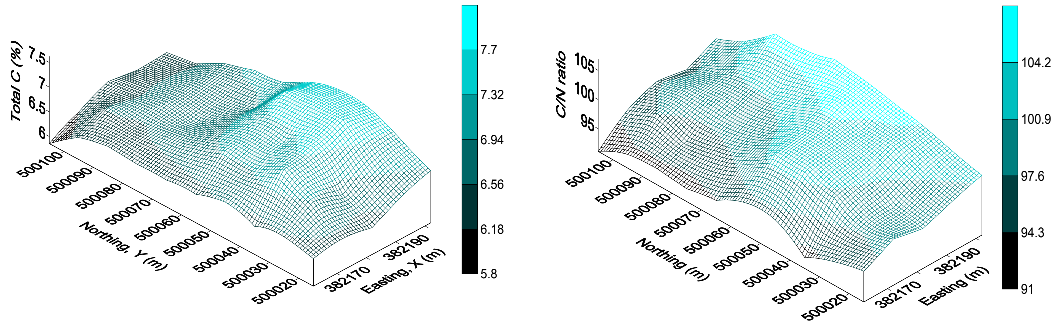
Generally, the spatial clustering of total C at various topographic positions did not follow similar trends although they were along the same catena, implying that presumption of total C according to geographical locations would be futile. Erratic total C values in toeslope might be due to natural or anthropogenic disturbances. Clustering of C:N was influenced by total C, reflecting the natural carbon and nitrogen cycling of soils. Accumulation of forest floor was dynamic and dependent on various environmental factors.

CONCLUSIONS

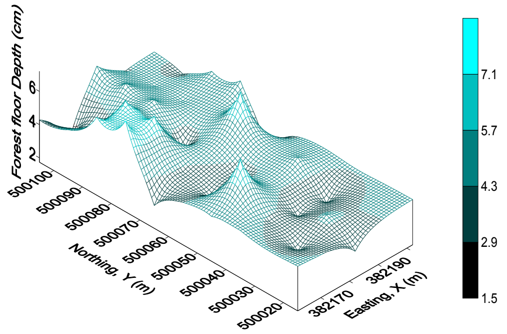
Soil total C, C:N and forest floor depth exhibited spatial variability along a catena (toposequence) within a montane forest and in an undulating lowland forest. Spatial structure of test variables varied across and within the catena and within the lowland forest. Most variables exhibited strong spatial dependence with the exception of C:N at the sideslope and forest floor depth at Jengka VJR which exhibited moderate spatial dependence. The summit and sideslope plots showed moderate effective range but at the



(a) Total C (%) at the summit (b) C:N at the summit



(c) Total C (%) at the sideslope (d) C:N at the sideslope

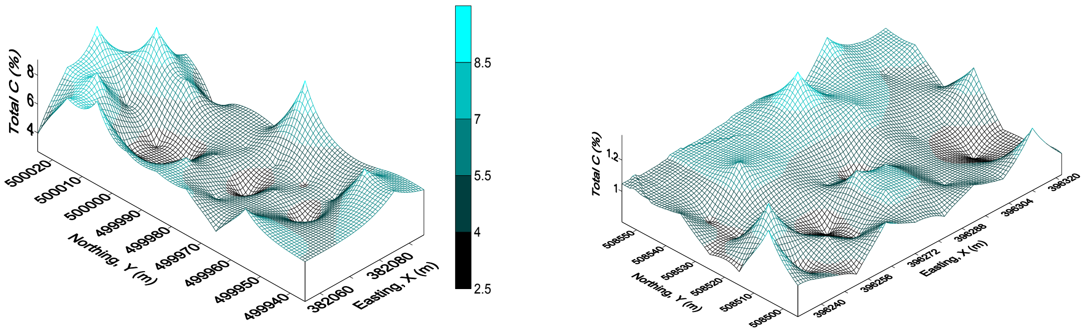


(e) Forest floor depth (cm) at the sideslope

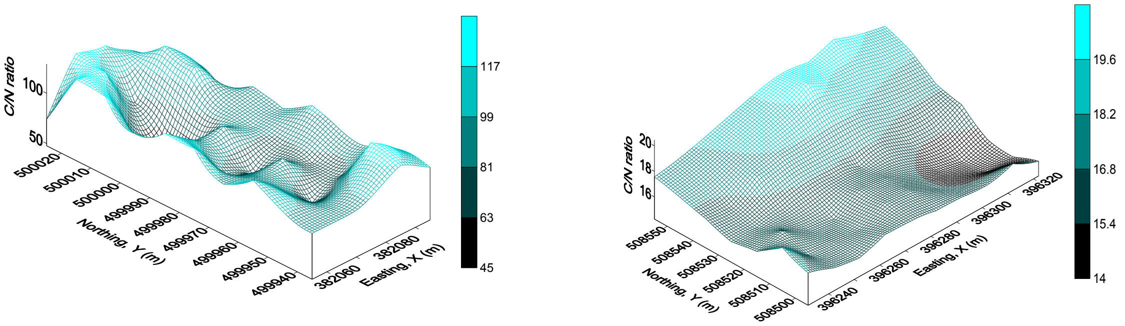
Figure 4 Spatial variability of C, C:N and forest floor depth (based on measured and kriged values) at the summit and sideslope of Sungai Kial FR

toeslope and Jengka VJR the value was relatively short, implying that spacing of samples should be closer in the lower parts of a topographic position than in the uplands. Moderate effective range also suggested that the distance between sampling could be increased, leading to cost savings. The majority of surface maps of the test variables showed distinct spatial clustering and displayed acceptable accuracy of interpolated values, suggesting that total C, C:N and forest floor depth along elevational gradients could be estimated reliably via geospatial analysis. Thus, site-specific management for monitoring of carbon sequestration in tropical forest should be based on topographic delineation.

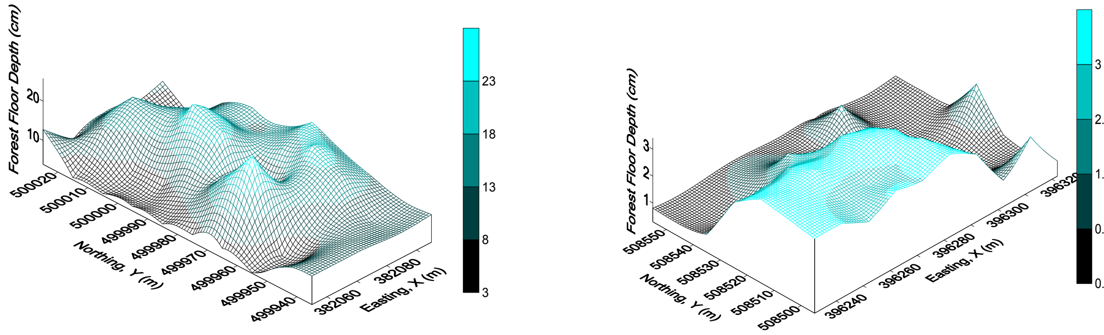
In line with the escalating efforts for attaining REDD+ and to reap the benefits of financial incentives, it is important to consider



(a) Total C (%) at the toeslope (d) Total C (%) at the Jengka VJR



(b) C:N at the toeslope (e) C:N at the Jengka VJR



(c) Forest floor depth (cm) at the toeslope (f) Forest floor depth (cm) at the Jengka VJR

Figure 5 Spatial variability of C, C:N and forest floor depth (based on measured and kriged values) in toeslope of Sungai Kial FR and Jengka VJR

management zones based on spatial variability at varying topographic positions and between different forest types. This study showed that C stocks for 0—15 cm soil depth were highest in the summit followed by toeslope, sideslope and Jengka VJR. Spatial variability maps and C stock estimation across a catena and lowland forest will clearly aid conservation of forest ecosystem with respect to C management. Additionally, the close relationship exhibited by total C and C:N should be exploited as a crucial indicator for carbon sequestration. Future studies should address the reliability of forest floor depth in sequestering C in relation to different forest systems.

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