CARBON STOCKS IN DIFFERENT CARBON POOLS OF A TROPICAL LOWLAND FOREST AND A MONTANE FOREST WITH VARYING TOPOGRAPHY

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JEYANNY V, HUSNI MHA, WAN RASIDAH K, SIVA KUMAR B, ARIFIN A & KAMARUL HISHAM M. 2014. Carbon stocks in different carbon pools of a tropical lowland forest and a montane forest with varying topography. Increasing atmospheric carbon dioxide concentrations at alarming rates have triggered the need to revisit potential opportunities in conserving and monitoring carbon (C) stocks for climate change mitigation. The dynamic nature of tropical forests based on topographic variations and biomass components needs reliable estimation of forest C to support conservation and forest monitoring strategies. This study was aimed to determine C stocks of varying components (i.e. litter, soil, aboveground biomass and roots) in a tropical lowland forest and a tropical montane forest at varying topographic positions. Systematically designed 10 m × 10 m plots were established for soil (0–15 cm depth), litter and aboveground biomass sampling along three slope positions at the montane forest and one plot in the lowland forest due to minimal topographic variability. Basic soil characteristics and botanical distribution of both forest sites were determined. Carbon stocks were significantly higher in the tropical montane forest, where litter and soil C stocks at the summit were three and five folds significantly higher compared with the lowland forest. No significant differences were found in vegetation structure (mean diameter at breast height, mean height and stand basal area) but the aboveground biomass ranged from 100 to 120 Mg C ha^{-1} and was the most dominant pool (> 40%) for all sites. Soil C pools were comparable (100 to 120 Mg C ha^{-1}) with aboveground biomass pools at the summit and toeslope position of the montane forest.

Keywords: Biomass, carbon storage, components, elevation, temperature, topographical diversity, tropics

INTRODUCTION

Progressive global industrial and agricultural developments have caused increased carbon dioxide (CO_2) emissions. The concentration of CO_2 in the atmosphere has been reported to soar up to 391 ppm in 2011 (IPCC 2013) compared with 280 ppm in the 1800s (Pitelka & Rojas 2001). According to the Intergovernmental Panel on Climate Change (IPCC 2013), this will simultaneously increase earth's temperature by 0.6 to 1.1 °C over the period of 1880 till 2012.

Tropical rainforests constitute the biggest portion, at 718 million ha (41%), of the lowland forests of the world (Singh 1993). In 1993, there was an estimated 159 Gt of carbon (C) in the above- and belowground vegetation of tropical forests, with an additional 216 Gt of C in tropical soils (Brown et al. 1993, Beer et al. 2010). Tropical forests clearly dominate the role of forests in the global C cycle based on both C flux and the volume of C stored. More than half of the C in tropical forests is in the neotropics and the remainder in Asian and African forests (Dixon et al. 1994). However, research studies in C dynamics in the montane forests of the tropics which are nestled above 1200 m above sea level (asl) compared with lowlands are also very scarce.

Carbon is stored in various components, particularly in soil, litter, aboveground biomass and in roots. Worldwide, soil organic carbon (SOC) in the top 1 m of soil comprises about 80% of the earth's terrestrial C (Lal 2008). Carbon stock for aboveground biomass is typically derived by assuming that 50% of the biomass is made up by C (Dixon et al. 1994, Basuki et al.

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2009) using allometric equations. Litter stocks were reported to be a small fraction of total C stocks, where Heath et al. (2003) reported that only 8% of total C is in the forest floor fraction. Root production in the forests can contribute 50% of the annual C cycle and constitutes 33% of the global annual net primary production (Vogt et al. 1998). In tropical forest, root C stock was 15% out of the total biomass stock in Pasoh lowland forest (Niiyama et al. 2010). Estimation of C stocks in tropical forests is vital to determine the major role each component partakes in contributing C stocks to conservation.

Carbon stocks can vary based on components due to the dynamic structure of tropical forests. For example, an African moist tropical forest had more than three times as much C in the aboveground biomass compared with the soil at 1-m depth (Djomo et al. 2011). In Asia, a tropical lowland forest in Malaysia (Turner 2010) contained twice as much C in biomass (64%) compared with the soil (36%) at 1-m depth, but a secondary forest in the Philippines contained 50% more C aboveground than in the soil (Lasco et al. 2004). Carbon stocks may also vary within sites due to topographical features and vegetational influences. Garten Jr et al. (1999) reported that C abundance in soil is significantly associated with elevation and temperature. Soil C stocks increased with elevation in a climo-toposequence in their study. In Malaysia, Lim (2002) showed how C stocks varied with increasing elevation where highest values were obtained at 300–1200 m asl.

Variations in C stocks among tropical forests are existent due to confounding factors which include vegetation species, soil type, elevational effect, climate and previous landuse. Ongoing exploitation of forests for timber and conversion to agricultural land has highlighted the need to conserve tropical forests and to accurately quantify C stocks. Carbon budget variations have also created uncertainties in C stocks reporting especially for the United Nation Framework on Climate Change. Thus, determination of C stocks in various components of forest and within sites is important to monitor C stocks and cycling, to calibrate global C cycle models, and to support frameworks such as the United Nations REDD+ programme (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) (Ngo et al. 2013). This study was carried out to quantify litter, soil, above- and belowground (i.e. roots) C stocks in a tropical lowland forest and a tropical montane forest with varying topography.

MATERIALS AND METHODS

Study sites

The research was carried out at two different sites, representing a montane forest and a lowland forest in Pahang, West Malaysia (Figure 1). The first site is located at Sungai Kial Forest Reserve (FR), Tringkap, Cameron Highlands, Pahang (4° 31' N, 101° 25' E) with steep to very steep topography ranging from 22° to 40°. This 1.2-ha site was divided into summit, sideslope and toeslope, measuring 0.4 ha each which would reflect the actual processes and effects of a catena of selected forest properties (Thwaites 2000). The site has elevation of between 1400 and 1600 m asl and is classified as a montane forest.

The second site is located at a secondary lowland forest in Virgin Jungle Reserve (VJR), Jengka 18, Pahang (3° 34' N, 102° 34' E) ranging from an undulating to rolling and moderately hilly area within 0.6 ha just above the floodplain of the Pahang River. The site is classified as a lowland forest and its elevation varies between 50 and 90 m asl. Jengka VJR was reported to have been logged once in 1968–1969, and is known as a relatively undisturbed forest (Laidlaw 2011).

Sampling design

At the montane forest, the boundary of the plot were first marked and determined using a Global Positioning System (GPS) receiver. A transect running from north-east towards south-west was established from the boundary for each slope type. Later, 10 m × 10 m quadrants were laid out using 0.5-m PVC poles as identification markers for every slope type systematically along the transect. The centre of the quadrant was marked using a GPS and a PVC pole (colour coded). Sampling intervals were spaced at approximately 10 m apart. 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.

Based on the plots established, basic information such as slope inclination, elevation, soil and air temperatures was collected at six random sampling points in Jengka VJR in April 2011 and five random sampling points for each

Figure 1 Locations of the study sites in the state of Pahang, Malaysia; FR = Forest Reserve, VJR = Virgin Jungle Reserve

slope type in Sungai Kial FR (July 2010) and are presented in Table 1. Field soil pH, soil and air temperature were measured using the pH meter where the probe was inserted into the soil at 5-cm depth and measurements were taken when the values stabilised whereas the air temperature was determined at 5 cm above the soil surface using the same probe. Slope inclination was recorded using a clinometer. The elevation was recorded using a GPS.

Soil examination and testing

Soil investigation was carried out by digging one soil pit at each forest type according to Soil Survey Staff (1993) methods. Bulk density samples and disturbed samples were collected based on horizon designations. Samples were tested for pH and electrical conductivity (EC). Samples were analysed for total C and nitrogen (N) by the dry combustion method using a CNS analyser. Available phosphorus (P) was determined by Bray and Kurtz Method II (Olsen & Sommers 1982). Exchangeable potassium (K), calcium (Ca) and magnesium (Mg) were extracted using 1-M ammonium acetate (NH_4OAc) calibrated at pH 7 followed by atomic absorption spectrometry and cation exchange capacity (CEC) was determined using the leaching method (Thomas 1982). Soil characteristics are given in Table 2 for Sungai Kial FR and Jengka VJR.

Table 1 Basic information on the environmental conditions at the study sites

Site	N	Elevation (m asl)	Slope (°)	pH (field)	Temperature (°C)	
					Soil	Air
Sungai Kial FR						
Summit	5	1609–1644	22–41	4.5–5.7	17.0–17.6	16.1–18.6
Sideslope	5	1431–1505	31–34	4.7–5.1	18.2–19.4	17.6–19.2
Toeslope	5	1405–1493	29–36	4.9–5.7	18.0–18.8	17.6–20.2
Jengka VJR	6	55–93	2–18	5.6–6.1	25.9–27.5	25.1–28.6

N = number of samples, FR = Forest Reserve, VJR = Virgin Jungle Reserve, asl = above sea level

Botanical collection and description

The botanical collection and aboveground biomass determination were carried out in 15 and 6 quadrants of Sungai Kial FR and Jengka VJR respectively. All trees which had a minimum diameter at breast height (dbh) of 5 cm within each quadrant were tagged and measured for dbh using a diameter tape and the total height estimated using the naked eye. Due to manpower and funding constraints, a total of 178 trees which represented the montane forest according to slope type (65+58+55) were enumerated whereas 83 trees were determined at the lowland forest. The mean dbh was later used for stand basal area and aboveground biomass determination for each tree. Concurrently, the maximum dbh, maximum height and tree density were also determined to describe the forest structure at each site. The numbers of trees for each slope type were summed up within the respective quadrants and reported on per hectare basis for tree density determination. The understorey vegetation was sparse at both sites (< 25%) and was not determined. Plant materials comprising leaves, fruits and flowers of the specified trees were collected manually. Specimens obtained were processed according to Bridson and Foreman (1992) and Maden (2004). The identification of each specimen was done by cross-referencing with previously identified herbarium specimens, dichotomous keys, published plant descriptions, illustrations and photographs. Only three common genera and families are presented in Table 3.

Meteorological data

Data on mean temperature and rainfall were collected for both sites from the period of 2009–2012. The stations which logged the data were the Felda Kampung Awah station (3° 31' N, 102° 30' E) and Tanah Rata, Cameron Highlands (4° 28' N, 101° 22' E). The trend showed that the monthly average air temperatures for Sungai Kial FR for the past 4 years were 16.5 to 18.5 °C (Figure 2). Higher temperatures were recorded in the month of May in 2010, about 19.5 °C. Higher rainfall occurred in the year 2011, especially in August 2011 where the amount of rainfall was 60% higher compared with August 2012 (Figure 2). Monthly rainfall in the montane forest was mostly above 200 mm providing a wet climate in the higher altitudes.

Some data were missing for Jengka VJR air temperatures but the average temperatures ranged from 29–35 °C (Figure 3). Jengka VJR had distinctive dry periods which fell in February, June and July where rainfalls recorded were below 200 mm (Figure 3).

Litter and soil sampling

A 25 cm × 25 cm frame was placed at the middle of the quadrant as the sampling point. The forest floor was characterised by the litter layer and the partially decomposing organic material above the mineral soil. The forest floor depth comprising litter and organic material was recorded using a 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 geo-referenced with the GPS device. At the same point, soil samples were collected at 0–15 cm using a marked Jarret auger. Samples were collected in triplicates to obtain one composite sample per quadrant. Five replicates of bulk density samples were collected

Table 2 Soil physio-chemical properties of the soil profiles at the study sites

Site/soil type		pH (1:1)	BD (g cm^{-3})	EC (μs cm^{-1})	CEC (cmol$_c$ kg^{-1})	C (%)	N (%)	P (μg g^{-1})	K (μg g^{-1})	Ca (μg g^{-1})	Mg (μg g^{-1})
Sungai Kial FR	0–5	3.5	0.26	476.00	26.36	40.22	0.06	66.01	439.00	161.70	217.00
Typic Haplohumult	5–17	4.0	0.50	356.00	25.29	9.20	0.66	31.85	20.90	2.40	5.90
(Ringlet series)	17–33	4.0	0.51	136.10	25.71	4.03	0.38	39.13	19.50	0.80	3.20
	33–48	4.3	0.96	27.80	16.93	1.65	0.17	39.20	11.30	0.00	2.20
	48–79	4.4	1.03	14.47	12.00	0.35	0.09	40.46	6.00	0.00	1.40
	79–130	4.4	1.35	12.88	22.79	0.11	0.06	39.06	5.00	0.70	6.40
Jengka VJR	0–11	3.9	1.19	114.80	15.79	2.20	0.32	35.49	382.00	47.90	98.00
Plinthaquic Paleudult	11–34	4.1	1.32	60.00	10.21	0.89	0.24	32.83	21.80	0.50	7.80
(Durian series)	34–79	4.4	1.36	15.90	14.36	0.36	0.22	39.06	19.80	0.40	2.40
	79–89	4.5	1.47	14.35	15.71	0.31	0.24	30.03	39.40	7.20	17.00
	89–135	4.3	1.54	26.60	13.50	0.76	0.23	38.15	31.60	0.20	3.80

pH (1:1 soil:water), BD = bulk density, EC = electrical conductivity, CEC = cation exchange capacity, FR = Forest Reserve, VJR = Virgin Jungle Reserve

Table 3 Brief botanical descriptions of vegetation in Sungai Kial FR and Jengka VJR

Site	Common tree families	Common genera	Total trees determined	Max dbh	Mean dbh (cm)	Max height (m)	Mean height estimated (m)	Stand basal area (m^2 ha^{-1})	Tree density (trees ha^{-1})
Sungai Kial FR									
Summit	Myrtaceae	*Syzygium*	65	41.5	13.7 a (1.60)	27.0	8.0 ab (0.43)	28.4 a (5.18)	1300
Sideslope	Polygalaceae	*Xanthophyllum*	58	44.8	14.7 a (1.24)	13.5	7.7 ab (0.29)	27.9 a (7.20)	1160
Toeslope	Lauraceae	*Litsea*	55	40.6	15.2 a (1.22)	12.0	6.9 b (0.28)	26.4 a (4.83)	1100
Jengka VJR	Phyllanthaceae	*Aporosa*							
	Dipterocarpaceae	*Shorea*	83	57.5	11.5 a	50.0	9.2a	22.8 a	1383
	Euphorbiaceae	*Croton*			(1.13)		(0.75)	(8.25)	

Individual values with different superscripts in columns are significantly different (Student Newmann Keul Test at $p \leq 0.05$), values in parentheses represent standard errors; dbh = diameter at breast height, FR = Forest Reserve, VJR = Virgin Forest Reserve

at each slope position and in the lowland forest for soil C stock calculation. A total of 120 and 60 composite samples were obtained at regular intervals for the montane forest and lowland forest respectively.

Laboratory analysis

All the composite soil samples were air dried, ground and sieved to pass through a 1-mm sieve and analysed for total C using a CNS analyser. Soil C densities were calculated by multiplying percentage of SOC by mass in fine soil with the volume of soil (bulk density) at the measured soil depth and converted to C tonnes ha^{-1}. Preliminary investigations revealed that there were no significant differences on C content in litter for both sites. Thus, only representative litter samples were analysed for C using a C analyser, which were a total of 6 and 12 (4 for

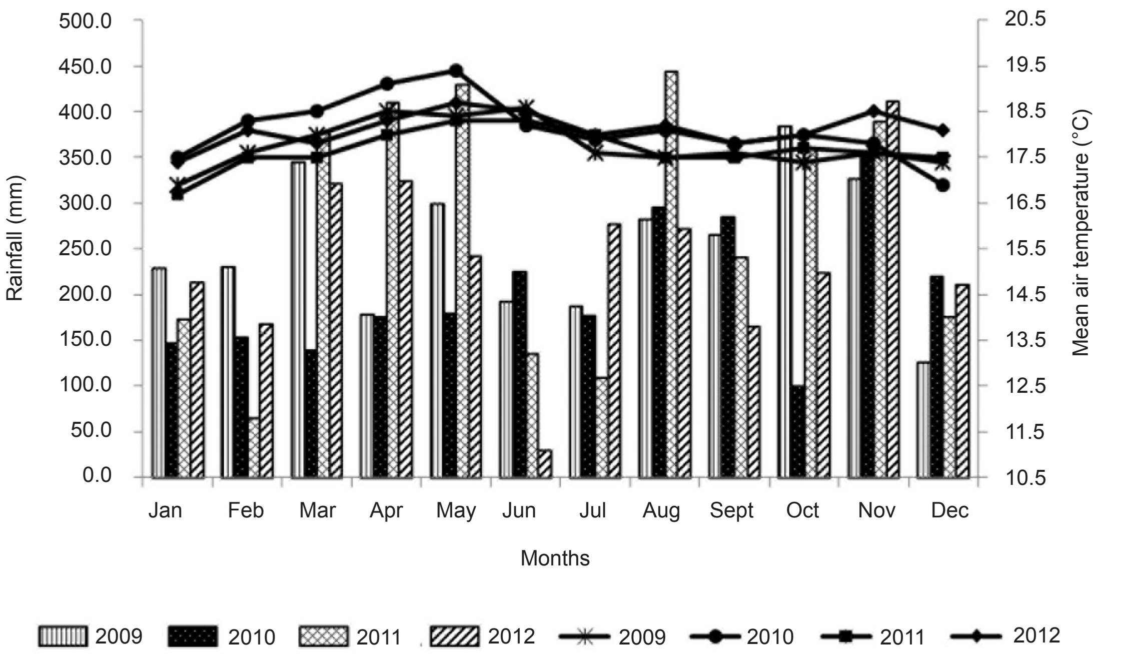

Figure 2 Annual mean air temperatures and rainfalls at Sungai Kial Forest Reserve from 2009 till 2012

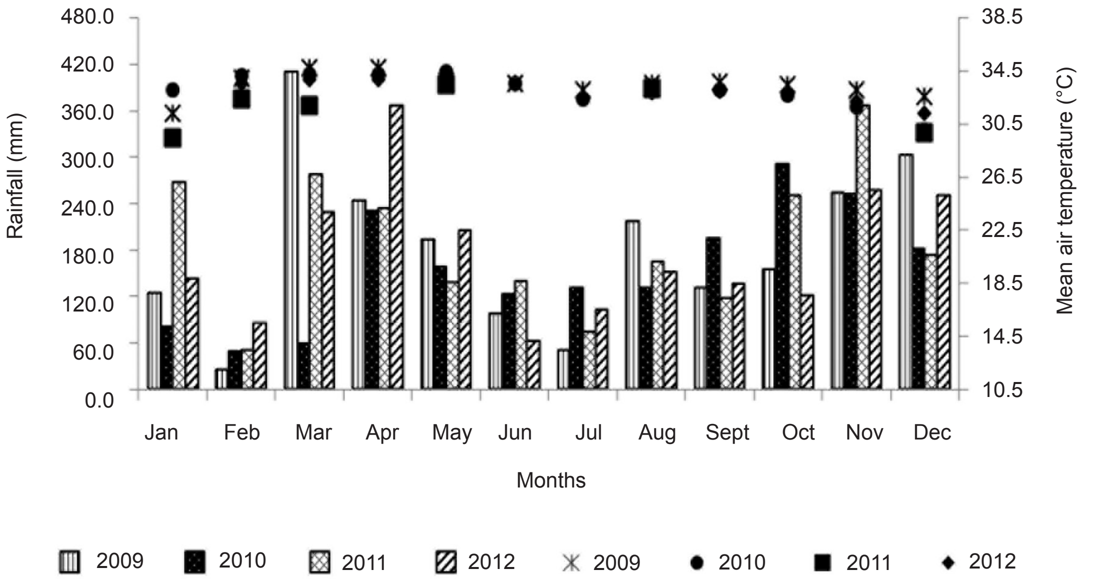

Figure 3 Annual mean air temperatures and rainfalls at Jengka Virgin Jungle Reserve from 2009 till 2012

each slope type) samples for Jengka VJR and Sungai Kial FR respectively. Litter C stocks were calculated by multiplying oven-dry mass per area with C concentration percentage. Aboveground biomass values were determined using two different allometric equations which are common for tropical forests, based on Brown's updated equation (Pearson et al. 2005) and that of Chave et al. (2005). Both equations were utilised in order to test the accuracy of data since destructive sampling was clearly avoided as the sites are gazetted as protected forests. Both equations are suitable for moist tropical forests, receiving 1500–4000 mm annual rainfall.

The equations used for aboveground biomass are as follows:

Aboveground biomass (kg) = exp (-2.289 + 2.649 × ln dbh – 0.021 × (ln dbh)^2)

(Pearson et al. 2005)

Aboveground biomass (kg) = ρ × exp (-1.499 + 2.148 × ln dbh + 0.207 × (ln (dbh))^2 – 0.0281 – (ln (dbh)^3)

(Chave et al. 2005)

where dbh constitutes the diameter at breast height and ρ is wood specific gravity. Species level average ρ values were obtained from the Global Wood Density Database (Chave et al. 2009). The belowground (roots) biomass was determined using the equation:

Belowground biomass (kg) = Exp (-1.0587 + 0.8836 × ln ABD)

(Pearson et al. 2005)

where ABD is aboveground biomass data determined using the Pearson et al. (2005) allometric equation.

The biomass values were determined for each tree and summed up for each quadrant and reflected according to slope type as mentioned earlier.

Statistical analysis

Treatment effects were analysed using analysis of variance and the means of these treatments were compared using the Student Newman Keul Test for mean dbh, mean height, stand basal area, soil bulk density, soil, litter, above- and belowground C stocks. The statistical software used was Statistical Analysis System version 9.13.

RESULTS

Environmental conditions

The main characteristics that distinguish the study sites are the topographical effects and the climatic conditions (Table 1). The slope characteristics of summit and toeslope were concave whereas those for the sideslope were fairly linear. The slope for Jengka VJR ranged from an undulating (2° to 6°) to rolling (6° to 12°) and moderately hilly (17–18°). Soil and air temperatures in the lowlands were higher compared with the highlands (Table 1) and were consistent with the meteorological data (Figures 2 and 3).

Soil characteristics

The soil type in Sungai Kial montane FR was Ringlet series (*Typic Haplohumult*) comprising clay loam texture (Table 2). The soil type in lowland Jengka VJR was Durian series (*Plinthaquic Paleudult*) comprising silty clay loam texture. Both sites had pH levels in the range of 3.5 to 4.5 which were acidic. Bulk density values for the montane forest were lower in the topsoil (0.3 to 0.5 g cm^{-3}) compared with the lowland forest which recorded values of between 1.2 and 1.3 g cm^{-3}. The values for EC and CEC were relatively higher in the montane forest, four and two folds respectively compared with the lowland Jengka VJR. Carbon values decreased with depth in both soil profiles but Sungai Kial FR had higher C content in the 0- to 17-cm depth. Levels of N fell below 1% for both sites and the topsoil of Sungai Kial FR had very high P levels compared with other horizons in both sites which were about 30–40 ppm. Values for K, Ca and Mg for both sites were higher in the topsoil of Sungai Kial FR and Jengka VJR, and decreased with increasing depth.

Botanical characteristics

The most common tree families in Sungai Kial FR were Myrtaceae, Polygalaceae and Lauraceae (Table 3). Species from the genera *Syzygium* and *Xanthophyllum* were widely distributed. Statistical analyses for mean dbh and stand basal area revealed that there were no significant differences among the sites studied. However, the mean height for Jengka VJR was significantly higher compared with trees at the toeslope. The maximum dbh and height encountered in the Sungai Kial FR ranged from 40 to 45 cm and from 10 to 50 m respectively. Stand basal area ranged from 26–28 m^2 ha^{-1} and the highest tree density was in the summit compared with the sideslope and toeslope.

Phyllanthaceae, Dipterocarpaceae and Euphorbiaceae were dominant in Jengka VJR with increased mean height but reduced mean dbh values compared with the montane forest. However, maximum dbh was relatively higher in the lowland forest. Common genera were *Aporosa, Shorea* and *Croton*. Although stand basal area was relatively lower compared with Sungai Kial FR (Table 3), tree density was the highest among all sites.

Components of carbon stocks

Soil bulk density values for the summit and sideslope were significantly lower and less than 1.0 g cm^{-3} compared with the toeslope in Sungai Kial FR and Jengka VJR (Table 4). Litter stocks at the summit were significantly higher compared with the rest of the sites investigated (Table 4). Values for the sideslope, toeslope and Jengka VJR were statistically the same. Following suit, soil C stocks at the summit were three, one and five folds higher compared with the sideslope, toeslope and Jengka VJR respectively. Soil C stocks were all significantly different at each site and the lowest values were recorded for Jengka VJR. However, above- and belowground (coarse roots) biomass values were not significantly different between sites. The aboveground biomass ranged from 75 to 120 Mg C ha^{-1} for all sites using both allometric equations. Belowground biomass (coarse roots) was relatively low in Jengka VJR compared with the rest.

Our data showed that the dominant pool for C stocks was projected by aboveground biomass, which was 47% of C or higher overall (Table 4). Soil C stocks at the summit and toeslope were lower compared with the aboveground biomass where values of 39 and 36% were recorded respectively at the 0–15 cm soil depth. Root C stocks (belowground biomass) ranged from 11 to 15% and litter stocks for all plots were minimal (≤ 3%).

DISCUSSION

Environmental conditions

As elevation increases, increased cloudiness and humidity occur where condensation processes are heightened during uplift (Hafkenscheid 2000). This influences soil and air temperatures, portraying cooler climates in the montane

Table 4 Soil bulk density values and carbon stock estimates in various carbon pools for Sungai Kial FR and Jengka VJR

Site	Soil bulk density (g cm^{-3})	Litter	Soil	AGB		BGB	Total	
		←		stocks (Mg C ha^{-1})				→
				x	y		x	y
Sungai Kial FR								
Summit	0.59 c	8.02 a	99.3 a	119.24 a	121.25 a	26.46 a	253.02	255.03
	(0.06)	(1.87)	(5.09)	(24.64)	(25.51)	(5.12)		
%		3	39	47		11	100	
Sideslope	0.32 b	4.50 b	32.31 c	117.78 a	118.75 a	26.15 a	180.74	181.71
	(0.05)	(0.32)	(0.77)	(31.47)	(31.97)	(6.83)		
%		3	18	65		14	100	
Toeslope	0.97 a	3.11 b	77.29 b	108.61 a	109.39 a	24.52 a	213.53	214.31
	(0.12)	(0.47)	(5.33)	(22.65)	(23.29)	(4.75)		
%		2	36	51		11	100	
Jengka VJR	1.17 a	2.71 b	18.60 d	75.35 a	75.75 a	16.78 a	113.44	113.84
	(0.12)	(0.43)	(0.65)	(25.51)	(26.53)	(5.33)		
%		2	16	67		15	100	

AGB = aboveground biomass, x = equation from Pearson et al. (2005), y = equation from Chave et al. (2005), BGB = belowground biomass, FR = Forest Reserve, VJR = Virgin Jungle Reserve; individual values in columns with different letters are significantly different (Student Newmann Keul Test at $p \leq 0.05$), values in parentheses represent standard errors forest than the lowlands. The steep to very steep topographic features in the higher altitudes clearly affect soil forming properties, vegetation distribution, nutrient uptake and transportation of debris and water. Unlike the montane forest, Jengka VJR is not affected by distinctive topographic variability and has warmer climate that is favourable for vegetational growth and microbial activities (Ho et al. 1987).

Soil characteristics

Tropical forest soils usually have an acidic range due to the high organic matter content (Brouwer & Reizbos 1998) in the upper layers of the soil profile. A slightly higher bulk density values in Jengka VJR compared with the Sungai Kial FR was probably due to the silty clay loam texture, where silt content was above 50% (data not shown) occupying the soil pore space. Lower soil bulk density values in the high altitude forest was presumed to be caused by the mixed material of organic and mineral layer (Jeyanny et al. 2011). The CEC, N and P values for Jengka VJR concur with values reported by Ho et al. (1987) in Jengka FR. Higher EC and CEC values in Sungai Kial FR topsoil may have contributed to better soil nutrient pools, particularly P, K, Ca and Mg which were relatively higher in the montane forest. Thus, based on the soil fertility status, Sungai Kial FR may have yielded better aboveground biomass values than Jengka VJR due to better nutrient uptake (Table 4). Similar to Sungai Kial FR, elevated levels of C (37.1%) and low levels of N (1.1%) were reported in an adjacent soil pit in Cameron Highlands due to the environmental conditions (i.e. high precipitation and low air temperatures) of the montane forests (Jeyanny et al. 2011).

Botanical characteristics

The montane forests of Malaysia are usually covered with epiphytes, ferns, byrophytes and liverworts. Common vegetation observed in Sungai Kial FR was consistent with studies done by Nizam and Rohaiza (2011) at adjacent forest reserves of Mentigi and Hulu Bertam in Cameron Highlands. The workers also reported that 56–80% of flora in their study area had dbh ranging from 5–15 cm, similar to our study. Most montane forests have been reported to display stunted vegetational growth compared with the lowlands, due to nutrient limitation affected by reduced temperatures, organic matter decomposition and water availability (Benner et al. 2010, Culmsee et al. 2010). This was evident where trees in Sungai Kial FR were relatively shorter compared with the lowlands. However, the dbh values were comparable with those of the lowlands. Tree density was reported to increase with altitudinal variation (Nakashizuka et al. 1992) in Genting Highland montane forest with minimal differences in stand basal area and this was true for our montane site as well.

The dominant species for Jengka VJR were from the Phyllanthaceae, Dipterocarpaceae and Euphorbiaceae families in the study site. Poore (1963) and Ho et al. (1987) both agreed that the forest was derived from the Red Meranti-Keruing type of lowland dipterocarp forest (Wyatt-Smith 1964), due to the existence of *Dipterocarpus* and *Shorea*. *Dipterocarpus* and *Shorea* are known as large emergent species that would have influenced the maximum dbh values in the lowlands. The previous logging in the late 1960s may have contributed to the regrowth and increased dominance of the tree family Dipterocarpaceae. Laidlaw (2011) observed that old logged-over forests such as the Sungai Lalang Forest Reserve in Jengka had a surge of 25% of dipterocarps, advocating a similar trend in our site which projected relatively higher tree density values.

Components of carbon stocks

The low soil bulk density values for the summit and sideslope were predictable due to the higher content of organic material on the forest floor (Table 4), which is common in tropical montane forests. Hafkenscheid (2000) reported that soil bulk density in the tropical montane forests of the Blue Mountain, Jamaica, ranged from 0.40 to 0.72 g cm^{-3} at the 0–14-cm depth in the forest. However, soil bulk density for toeslope was similar to that for the lowlands due to the downward mobilisation of debris. The high litter C stocks at the summit confirmed the distinctive presence of forest floor mass and its prolonged accumulation over a longer period of time compared with other sites. Higher altitudes usually have lower temperatures as shown in Figure 2, delaying decomposition processes (Majila et al. 2005) and preserving more litter mass and C stocks. Conversely, it is believed that Jengka VJR gave higher density as it is a secondary forest with rapid litter decomposition trends influenced by higher air mean temperatures (Figure 3).

Studies have indicated that C concentrations in soil increase with altitude in a mountainous terrain (Nakashizuka et al. 1992, Garten Jr & Hanson 2006). Griffiths et al. (2009) reported values for C which increased by 44% in the high elevations compared with the lowlands due to soil organic matter content at elevations above 1000 m. The soil C stocks were clearly different even within the montane forest due to several factors. At the summit, frequent and persistent fog formation is capable of reducing solar irradiance by at least 10–50% (Hafkenscheid 2000) and altering the water balance of the microclimate, keeping soils constantly wet and impeding decomposition. At the toeslope, the physical concave topographic feature facilitates downward movement of soil, organic debris and water (Huggett & Cheesman 2002), allowing accumulation of an ecto-organic layer (van Wesemael & Verstraten 1993) with higher soil C stocks compared with the sideslope which is fairly linear. The vegetation diversity along a varying topography as found in lowland and montane forest reflects changing balances of soil C inputs and losses, due to abiotic and biotic factors such as litter quality, decomposition, temperature and soil moisture. Low soil and air temperatures in Sungai Kial FR (Table 1, Figure 2) may have slowed down the decomposition processes, causing accumulation of organic matter (Satrio et al. 2009, Aznar et al. 2010), thus giving higher values for soil C stocks overall compared with the lowlands. A previous study by Jeyanny et al. (2013) confirmed that values for total C were elevated (> 5%) in the montane forest compared with the lowland (± 1%). Even the initial values from the soil profile in Sungai Kial FR at the 0–5 cm horizon confirmed that there was more than 40% C due to the presence of well-decomposed (sapric) organic material (Table 2).

Aboveground biomass in tropical equatorial forests is reported to be about 164 Mg C ha^{-1} (Gibbs et al. 2007). In Sabah, Saner et al. (2012) reported aboveground biomass of 92 Mg C ha^{-1}. Although we expected higher aboveground biomass in lowland forest due to better net primary production compared with montane forests, results from both areas did not reflect this. This was probably due to the logged-over effect of the lowland forest compared with the montane forest and the enhanced soil fertility status of the montane forest. However, our results were within the range reported for tropical forest ecosystems (IPCC 2006, Saner et al. 2012, Ngo et al. 2013).

Allometric equations are commonly used for estimating coarse root biomass and based on the equations used, root biomass was lower compared with values in Pasoh FR, which constituted almost 41.4 Mg C ha^{-1} (based on 0.5 C fraction) after corrections (Niiyama et al. 2010). Ngo et al. (2013) reported that coarse roots constituted 40.2 and 18.8 Mg C ha^{-1} in a primary and a secondary forest of Bukit Timah FR in Singapore respectively. Values for Jengka VJR were comparable with those of Ngo et al. (2013) for a secondary forest. Besides allometric equations, root:shoot ratios are also commonly reported to reflect the net effects of C allocation between the above- and below-ground components (Mokany et al. 2006). The root:shoot ratios of our study sites are also in acceptable levels (0.17 to 0.22) as values for tropical forests were between 0.18 and 0.24 (Cairns et al. 1997, Niiyama et al. 2010).

The changes in C stocks at varying topography in Sungai Kial FR in different components were exhibited in this study, reconfirming the need to compartmentalise tropical montane forests for C dynamics research. Precise estimation becomes more important as Malaysia has 2.4 million ha of tropical montane forest out of 19.3 million ha of total forest cover (Peh et al. 2011). Generalising values based on a certain forest type or component would be erroneous particularly in C stock reporting and devising appropriate management strategies for C stock monitoring and conservation.

CONCLUSIONS

Litter and soil C stocks were at least 44 and 22% significantly higher at the summit compared with the rest of the sites. The total C stocks at the summit and toeslope were relatively higher compared with the sideslope and Jengka VJR. No significant differences were encountered for mean height, mean dbh and stand basal area among all sites. Aboveground biomass contributed the largest C stocks (more than 40%) but soil C stock at the summit was comparable with the aboveground biomass at the summit, sideslope and toeslope, showing diversity at varying topography. Tropical montane forests are able to sequester more C stocks at higher altitudes compared with lowlands due to minimised disturbances and suitable environmental conditions. Future research should be undertaken to quantify C stocks in other montane forests of Malaysia. It is also necessary to improvise methodology to determine the forest floor components of tropical montane forest to reflect the C stocks stored in the decomposing layers.

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REFERENCES

Aznar J, Paucar-Munoz H, Richer-Lafleche M & Begin Y. 2010. Field litter thickness assessed by gamma-ray spectrometry. *Forest Ecology and Management* 260: 1640–1645.

Basuki T, Van Laak P, Skidmore A & Hussin Y. 2009. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management* 257: 1684–1694.

Beer C et al. 2010. Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. *Science* 329: 834–838.

Benner J, Vitousek PM & Ostertag R. 2010. Nutrient cycling and nutrient limitation in tropical montane cloud forests. Pp 90–100 in Bruijnzeel LA, Scatena FN & Hamilton LS (eds) *Tropical Montane Cloud Forests: Science for Conservation and Management*. Cambridge University Press, Cambridge.

Bridson D & Forman L. 1992. *The Herbarium Handbook*. Second edition. Kew Royal Botanic Gardens, Surrey.

Brouwer LC & Riezbos HT. 1998. Nutrient dynamics in intact and logged tropical rain forest in Guyana. Pp 73–86 in Schulte A & Ruhiyat D (eds) *Soils of Tropical Forest Ecosystems: Characteristics, Ecology and Management*. Springer, New York.

Brown S, Hall CAS, Knabe W, Raich J, Trexler MC & Woomer P. 1993. Tropical forests: their past, present, and potential future role in the terrestrial carbon budget. *Water, Air and Soil Pollution* 70: 71–94.

Cairns MA, Brown S, Helmer EH & Baumgardner GA. 1997. Root biomass allocation in the world's upland forests. *Oecologia* 111: 1–11.

Chave J et al. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87–99.

Chave J, Coomes DA, Jansen S, Lewis SL, Swenson NG & Zanne AE. 2009. Towards a worldwide wood economics spectrum. *Ecology Letters* 12: 351–366.

Culmsee H, Leuschner C, Moser G & Pitopang R. 2010. Forest aboveground biomass along an elevational transect in Sulawesi, Indonesia, and the role of Fagaceae in tropical montane rain forests. *Journal of Biogeography* 37: 960–974.

Dixon RK, Solomon AM, Brown S, Houghton RA, Trexler MC & Wisniewski J. 1994. Carbon pools and flux of global forest ecosystems. *Science* 263: 185–190.

Djomo AN, Knohl A & Gravenhorst G. 2011. Estimations of total ecosystem carbon pools distribution and carbon biomass current annual increment of a moist tropical forest. *Forest Ecology and Management* 261: 1448–1459.

Garten Jr CT & Hanson PJ. 2006. Measured forest soil C stocks and estimated turnover times along an elevation gradient. *Geoderma* 136: 342–352.

Garten Jr CT, Post WM, Hanson PJ & Cooper LW. 1999. Forest soil carbon inventories and dynamics along an elevation gradient in the southern Appalachian mountains. *Biogeochemistry* 45: 115–145.

Gibbs HK, Brown S, Niles JO & Foley JA. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters* 2: 045023.

Griffiths RP, Madritch MD & Swanson AK. 2009. The effects of topography on forest soil characteristics in the Oregon Cascade Mountains (USA): implications for the effects of climate change on soil properties. *Forest Ecology and Management* 257: 1–7.

Hafkenscheid RLLJ. 2000. Hydrology and biogeochemistry of montane rain forests of contrasting stature in the Blue Mountains of Jamaica. PhD thesis, Vrije Universiteit, Amsterdam.

Heath LS, Smith JE & Birdsey RA. 2003. Carbon trends in US forest lands: a context for the role of soils in forest carbon sequestration. Pp 35–45 in Kimble JM et al. (eds) *The Potential of US Forest Soil to Sequester Carbon and Mitigate the Greenhouse Effect*. CRC Press, Boca Raton.

Ho CC, Newbery DM & Poore M. 1987. Forest composition and inferred dynamics in Jengka Forest Reserve, Malaysia. *Journal of Tropical Ecology* 3: 25–56.

Hugget JR & Cheesman J. 2002. *Topography and the Environment*. Prentice Hall, Harlow.

IPCC. (Intergovermental Panel on Climate Change). 2006. *IPCC Guidelines for National Greenhouse Gas Inventories. Vol 4: Agriculture, Forestry & Other Land Use*. National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies, Kanagawa.

IPCC. (Intergovermental Panel on Climate Change). 2013. Summary for policymakers: climate change 2013: the physical science basis. In Stocker TF et al. (eds) *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

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. *Journal of Tropical Forest Science* 25: 577–591.

Jeyanny V, Wan Rasidah K, Lim JS, Fakhri MI, Rozita A & Suhaimi WC. 2011. Preliminary findings on temporal changes of selected soil chemical properties in tropical montane forest soils. Pp 245–249 in Mahmud S et al. (eds) *Proceedings of the SOILS 2011 Conference*. 19–21 April 2011, Kota Kinabalu.

Laidlaw RK. 2011. Effects of habitat disturbance and protected areas on mammals of Peninsular Malaysia. *Conservation Biology* 14: 1639–1648.

Lal R. 2008. Carbon sequestration. *Philosophical Transactions of the Royal Society B* 363: 815–830.

Lasco RD, Guillermo IQ, Cruz RVO, Bantayan NC & Pulhin FB. 2004. Carbon stocks assessment of a secondary forest in Mount Makiling Forest Reserve, Philippines. *Journal of Tropical Forest Science* 16: 35–45.

Lim JS. 2002. Estimating organic carbon in soils of Peninsular Malaysia. Paper presented at the Seminar on Climate Change Carbon Accounting. SIRIM, Shah Alam.

Maden K. 2004. Plant collection and herbarium techniques. *Our Nature* 2: 53–57.

Majila BS, Joshi GC & Kala CP. 2005. Patterns in litter fall and litter decomposition along an altitudinal gradient in the Binsar Wildlife Sanctuary, Central Himalaya. *International Journal of Sustainable Development and World Ecology* 12: 205–212.

McKenzie N, Ryan P, Fogarty P & Wood J. 2000. *Sampling, Measurement and Analytical Protocols for Carbon Estimation in Soil, Litter and Coarse Woody Debris.* National Carbon Accounting Technical Report 14. Australian Greenhouse Office, Canberra.

Mokany K, Raison RJ & Prokushkin AS. 2006. Critical analysis of root:shoot ratios in terrestrial biomes. *Global Change Biology* 12*:* 84–96.

Nakashizuka T, Yusop Z & Nik AR. 1992. Altitudinal zonation of forest communities in Selangor, Peninsular Malaysia. *Journal of Tropical Forest Science* 4: 233–244.

Ngo KM, Turner BL, Muller-Landau HC, Davies SJ, Larjavaara M, Nik Hassan NFB & Lum S. 2013. Carbon stocks in primary and secondary tropical forests in Singapore. *Forest Ecology and Management* 296: 81–89.

Niiyama K, Kajimoto T, Matsuura Y, Yamashita T, Matsuo N, Yashiro Y, Ripin A, Kassim AR & Noor NS. 2010. Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. *Journal of Tropical Ecology* 26: 71–284.

Nizam MS & Rohaiza D. 2011. Species composition, diversity and biomass of tree communities at two forest reserves at Cameron Highlands. Pp 97–107 in Abdul Rahman AR et al. (eds) *Hutan Pergunungan Cameron Highlands: Pengurusan Hutan, Persekitaran Fizikal dan Kepelbagaian Biologi (Vol. 14)*. Forestry Department of Peninsular Malaysia, Kuala Lumpur.

Olsen SR & Sommers LE. 1982. Phosphorus. Pp 403–430 in Page AL et al. (eds) *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties.* Second edition. ASA and SSSA, Madison.

Pearson T, Walker S & Brown S. 2005. Source book for land use, land-use change and forestry projects. Http://www.goldstandard.org/wp-content/uploads/2013/07/Winrock-BioCarbon_Fund_Sourcebook-compressed.pdf

Peh KSH, Soh MCK, Sodhi NS, Laurance WF, Ong DJ & Clements R. 2011. Up in the clouds: Is sustainable use of tropical montane cloud forests possible in Malaysia? *Bioscience* 61: 27–38.

Pitelka L & Rojas AR. 2001. IPCC WGI Third Assessment Report, Chapter 3: The carbon cycle and atmospheric carbon dioxide. Http://www.ipcc.ch/ipccreports/tar/wg1/558.htm.

Poore MED. 1968. Studies in Malaysian rainforest: I. The forest on Triassic sediments in Jengka Forest Reserve. *Journal of Ecology* 56: 143–196.

Saner P, Loh YY, Ong RC & Hector A. 2012. Carbon stocks and fluxes in tropical lowland Dipterocarp rainforests in Sabah, Malaysian Borneo. *PLoS ONE* 7: e29642.

Satrio AE, Gandaseca S, Ahme OH & Majid NMA. 2009. Influence of chemical properties on soil carbon storage of a tropical peat swamp forest. *American Journal of Applied Sciences* 6: 1970–1973.

Singh KD. 1993. The 1990 tropical forest resources assessment. Http://www.fao.org/docrep/v0290E/v0290e04.

Soil Survey Staff. 1993. *Soil Survey Manual.* USDA Agricultural Handbook No. 18. US Government Printing Office, Washington, DC.

Thwaites RN. 2000. From biodiversity to geodiversity and soil diversity. A spatial understanding of soil in ecological studies of the forest landscape. *Journal of Tropical Forest Science* 12: 388–405.

Thomas GW. 1982. Exchangeable cations. Pp 159–165 in Page AL, Miller RH & Keeney (eds) *Methods of Soil Analysis. Part 2, Chemical and Microbiological Properties.* ASA and SSSA, Madison.

Turner BL. 2010. Soil carbon in tropical forests: an inventory in CTFS forest dynamics plots. Paper presented in Soil Carbon Seminar. Forest Research Institute Malaysia, Kepong.

Van Wesemael B & Verstraten J. 1993. Organic acids in a moder type humus profile under a Mediterranean oak forest. *Geoderma* 59: 75–88.

Vogt KA, Vogt DJ & Bloomfield J. 1998. Analysis of some direct and indirect methods for estimating root biomass and production of forests at an ecosystem level. *Plant and Soil* 200: 71–89.

Wyatt-Smith J. 1964. *Manual of Malayan Silviculture for Inland Forest. Part III, Natural Regeneration.* Malayan Forest Records No. 23. Forest Research Institute, Kepong.