CONTRIBUTIONS OF FOREST BIOMASS AND ORGANIC MATTER TO ABOVE- AND BELOWGROUND CARBON CONTENTS AT AYER HITAM FOREST RESERVE, MALAYSIA

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NETO V, AHMAD AINUDDIN N, WONG MY & TING HL. 2012. Contributions of forest biomass and organic matter to above- and belowground carbon contents at Ayer Hitam Forest Reserve, Malaysia. Three 0.1 ha forest plots in Peninsular Malaysia were studied for aboveground carbon from biomass and belowground carbon in the soil. Soil samples were collected from four layers for determination of colour, texture, bulk density and carbon with the carbon–nitrogen–sulphur analyser. Herbaceous plants were extracted from subplots and processed for determination of biomass and carbon of aerial parts and roots. Stem diameters of trees were obtained. Total carbon content in the soil decreased with depth from 1.86 (0–29 cm) to 0.81% (90–120 cm), whereas bulk density in the same layers increased from 1.15 to 1.51 g cm^{-3}. The 60–120 cm layers contained 42% of the total carbon. The amounts of carbon found up to 120 cm depth, excluding large roots, superficial litter and coarse debris were 154, 174 and 208 t ha^{-1} in the three plots studied. Plots were very heterogeneous with regard to herbaceous vegetation, these contributing less than 0.01 t ha^{-1} carbon—main roots making up 30% and aerial parts being 3% richer. The three plots had 87, 195 and 205 t ha^{-1} of carbon from biomass of trees above the ground. Annual increments of litter, debris and root carbon were estimated.

Keywords: Soil carbon, carbon storage, carbon sequestration, climate change, tropical forest

NETO V, AHMAD AINUDDIN N, WONG MY & TING HL. 2012. Sumbangan biojisim hutan dan bahan organik terhadap kandungan karbon di bahagian atas dan bahagian bawah tanah di Hutan Simpan Ayer Hitam, Malaysia. Tiga plot hutan di Semenanjung Malaysia masing-masing bersaiz 0.1 ha dinilai kandungan karbon daripada biojisim di atas tanah dan karbon di dalam tanah. Sampel tanah diperoleh daripada empat lapisan untuk penentuan warna, tekstur, ketumpatan pukal dan karbon menggunakan penganalisis karbon–nitrogen–sulfur. Tumbuhan herba diperoleh daripada subplot dan diproses untuk menentukan biojisim dan karbon keseluruhan pokok dan akar. Diameter pokok juga diperoleh. Jumlah kandungan karbon di dalam tanah menurun dengan kedalaman iaitu dari 1.86% (0–29 cm) hingga 0.81% (90–120 cm) manakala ketumpatan pukal daripada lapisan yang sama meningkat dari 1.15 g cm^{-3} hingga 1.51 g cm^{-3}. Lapisan 60–120 cm mengandungi 42% daripada jumlah karbon. Jumlah karbon sehingga kedalaman 120 cm (tidak termasuk akar yang besar, sarap permukaan dan serpihan kasar) ialah 154 t ha^{-1}, 174 t ha^{-1} dan 208 t ha^{-1} dalam ketiga-tiga plot yang dikaji. Plot mempunyai tumbuhan herba yang heterogenus yang menyumbang kurang daripada 0.01 t ha^{-1} karbon—akar utama mengandungi sebanyak 30% kandungan karbon manakala bahagian atas tanah 33%. Ketiga-tiga plot mengandungi 87 t ha^{-1}, 195 t ha^{-1} dan 205 t ha^{-1} karbon daripada biojisim pokok di atas tanah. Kenaikan tahunan karbon daripada sarap, serpihan dan akar juga dianggarkan.

INTRODUCTION

The concentration of atmospheric carbon dioxide (CO_2) in 2005 was approximately 36% higher than that in 1750 (IPCC 2007a). In 2009, the amount of CO_2 in the air was 387 ppm, with an annual rate of increase of about 1.4 ppm averaged over the 1960–2005 period (NOAA/ESRL 2009). Atmospheric CO_2 is the greenhouse gas that contributes more to global warming compared with other greenhouse gases, ultimately leading to dramatic changes in the earth's climate if the current trend is maintained (Gower 2003, Thomas et al. 2004, Tremblay et al. 2005). To stabilise the atmospheric content of CO_2, thus mitigating climate change, it is necessary to preserve or improve the carbon sequestration and belowground carbon storage of tropical forests (IPCC 2007b).

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Estimates of carbon stocks of forests are mainly based on measurements of trees aboveground, providing an indication of wood volume and biomass per horizontal surface through the application of models for the stand type surveyed. Biomass per unit area is generally halved to reflect the amount of carbon in the vegetation, commonly expressed as t ha^{-1} (Brown 1997). Estimates of biomass or carbon content often refer only to the aboveground parts or when the belowground fraction is considered, it is roughly estimated. Besides, it is not always clear if the estimates given of carbon stored in the soil refer to live roots only or are inclusive of other organic matter and the depth which is being considered. Typically, only superficial layers are sampled. In any case, the underlying models seldom take into account small herbaceous plants, which also contribute to the forest carbon cycle in a fast succession.

Relationships between belowground carbon storage and aboveground carbon sequestration by aerial plant parts are essential for understanding the details of the carbon cycle (Schroeder 1995). In undisturbed tropical forests, over 40% of the organic carbon is stored in the soil (Trumper et al. 2009). There are numerous practical difficulties in assessing carbon storage belowground (Raich & Nadelhoffer 1989). Estimates of root mass are usually indirect as measuring root mass or volume is a destructive procedure, which requires felling the trees. Permanent plots monitored over time are superior means to obtain estimates of carbon changes above- and belowground but are rarely available.

The main objectives of this study of the three plots selected at Ayer Hitam Forest Reserve (AHFR) were to (1) assess variation of soil properties with depth, particularly the distribution pattern of the total carbon content in the soil, (2) determine the biomass and carbon content of aerial parts and roots of herbaceous vegetation and examine plant composition in subplots of the three plots and (3) estimate the total carbon above- and belowground, the corresponding partition and the contribution of the various components of biomass and organic matter in the three plots and compare them with other places.

Definitions of biomass, carbon in the soil and other terms are not consistent or clear in the literature. A brief explanation of terms frequently used is essential. This is based on commonly accepted concepts to elucidate the matter. Biomass refers to oven-dry weight of plant material until constant mass is achieved; this applies to aerial plant parts and roots. Litter fall and coarse debris are not considered biomass, neither are they soil organic matter until decomposed; these are measured as dry weights. Hence, aboveground biomass per unit area is derived from aerial plant organs of combined live vegetation and belowground biomass is from live main roots and fine roots. Elsewhere biomass may include non-living vegetation and litter. Obviously, there are controversial cases such as the standing dead tree and small dry vegetation. Numerous and contradictory definitions of biomass can be found. Glossaries of terms mentioned above are available in Schoene et al. (2007).

Herbaceous vegetation consists of all plants found in a specified area that do not develop woody structures over time, thus excluding young trees. Taxa are convenient taxonomic categories used to group herbaceous plants found in the plots of this study that can either be a single species or a family.

Total carbon in the soil refers to joint inorganic and organic carbon contained in a soil layer as percentage of the weight or per unit area. Inorganic carbon is part of minerals in the soil and organic carbon is part of the soil organic matter, which consists of decomposing organic residue less than 2 mm, from different origins and at various stages of decay. Therefore, live fine roots, because of their size, are often regarded as soil organic matter, instead of belowground biomass.

MATERIALS AND METHODS

Study site

Ayer Hitam Forest Reserve is a 1248 ha forest located in Selangor, Peninsular Malaysia. The approximate coordinates of the centre are 03° 01' N and 101° 39' E. This is a secondary disturbed lowland dipterocarp forest with logging history and is currently under sustainable management by Universiti Putra Malaysia (UPM). AHFR is surrounded by urban development. The study was carried out in compartments 14 and 15. These compartments are western divisions of the forest reserve, totalling about 500 ha.

AHFR stands in the Kenny Hill geological formation south of Kuala Lumpur (Government of Malaysia 1976). This formation is a sequence of interbedded shales, mudstones and sandstones, mainly Carboniferous, with sediments being deposited in marine waters not far from the landmass and not very deep (Stauffer 1973). The landscape is irregular with elevation ranging from 15 to 200 m above sea level (asl), forming slopes of 10 to 20% on average. The AHFR area is classified as steepland, with a combination of Serdang, Kedah and Durian soil series, derived from sedimentary and metamorphic rocks (Wong 1970). The parent materials are quartzites, sandstones and sandy shales with intercalations of silty and micaceous shales and phyllites. Soils of the Serdang series are characteristics of undulating and rolling to hilly land, giving place to shallower soils of the Kedah series on steeper terrain, where the Durian series can also be present. The colours of these soils vary mostly from dark brown to varied tones of greyish- or yellowish-brown. In general, textures range from sandy loam to sandy clay loam or sandy clay. The pH is about 5. Along streams and at the base of hills and ridges, young soils of local alluvium are found in association with colluvium, weathered rock material originated from upper areas.

The UPM farm in the vicinity of AHFR has the same geological origin as the forest reserve and consists of nine soil series, the most represented being Penambang (28%) in well-drained recent river terraces and bordering the lowest parts, Padang Besar (24%) in the crests of the residual hills and Bungor (19%) lying more between Pedang Besar and the lower alluvial plains (Tessens & Shamshuddin 1979). These three series exhibit predominance of brown or yellowish-brown tones, pH below 5, sandy clay loam or sandy clayey texture and organic carbon content about 3% near the surface, decreasing to less than 0.5% at 1.3 m of depth. These characteristics are similar to the Serdang, Kedah and Durian associations (Wong 1970). Consequently, AHFR soils could be broadly classified as Ultisols (Shamshuddin & Che 2010).

The climate of Peninsular Malaysia is tropical and affected by the SW and NE monsoons. It is characterised by uniform temperature throughout the year, light winds and high humidity. The monthly mean temperature in Kuala Lumpur varies less than 2 °C a year, but the daily variation is about 10 °C (Dale 1974). Pusat Pertanian Serdang (3° 00' N, 101° 42' E, 44 m asl) from 1992–2009 registered 2557 mm of average annual rainfall over 16 years, corresponding to 206 rainy days, 24 °C of average temperature at 8 a.m. (9 years) and 94% of average relative humidity at 8 a.m. (8 years). The Malaysian Agricultural Research and Development Institute (MARDI) Serdang (2° 59' N, 101° 40' E, 38 m asl) from 1985–2004 had 2463 mm of average annual rainfall (20 years), corresponding to 191 rainy days, 24 °C of average temperature at 8 a.m. (19 years) and 96% of average relative humidity at 8 a.m. (8 years). These stations are, respectively, 6 and 4 km away from AHFR towards S–SE (MMD 2010). Rainfall in the West region has two maxima in April and October–November and two minima in February and July (Dale 1974).

AHFR is mainly classified as kempas–kendondong forest type, poor in members of the genus *Shorea* from the Dipterocarpaceae family and populated by commercial species of low economic value (Wyatt-Smith 1961, Wyatt-Smith et al. 1995). Taxa inventory of six trails found 86 species of seed plants belonging to 68 genera and 32 families, of which 22 were timber species. Anacardiaceae, Euphorbiaceae and Myristicaceae were the most common families in number of species. Nevertheless, a few *Shorea* spp. were also present (Faridah et al. 2001a). In the SW compartment 15 of AHFR, 6621 trees from 50 families, 148 genera and 319 species were recorded, heterogeneously distributed within the 5 ha plot, with average height of 16 m, basal area of 32.3 m^2 ha^{-1} and 355 t ha^{-1} of biomass above ground (Lepun et al. 2007).

In six transects dispersed over AHFR, Ismariah and Ahmad (2007) sampled 375 trees with diameters at breast height (dbh) above 10 cm in a total of 0.6 ha, estimating 187 t ha^{-1} of carbon stored aboveground from an allometric relationship, without including litter and small branches and considering 50% carbon content of the biomass. The 15–30 cm diameter class comprised 80% of the trees; the Dipterocarpaceae, including *Shorea* spp., constituted 13% of the total number of trees. From inventory data of AHFR, the density of trees with dbh > 10 cm in compartment 14 was 287 trees ha^{-1} and in compartment 15, 366 trees ha^{-1}. The aboveground biomass calculated from an adapted equation was 232 and 183 t ha^{-1} for compartments 14 and 15 respectively. The Dipterocarpaceae represented 31 and 8% of the total number of individuals counted in compartments 14 and 15 respectively (Kueh & Lim 1999). A three-day expedition following set trails listed 27 species of herbaceous plants from 19 families; the ferns and fern-allies being the most represented. Overall, 430 species of seed plants from 72 families, 33 species of fern and fern-allies from 14 families and a total of 86 species of herbaceous plants had been identified at AHFR (Rusea et al. 2001).

Experimental design

This study had main units and subunits selected in two stages: the first stage consisting of simple random sampling of main units or plots and the second stage involving structured sampling of subunits or elementary units within the plots, with two available grid positions defining the location of the three dimensional elementary soil units. From the available representative areas of compartments 14 and 15 of AHFR, determined in a previous biomass research project, 10 main plots were identified randomly.

Three plots (50 × 20 m^2) were randomly selected from the set of 10 available plots scattered over different altitudes, mostly in the NW side of AHFR: plot E (03° 01' 12" N, 101° 38' 43" E, 112 m asl) and plot I (03° 01' 12" N, 101° 38' 23" E, 157 m asl) both situated in compartment 14 and plot A (03° 01' 07" N, 101° 38' 01" E, 94 m asl), compartment 15.

Plots were imaginarily divided in a 5 × 5 m^2 grid in a chess-like arrangement, where the centre of each square was the target location for collection of soil samples. Hence, each plot was subdivided into four imaginary rows, 10 columns and four layers, defining three dimensional elementary soil units of 5 × 5 × 0.3 m^3. The starting point of the grid was randomly chosen with a coin. In the deepest layer, only elementary units falling in one of the four rows were sampled. In each plot, 60 soil samples were obtained in alternate positions at depths of 0–29, 30–59 and 60–89 cm. Five positions in a row were additionally sampled at 90–120 cm. Therefore, a total of 65 × 3 soil samples were taken in the three plots for different tests. The total carbon content in the soil as percentage of weight was determined in the 65 × 3 soil samples, while other soil tests were carried out in part of these samples, following a predetermined systematic arrangement.

The biomass of herbaceous vegetation was estimated in 175 m^2 subplots, one laid in each of the three plots. The L-shaped subplots were randomly positioned: first by drawing the row hosting the long leg of the L, then by choosing the starting point of the long leg (25 × 5 m^2) and last by selecting the extremity of the long leg to which the short leg (10 × 5 m^2) should be attached. Herbaceous plants were harvested in the subplots, including the roots.

Processing of soil samples

The selected positions were sampled for soil at required depths with an auger. Undisturbed soil samples for bulk density determination were obtained separately with a steel cylinder tube of 98.1748 cm^3 internal volume. The soil samples were placed in plastic bags and labelled with the necessary information, including weather.

Soil samples collected from the auger holes were homogenised prior to analyses, excluding major roots, stones and large organic debris. Two subsamples from each sample were taken to determine the carbon content. Subsamples analysed with the elemental carbon–nitrogen–sulphur analyser (CNS) were air dried and finely ground. Subsequently, an amount close to 0.100 g was weighed in each crucible and placed in the machine autoloader for combustion in the furnace at 1350 °C. Combustion gases were blown to the detectors where CO_2 was measured by infra-red absorption. This method gave the total carbon content in the soil as percentage of weight, both organic and inorganic.

The colour test with the Munsell Soil Colour Chart was carried out in 13 × 3 soil samples obtained with the auger, at depths referred to earlier, from four diagonal plot positions. The bulk density determination, or the mass of air-dried soil per unit volume in g cm^{-3}, was conducted in 7 × 3 undisturbed soil samples collected at depths mentioned before in two diagonal positions per plot. The undisturbed soil samples were obtained using a steel cylinder tube, 5 cm long by 5 cm internal diameter. Soil samples collected with the auger near the same diagonal positions selected for bulk density determination were used for texture analysis following the United States Department of Agriculture standards (USDA 2009).

Processing of plant material

The herbaceous plants found in the L-shaped subplots were carefully extracted, together with intact roots. A 20 cm long by 3 cm in diameter aluminium pipe (141.4 cm^3) was vertically inserted into the soil surface in the vicinity of the extracted plants. This was to collect soil of the top 20 cm layer, excluding superficial litter and debris, for determination of the amount of fine roots left behind. Ten such soil samples were obtained in each subplot.

The soil was separated from roots of the plants harvested for biomass determination by immersion in water. The plants were grouped per taxonomic class and their fresh weights were recorded, aerial parts and roots separately, using a digital scale. Subsequently, plant parts were left to dry in the open for a week and then oven dried at 60–70 °C for 24 hours or until constant dry weight was obtained.

Carbon contents of aerial parts and roots were determined with the CNS analyser. Plant material of each taxonomic group was ground, sieved, homogenised and oven dried again prior to three subsamples of about 0.100 g being taken which were weighed in each crucible and placed in the machine. Soil samples collected in the vicinity of the extracted plants were firstly dry sieved with a 1.75 mm aperture mesh and secondly sieved with aperture 0.16 mm while immersed in water and stirred. Fine roots and other unidentified organic residue separated from the soil were subjected to identical processing as the other plant parts: oven dried to obtain the biomass and placed in the CNS analyser to acquire the carbon content.

Tree data of the three plots were obtained from a previous study. Individual trees above 10 cm dbh were identified by species and their diameters were taken for calculations of cross-section area and biomass.

Data analyses

Data from different determinations were organised into tables, inspected for outliers and summarised. Preliminary exploratory analyses were conducted, pictures produced to help interpretation and, where appropriate, analyses of variance and t-tests were performed. Processing of data was carried out with Excel and SPSS 16.0.

RESULTS AND DISCUSSION

Total carbon in the soil

The analyses of variance by plot of the percentage of total carbon in the soil revealed significant differences between plot columns in the case of plots A and I (Table 1). However, inspection of the column and row means and two-directional graphs (not shown) did not indicate any consistent gradient along columns or row. Adjusted means produced from the same analyses of variance were used in Figure 1. No spatial horizontal patterns were discernible within plots from the two-directional graphs, except in plot E where richer areas appeared to follow a diagonal pattern.

Table 1 Analyses of variance of total carbon content in the soil w/w (%) of the three plots and polynomial contrasts of soil depth layer

Source of variation	[a] Df	Plot A – [b] p(F)	Plot E – [b] p(F)	Plot I – [b] p(F)
Column	9	0.002	0.053	0.006
Layer	3	0.002	0.000	0.000
Linear	1	0.004	0.000	0.000
Quadratic	1	0.397	0.000	0.563
Cubic	1	0.821	0.058	0.950
Residual mean square	52	0.135	0.160	0.168
Mean (% total carbon)		[c] 0.91	[c] 1.39	[c] 1.25

[a] Df degrees of freedom, [b] probability of the F-value, [c] least square means from the analyses of variance with type III sum of squares; fixed effects models are Y(ijk) carbon content of an elementary 3D soil unit = overall mean + effect of column (i) where the unit is located + effect of depth layer (j) where the unit is located + random error of the unit (ijk), where i = 1, …, 10 columns, j = 1, …, 4 layers, k = 1, …, 4 rows

The partition of the layer effect into orthogonal polynomials is presented in Table 1. Linear components were significant at the 1% level in plot A and 0.1% in plots E and I. However, in plot E the quadratic component was also significant at 0.1%, indicating a deviation from the straight line as seen in Figure 1. In the three plots, total carbon decreased with soil depth, although the lines had different slopes.

The results obtained were in agreement with previous soil analyses of the UPM farm in the vicinity of AHFR (Tessens & Shamshuddin 1979), where organic carbon content determined by the Walkley-Black method was about 3% near the surface, decreasing to less than 0.5% at 1.3 m for the major soil series. This also corroborates the idea that soils of the three plots are very poor in inorganic carbon that probably does not exceed 0.5% of the total carbon. Nevertheless, no determination of organic carbon by the Walkley-Black method was carried out in the present study to verify the amount of inorganic carbon.

The averages of the coefficients of variation (CV) of the two subsamples from each of the 65 samples per plot were 8.9% in plot A, 8.1% in plot E and 4.9% in plot I; in 11 cases, CV > 20%. This information of the quality of the analytical procedure shows the advantage of taking two subsamples instead of one, the necessity of further improving the pre-treatment technique of the subsamples loaded into the CNS analyser and the importance of preliminary data scrutiny in order to repeat samples for subsamples which give disparate results.

Soil colour, texture and density

The soil colour determined in four diagonal positions in each plot is presented in Table 2. The soil colour showed predominance of brown and yellow tones in the three plots. Darker and browner tones were present more in the upper layers, which contained larger amounts of organic matter. With depth, tones of brown became less intense whereas yellow became prevalent. In the lowest layer, yellow and orange tones were visible.

Figure 1 shows an increasing trend in soil density with increase in depth, particularly in plot E. The generalised linear model with dependent variable bulk density revealed highly significant differences between plots ($p < 0.001$) and between layers within plots ($p < 0.001$) but no significant differences between positions within plots ($p = 0.504$). Plots differed in soil texture but down the same profile texture varied consistently. Soil of plot A was sandy-loam, whereas soil of plots E and I was sandy-clay-loam to clay. Overall, textures of the soil samples collected in the three plots were located towards the left side of the USDA classification triangle.

Estimates of total mass of carbon in the soil per unit area

Taking the means of percentage of total carbon in the soil w/w and bulk density per layer, the total mass of carbon in the soil up to 120 cm depth, excluding large roots, superficial litter and coarse organic debris, could be estimated

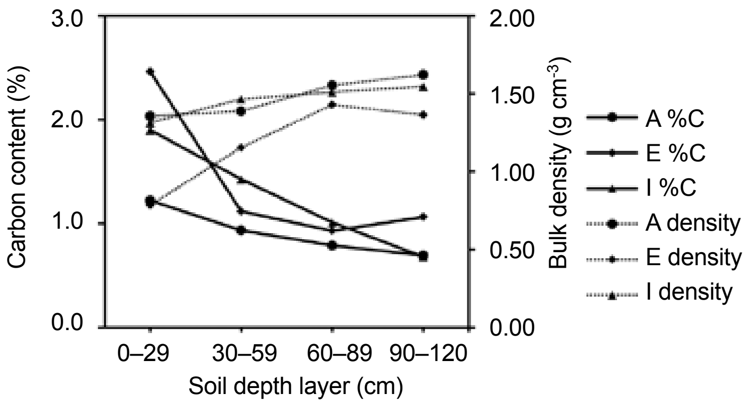

Figure 1 Solid lines: total carbon in the soil in w/w (%) in plots A, E and I at four depth layers; least square means of the first three layers are based on 20 observations each and have standard errors of the means (SE) ≈ 0.09; least square means of the deeper layer are based on five observations each and have SE ≈ 0.18; dash lines: soil bulk density (g cm^{-3}) in the same plots; the estimated model means of the first three layers are based on two observations each, SE = 0.027 and the values of the deeper layer refer to one observation, SE = 0.041

Table 2 Colour of the soil, soil texture class (USDA) and estimated mean soil bulk density in the three plots

Layer (cm)	Property	[a] Position	Plot A	Plot E	Plot I
0–29	Colour	4	Dark brown and dark yellowish brown	Dark brown	Dark brown and dark yellowish brown
	Texture	2	Sandy loam	Sandy clay loam	Sandy clay loam and clay
30–59	Colour	4	Yellowish brown and brownish yellow	Yellowish brown and brownish yellow	Brownish yellow and yellowish brown
	Texture	2	Sandy loam	Sandy clay loam and sandy clay	Sandy clay and clay
60–89	Colour	4	Yellowish and yellowish orange	Yellowish	Yellowish
	Texture	2	Sandy loam	Sandy clay	Sandy clay loam and clay
90–120	Colour	1	Yellowish orange	Reddish orange	Yellowish orange
	Texture	1	Sandy loam	Sandy clay	Sandy clay loam and clay
Mean density (g cm^{-3})			[b] 1.48	[b] 1.19	[b] 1.46

[a] Number of diagonal plot positions; [b] linear model estimates, each with SE = 0.016

at 154, 174 and 208 t ha^{-1} for plots A, E and I respectively (Table 3). Once the fresh mass of large roots is measured per unit area in further studies, the corresponding biomass can be determined and, subsequently, their carbon content known with the CNS analyser. Hence, the carbon mass of large roots per unit area (t ha^{-1}) can be estimated, a quantity to be added to the total mass of carbon in the soil presented in Table 3, which is underestimated. Inorganic carbon of unknown amount thought to be less than 0.5% of soil weight should be deducted from the total carbon to obtain the total mass of organic carbon in the soil per unit area.

Table 3 shows that the total amount of carbon in the soil of deeper layers is not negligible. Despite the lower carbon percentages of the lower layers in comparison with the upper layers, this was compensated by soil density increase with depth (Figure 1). This also shows that substantial amounts of carbon are stored in AHFR soils, which are generally considered mineral soils poor in organic matter in contrast to organic soils such as peat.

Table 3 Estimates of total carbon in the soil and occurrence of trees with dbh > 10 cm in the three plots

Parameter	Plot		
	A	E	I
Total carbon in the soil 0–29 cm (t ha^{-1})	48.0	56.0	72.4
Total carbon in the soil 30–59 cm (t ha^{-1})	37.6	37.4	60.6
Total carbon in the soil 60–89 cm (t ha^{-1})	35.5	38.5	44.2
Total carbon in the soil 90–120 cm (t ha^{-1})	32.5	42.1	30.5
[b] Total carbon in the soil 0–120 cm (t ha^{-1})	153.7	174.0	207.8
Number of trees with [a] dbh > 10 cm	34	49	48
[c] Number of families	16	13	23
[c] Cross-section area of trees (m^2 ha^{-1})	18.96	36.69	39.62

[a] Diameter at breast height is 1.3 m from the ground; [b] sum of the four layers; [c] refers to the same trees with dbh > 10 cm

Biomass of herbaceous vegetation

The average moisture contents of all 106 plants extracted from the three subplots were 78.4% (CV = 16%) of the fresh weight for aerial parts and 76.6% (CV = 15%) for main roots (results not shown). Table 4 presents the amounts of biomass of whole plants per subplot and taxon, the corresponding percentage of biomass the main roots and the percentage of carbon contained in aerial plant parts and in main roots.

The variation in biomass between plants of the same taxonomic class was high, as indicated by the coefficient of variation in Table 4—the highest being 159% for the 43 Gramineae plants. Individual plants differed considerably in size and weight. Taking the three subplots together, the classes with more expression in terms of mass were, by descending order, *Pandanus* spp., *Mapania cuspidata* and Gramineae spp. When the number of individual plants was considered, the order was Gramineae spp., Zingerberaceae spp. and Araceae spp. Contributions of the different classes to the biomass of the subplots were very heterogeneous. The wide differences in biomass recorded in the three subplots and the variability between individual plants within the same taxonomic group suggested the need of using larger sampling subplots for studies of this nature.

Overall, the mean carbon content of aerial plant parts was 42.4% and the mean carbon content of main roots was 39.1%. The paired t-test of the 10 classes in the last two columns of Table 4, with subplots combined, was significant at the 5% level ($p = 0.028$). The aerial plant parts of herbaceous vegetation found in the three subplots were about 3% richer in carbon compared with roots.

Excluding subplot means, each of the 20 values of the last two columns of Table 4 is a mean from three determinations (not shown here), obtained with the CNS analyser. The referred 20 values have coefficients of variation (not shown here) averaging 1.32%, the variability of carbon content within each of the 20 sets of three subsamples of biomass. This amount reflects good quality of the analytical procedure. This indicates that in future two subsamples of biomass should be sufficient to determine the carbon content, provided the technique used to process the plant material submitted to the CNS analyser is maintained.

Table 4 Plant biomass recorded in each 175 m^2 L-shaped subplot per taxonomic classification and carbon content in biomass of aerial plant parts and main roots

Subplot	Taxon	Number of plants	Biomass total (g)	CV (%)	Root biomass (%)	Aerial carbon (%)	Root carbon (%)
A	Araceae spp.	14	29	88	25	41	39
	Gramineae spp.	43	85	159	19	40	36
	Griffiths forrestia	2	6	93	21	38	37
	Mapania cuspidata	7	101	86	26	40	41
	Molineria latifolia	5	4	37	16	44	32
	Acanthus spp.	4	2	59	20		
	Piper spp.	2	6	12	38	[a] 45	[a] 36
	Tetracera sp.	1	2	–	–		
	Zingerberaceae spp.	17	66	59	29	40	38
	Total	95	301.8	Mean	24.2	41.1	37.1
E	*Pandanus* spp.	3	33.0	49	30.7	45.5	44.8
I	*Dracaena* spp.	2	58	24	31	44	44
	Pandanus spp.	6	100	47	46	46	42
	Total	8	158.6	Mean	38.6	45.2	43.1

[a] Carbon content determined jointly; coefficient of variation (CV) = variation in biomass between plants within the same taxon; values were rounded up

In Table 3, carbon in the soil per unit of surface and occurrence of trees with dbh > 10 cm were put together for comparison. Table 3 might suggest associations that would remain speculative until a larger set of data collected in plots of appropriate size ascertained the nature of the relationships between the variables listed. It would be interesting, for example, to verify systematically how the carbon content of each soil series is associated with the biomass of the different vegetation types it carries.

The biomass of fine roots and other fine organic residue (residual biomass) found in the top 20 cm layer of soil in the proximity of extracted plants, not including superficial litter or coarse debris, is presented in Table 5. The fine roots separated from the soil did not belong exclusively to the vegetation extracted and the soil might have been disturbed during plant extraction. The average moisture content of the residual biomass in the three subplots was 80.2% of the fresh weight (results not shown). Subplot A with the largest amount of total biomass of herbaceous vegetation also contained more residual biomass. The average carbon content of the residual biomass was 42.5%.

Table 5 also presents the amounts of residual biomass in the top 20 cm of soil per unit area in the vicinity of removed plants as an indication not to be extrapolated to the subplot area, just to provide an idea of the dimension of these values. Nevertheless, fine roots and other small organic residue were included in the percentages of total carbon in the soil discussed earlier (Figure 1), whereas major roots and coarse residue were excluded from the soil samples for carbon determination.

Bruckman (2006) who studied the fine root distribution of three tree species at Pasoh found average values of fine root biomass in the top 20 cm of soil ranging from 40–190 g m^{-2}, with higher values in non-disturbed forest plots. He suggested that herbaceous plants accounted for a substantial part of fine root biomass in the upper most layers of the soil. Thuille and Schulze (2006) assumed fine root biomass from forest as 2% of stem biomass while considering 40% of fine root biomass annually entering the organic carbon stock.

The most revealing aspect of Table 5 is the small mass of carbon from herbaceous vegetation per unit area compared with trees. The other interesting aspect was that, on average, 30% of the carbon contained in herbaceous vegetation resided in main roots. This value was an underestimate because fine roots left behind in the soil were not included in the calculations. Besides, there were considerable differences between the three subplots in percentages of carbon contributed by the main roots of herbaceous plants. This was due to the heterogeneous composition of vegetation harvested in the subplots and differences in characteristics from the reduced number of individuals collected in subplots E and I.

The current study is time independent. Although the mass of carbon from herbaceous vegetation per unit area was relatively small, these were annual plants with life cycles much shorter than trees, thus contributing to surface debris and decomposing organic matter of the top soil in fast succession. The values of herbaceous vegetation curently presented for plots A, E and I were very small compared with those of Lasco

Table 5 Total biomass of herbaceous vegetation, aerial carbon and main root carbon per unit area based on subplot totals and means

Subplot	Biomass (t ha^{-1})	Aerial carbon (t ha^{-1})	Root carbon (t ha^{-1})	[a] Root carbon (%)	Residual biomass (g cm^{-3})	[b] Carbon (%)	[c] Residual biomass (g m^{-2})	[c] Carbon (g m^{-2})
A	0.017	0.0054	0.0015	22.4	0.0015	35	290	102
E	0.002	0.0006	0.0003	30.4	0.0008	44	163	72
I	0.009	0.0025	0.0015	37.5	0.0009	48	184	88
Mean	0.0094	0.00283	0.00111	30.07	–	42.5	–	–

[a] Root carbon as percentage of total carbon in herbaceous plants; [b] percentage of carbon in residual biomass; [c] only in the proximity of extracted plants and up to 20 cm depth; values of residual biomass are based on the pooled soil volume from 10 cylinders per subplot

et al. (2006), although the understorey they referred to was not just herbaceous.

Estimates of total carbon above- and belowground

Estimates of aboveground carbon in AHFR reported values of 171 t ha^{-1} in compartment 15 (Lepun et al. 2007), 180 t ha^{-1} in dispersed transects (Ismariah & Ahmad 2007), 112 t ha^{-1} in compartment 14 and 88 t ha^{-1} in compartment 15 (Kueh & Lim 1999). In Pasoh lowland forest, 80 km eastwards of AHFR, aboveground carbon was estimated at 228 t ha^{-1} (Kato et al. 1978). Yet in Pasoh, the disturbed compartment 121 recorded only 67 t ha^{-1} (Faridah et al. 2001b). These estimates were based on 48% carbon content of live biomass obtained from diverse allometric relationships. Table 6 presents estimates of aboveground carbon mass per unit area for the three AHFR plots, based on equations used by Ismariah and Ahmad (2007) after Brown (1997), and Kueh and Lim (1999) modified from Kato et al. (1978).

Plots E and I had around 200 t ha^{-1} of carbon from biomass aboveground. The aboveground carbon estimate in mature Pasoh stands can be an indicator of the potential of AHFR, which has not entirely recovered from past loggings. Koskela et al. (2000) estimated the potential aboveground carbon stock of tropical rainforests in continental Asia at 216 t ha^{-1} based on biomass data, assuming 48% carbon content in tree biomass. They mentioned that secondary vegetation in natural succession might take centuries to reach the typical carbon stock of mature forests.

Gibbs et al. (2007) presented carbon stocks of tropical equatorial Asian forests compiled from different sources at 250 t ha^{-1} based on measurements from ecological studies, at 164 t ha^{-1} by taking the average forest carbon stock while accounting for anthropogenic disturbances and at 180 t ha^{-1} for continental South-East Asia. In the Philippines, fixed plots in primary dipterocarp forest were reported to stock 258 t ha^{-1} of carbon, 65 t ha^{-1} of which was soil organic carbon to a depth of 30 cm (Lasco et al. 2006). Logged forest in the area had just 100 t ha^{-1} of aboveground carbon, taking one cycle of 35 years to recover 70% of the original aboveground stock. Logging appears not to have influenced belowground carbon, with average soil organic carbon in the top 30 cm layer varying from 31 to 106 t ha^{-1} in sets of plots at different stages of reforestation. Koskela et al. (2000), referring to studies in Amazonia, presented belowground carbon stocks of the top 1 m layer at approximately 102 t ha^{-1}, regardless of vegetation cover although litter fall and root inputs were higher in mature rainforests. In compensation, there was also more efflux of CO_2 caused by the fast recycling of soil organic matter to vegetation in rainforests. Thuille and Schulze (2006), in a study of carbon dynamics of spruce stands in Thuringia and the Alps, noted the great stability of carbon stocks in mineral soils, nevertheless

Table 6 Allometric estimates of carbon aboveground based on trees with dbh > 10 cm and considering 48% carbon content of tree biomass in plots A, E and I

Parameter	Plot			Pasoh
	A	E	I	
[a] Equation 3.2.4 from Brown (1997)	88	197	207	–
[b] Equation from Kueh and Lim (1999)	85	193	202	–
[c] Carbon aboveground (t ha^{-1})	87	195	205	[d] 228
[e] Litter fall carbon (t ha^{-1} $year^{-1}$)	*1.9*	*4.4*	*4.6*	5.1
[e] Coarse debris carbon (t ha^{-1} $year^{-1}$)	*1.2*	*2.7*	*2.8*	3.1
[f] Root carbon increment (t ha^{-1} $year^{-1}$)	*5.0*	*9.6*	*10.1*	*11.1*
[g] Root carbon (t ha^{-1})	*10.4*	*23.4*	*24.6*	*27.4*

[a] Y = exp {-2.134 + 2.530 * ln (D)}, [b] Y = 0.0921 * (D^2.5899), Y = biomass (kg), D = dbh (cm); [c] mean of the two allometric equations for plots A, E and I; [d] Kato et al. (1978) equation; [e] (*italic*) based on carbon aboveground and calculated after the proportions found in Pasoh, not measured; [f] (*italic*) obtained after litter fall and derived from Raich and Nadelhoffer (1989), not observed; [g] (*italic*) calculated after 0.12 root/shoot average ratio based on carbon aboveground (Brown 1997), not measured

dropping with the change in the original forest cover and taking beyond 80 years to regain former carbon stock levels.

Plots E and I at AHFR, with an estimated 200 t ha^{-1} of aboveground carbon from biomass of trees, appeared as not having reached a mature stage. The amount of carbon contained in the herbaceous vegetation was too small to make any difference except for the long-term contribution to soil organic matter. Plots E and I at AHFR (Table 3) with 174 and 208 t ha^{-1} of belowground carbon up to 120 cm depth, of which 56 and 72 t ha^{-1} were in the first 30 cm, and 132 and 177 t ha^{-1} in the first 90 cm respectively, had more carbon stored than Amazonian soils referred to by Koskela et al. (2000) but within the ranges found in the top layer by Lasco et al. (2006). The total carbon above- and belowground in plots E and I were thus estimated at about 369 and 413 t ha^{-1} respectively (Figure 2). These quantities need adjustment for contributions from superficial litter, coarse debris and main roots. To estimate the total organic carbon, the adjusted values need further correction to deduct the inorganic carbon in the soil.

Plot A situated 300 m from the houses was affected by encroachment of developers in the forest perimeter, besides past loggings. The perimeter of the forest was cleared of trees by building companies to create a buffer zone outside their land and construction materials left over could be found dispersed in the surrounding area. Remains of a makeshift camp for workers were also visible in the vicinity. The total carbon above- and belowground in plot A estimated at 241 t ha^{-1} appeared less typical than the values obtained for plots E and I (Figure 2). Soil characteristics, particularly nutrient availability, are known to be responsible for forest productivity. Plot A had lighter soils with 69% of sand, in comparison with plots E and I with 54 and 46% respectively. This is an indication that plot A may have lower carbon accumulation potential than plots E and I. However, the belowground carbon fraction of plot A was not so affected by disturbance as the upper fraction in comparison with plots E and I. This is also in agreement with Harrison et al. (1995) who reported the loss and long recovery of soil organic matter following felling and with Singh (2010) who reported decrease in soil organic carbon in all depth classes with decrease in forest density.

Studies of litter fall in Peruvian flood plain forests reported a value of 7.0 t ha^{-1} $year^{-1}$ where biomass aboveground exceeded 345 t ha^{-1} (Nebel et al. 2001) while forests of southern China averaged 6.7 t ha^{-1} $year^{-1}$ in stands with mean volume of 344 m^3 ha^{-1} of dominant tree species (Yu et al. 2005). Raich and Nadelhoffer (1989) listed studies of Sarawak dipterocarp forests where litter fall was, on average, 9.8 t ha^{-1} $year^{-1}$. In mature forests of Amazonia, litter fall was calculated as carbon at 4.5 t ha^{-1} $year^{-1}$ (Koskela et al. 2000). Lasco et al. (2006) reported 5.8 t ha^{-1} of litter fall from undisturbed plots of a dipterocarp forest in the Philippines. Kato et al. (1978) reported 10.6 t ha^{-1} $year^{-1}$ of litter fall and 6.5 t ha^{-1} $year^{-1}$ of coarse debris production in Pasoh non-disturbed dipterocarp forest. Carbon from litter fall and coarse organic debris deposited per year were roughly estimated in plots A, E and I, following the proportions found in Pasoh and based on the amounts of total carbon aboveground from trees (Table 6 and Figure 2).

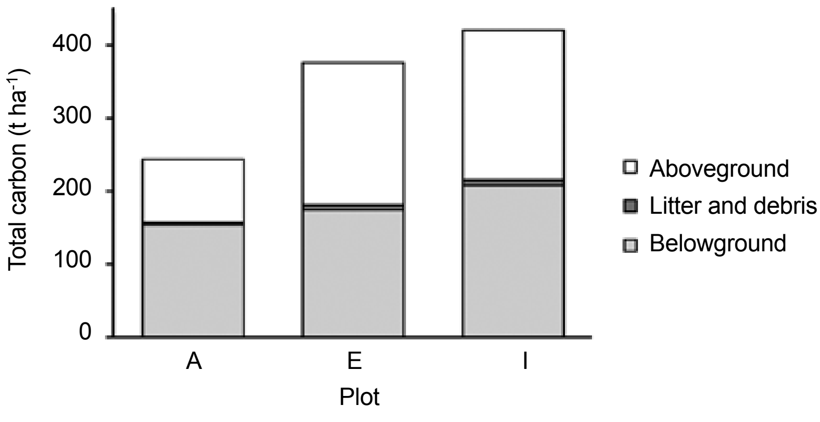

Figure 2 Total carbon above- and belowground in plots A, E and I; litter fall carbon and coarse debris carbon refer to one year increment

Raich and Nadelhoffer (1989) found highly significant positive correlation between litter fall and soil respiration rates, based on studies of numerous forests of different types. Total carbon allocation to roots was estimated by the difference between soil respiration and litter fall according to the regression equation R = 1.92 L + 130 where R is the root carbon allocation (g m^{-2} $year^{-1}$) and L is the litter fall carbon (g m^{-2} $year^{-1}$). These authors recognise that the root carbon allocation is overestimated by a small amount because of ignoring coarse debris and herbaceous vegetation inputs to the soil. Carbon allocations to roots based on Raich and Nadelhoffer (1989) were obtained for the three AHFR plots and Pasoh (Table 6). Carbon allocation to roots could not be directly added to the values presented earlier for plots A, E and I because carbon determinations of soil samples included fine roots. Besides, the values refer to an increment over a time interval of one year and not to a total mass of root carbon at a point in time.

To accurately determine the carbon contained in the root system is a difficult task. It requires the use of indirect methods of measuring litter fall and soil respiration over long periods, in addition to destructive sampling by uprooting the trees. It would be interesting to investigate systematically at AHFR the proportion of carbon, above- and belowground, in the biomass of tree species. There are considerable differences between species in carbon allocation to plant organs. A study by Cuevas et al. (1991) in Puerto Rico found that *Pinus caribaea* allocated practically all living biomass aboveground, whereas secondary forest in the region allocated 10% of live biomass to fine roots, although having similar total organic matter productions. Brown (1997) reported root to shoot ratios of lowland moist forests varying from 0.04 to 0.33, with an average of 0.12. Root carbon for plots A, E and I was calculated based on this average but should not be added to the values of total carbon estimated considering the uncertainty of the root/shoot ratio at AHFR and because carbon determinations of soil samples already included fine roots (Table 6).

CONCLUSIONS

The total carbon in the soil decreased significantly with depth from 1.86% in the uppermost 0–29 cm layer to 0.81% in the 90–120 cm deep layer. In plots A and I, the corresponding lines were nearly straight, while in plot E there was deviation from linearity.

There was predominance of darker and browner tones in the upper soil layers of the three plots. The tone became less intense with depth where yellow had prevalence. Soil texture was sandy loam in plot A and varied from sandy clay loam, sandy clay and clay in plots E and I. Bulk density increased significantly with depth from 1.15 g cm^{-3} in the top layer to 1.51 g cm^{-3} in the lowermost layer. The total carbon in the soil up to 120 cm depth, excluding large roots, superficial litter and coarse organic debris, was estimated at 154, 174 and 208 t ha^{-1} for plots A, E and I respectively. Overall, 42% of the total soil carbon was stored in the 60–120 cm layers, despite a reduction in carbon content with soil depth. In compensation, bulk density increased with distance from the surface. Hence, estimation of belowground carbon for stock assessment must consider deeper soil layers.

There were large differences in biomass of herbaceous vegetation between subplots and the contribution of the various taxa was very heterogeneous, especially with individuals of the same class differing widely in weight. The use of larger sampling units for biomass studies of this vegetation was suggested. Aerial parts of herbaceous plants were significantly richer in carbon (42.4%) compared with the main roots (39.1%). Biomass of herbaceous vegetation per unit area was less than 0.02 t ha^{-1} with 30% of the carbon coming from main roots. Thus, their contribution to the mass of carbon per unit area was very small compared with trees. Biomass from fine roots and other fine organic residue contained 42.5% carbon and was higher in subplot A, which also had higher biomass from herbaceous plants.

Plots A, E and I had respectively 87, 195 and 205 t ha^{-1} of carbon from biomass aboveground. Plots had 241, 369 and 413 t ha^{-1} of combined total carbon above- and belowground respectively. These values need adjustment for contributions of superficial litter, coarse debris and main roots. In plot A, the most disturbed, the belowground carbon fraction seemed less affected than the upperground.

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