FIELD NOTE

Fine root biomass in a tropical moist forest in the upper Negro River basin, Brazilian Amazon

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ABSTRACT Limited information on fine roots is hindering understanding of the geographical-scale variations in belowground carbon stock across the Amazon Basin. Fine root biomass (<2 mm in diameter) was studied in the upper Negro River basin of Brazil, where no previous study on fine roots had been reported. Two plots (20 × 125 m), each of which included 3 subplots (20 × 20 m), were set in a tropical moist forest at São Gabriel da Cachoeira, north-western Brazil. The diameter of the trees (*dbh* > 10 cm) within each subplot was measured, and fine roots were sampled by coring soils from depths of 0–5, 5–10 and 10–20 cm at 12 points in each subplot. The fine root, coarse root, and aboveground biomass in the study forest were estimated as 7.03 ± 0.65 (95 % CI), 32.6 ± 15.0 and 253.6 ± 152.7 Mg ha⁻¹, respectively. Most of the spatial variance in fine root biomass was accounted among and within the subplot spatial scale of less than 20 × 20 m. The fine root biomass of the study site exceeded the values reported for some tropical forests in the central and eastern Amazon, which suggested regional differences in the fine root biomass in Amazonian forests.

Key words: forest structure, regional difference, north-western Brazil, São Gabriel da Cachoeira, variance components

INTRODUCTION

Fine root biomass (FRB) has been treated as a key component of carbon flow in tropical forests (Malhi et al. 2011); as it comprise a large fraction (3–54 %) of the net primary production of forests (Jackson et al. 1997, Vogt et al. 1996). However, available data on fine root biomass in Amazonian forests remains limited compared to the case of aboveground biomass (Nogueira et al. 2008), probably due to the technical difficulties of root sampling (Vogt and Persson 1991). Besides, fine root studies in the Amazon region have only been conducted at a limited number of research sites, i.e. in the eastern (Silver et al. 2005) and central parts (Klinge 1973) of Brazil, Colombia (Jiménez et al. 2009), Venezuela (Sanford 1989) and Peru (Powers et al. 2005).

This study aimed to estimate the FRB in the north-western Brazilian Amazon, where no previous study on fine roots had been reported. Accordingly, we selected an old-growth tropical moist forest (*terra firme*) found typically in the region, where the structure of aboveground vegetation and coarse roots was reported (Lima et al. 2012). To

analyze spatial variation in FRB at the study site, we assessed the variance components on differing spatial scales and examined the relation of aboveground biomass to FRB at a 20 × 20 m scale.

MATERIALS AND METHODS

Study site

The study site (0° 7' S, 67° 3' W) was selected within the São Gabriel da Cachoeira Campus of Instituto Federal do Amazonas, near the city of São Gabriel da Cachoeira (Fig. 1). The annual mean temperature was 25.9°C (averaged from 1922 to 2004), and the mean annual precipitation was 2897 mm (averaged from 1922 to 2005) without marked dry months (National Oceanic and Atmospheric Administration, USA).

The study site soil was *Argissolos Vermelho-Amarelos Distróficos* + *Latossolos Vermelho-Amarelos Distróficos* (EMBRAPA 2006, Santos et al. 2011), which corresponds to the order Ultisol and Oxisol according to the USDA soil classification system. Greyish- to yellowish-brown-colored

Fig. 1. Location of the study site. Solid lines in the smaller map indicate the main roads.

sandy soil (7.5YR 5/2–10YR 7/2 in the Munsell color system; Standard Soil Color Charts, Fujihara Industry Co.) dominated the site, while the top soil (around 3–5 cm thick) was dark-colored (10YR 5/2). Some tree species of Fabaceae, Euphorbiaceae and Sapotaceae predominated in the forest, comprising the canopy layer.

Field measurements and sample processing

Field measurements and sampling were conducted from 28 August to 29 September, 2010. Two forest inventory plots with similar soil types and stand physiognomy were established at a distance of ca. 200 m, both of which were located in a lower part of a gently undulating slope (approx. 25 m difference from valleys to the plateaus), and the relative elevation of Plot 2 was ca. 6 m higher than Plot 1.

Three subplots (20 × 20 m) for the fine root sampling were randomly set within each plot (Subplots 1–3 and 4–6 for Plots 1 and 2, respectively), and diameters at breast height (*dbh*; cm) were measured for all trees exceeding 10 cm in *dbh* in each of the subplots. The aboveground biomass (*AGB*) and coarse root biomass (*CRB*; diameter > 2 mm) of each subplot were also calculated by applying the following allometric equation for individual trees developed by Lima et al. (2012): $AGB_{tree} = 0.488 dbh^{2.083}$, $CRB_{tree} = 0.320 dbh^{1.636}$, where AGB_{tree} (kg) and CRB_{tree} (kg) are the aboveground total dry mass and the coarse root dry mass (kg) of individual tree, respectively. Fine roots (< 2 mm in

diameter) were sampled from three randomly selected positions (at least 1 m apart from neighboring trees) in each quarter (10 × 10 m) of these subplots (a total of 12 positions per subplot). In each position, soil was cored using a steel cylinder (5 cm high; 100 cm³ in total volume) from the three depth classes; 0–5, 5–10 and 10–20 cm, respectively. Samples of these upper two classes were carefully collected by cutting the roots surrounding the cylinder with sharp knives and scissors. For the bottom soil layer, at a depth of 10–20 cm, the same cylinder was used to sample 5-cm-tall cores with a soil auger (DIK-1601, Daiki Rika Kogyo Co., Ltd, Saitama, Japan). Each coring sample was rinsed in water on a 2-mm mesh steel sieve, removing any soil having adhered to the root surface using small paintbrushes, then picking fine roots with forceps. Dead and living roots were separated by visual inspection and textures (Vogt and Persson 1991). Materials having passed through the sieve were then filtered by a 1-mm mesh oil strainer, and smaller pieces which were recognizable as fine roots had also been picked up. These procedures were conducted within 10 days of sample collection. The dry mass of these sample roots was measured after oven-drying at 65°C for more than 48 hours until a constant value had been attained. Some samples ($n = 3$ in Subplot 3, $n = 3$ in Subplot 5), which had been likely subject to errors during handling (e.g. partial loss of roots), were eliminated from the following data analysis. Only living fine roots were weighed and used for analysis.

Data analysis

The fine root mass of each soil layer and the cumulative fine root biomass at specific depths were calculated from the corresponding soil cores, assuming uniform fine root density within each layer. The FRB at each sampling point was determined as a sum of the fine root mass of the three depth layers (0–5, 5–10, and 10–20 cm respectively).

We conducted all of the following statistical analyses on R 2.15.2. To examine the fraction in the FRB variation accounted for in each spatial scale (between plots, among subplots in the plots, and within subplots), we calculated the variance components (Venables and Ripley 2002) of the log-normalized FRB values using a linear mixed-effects model ('lme' command in an 'nlme' package of R) fit by the restricted mixed linear (REML) method (Pinheiro and Bates 2000). In this analysis, we treated both plots and subplots as nested random effects.

The FRB at each sampling point (0–20 cm depth; $n = 66$) was then regressed by each of the aboveground biomass and the tree density of each subplots after log-normalization

Table 1. Some indices of stand structure and estimates of fine root biomass (FRB) at soil depths of 0–20 cm in each of the 6 20 × 20 m subplots within 2 plots at the study site in São Gabriel da Cachoeira. Mean dbh values are indicated with the standard deviations in the parentheses. For fine root biomass, the mean value of each subplot is indicated with 95 % confidence intervals in parentheses.

Plot	Number of trees (n ha ⁻¹)	Mean dbh (cm)	Aboveground biomass (Mg ha ⁻¹)	Coarse root biomass (Mg ha ⁻¹)	<i>n</i> [†]	FRB at 0–20 cm depth (Mg ha ⁻¹)	Proportion of fine roots [‡]
Plot 1							
Subplot 1	575	22.2 (± 11.9)	235	33.2	12	5.13 (± 1.21)	0.019
Subplot 2	600	27.9 (± 23.0)	526	58.0	12	9.39 (± 2.31)	0.016
Subplot 3	600	22.3 (± 12.8)	257	35.6	9	7.57 (± 1.60)	0.025
Plot 2							
Subplot 4	500	13.8 (± 4.3)	64	12.2	12	5.69 (± 1.01)	0.070
Subplot 5	600	18.8 (± 10.3)	175	26.5	9	6.46 (± 1.41)	0.031
Subplot 6	275	30.8 (± 22.8)	265	29.8	12	7.93 (± 1.07)	0.026

[†] : Number of samples for the fine root biomass

[‡] : Proportion of FRB at soil depth of 0–20 cm depth against the sum of FRB, aboveground biomass and coarse root biomass.

('lm' command on R). The proportion of FRB against total biomass (i.e. the sum of the three components AGB, CRB, and FRB) was also calculated to illustrate the contribution of the fine roots to the carbon stock of this stand.

RESULTS AND DISCUSSION

The fine root mass in the study site decreased rapidly with soil depth from 3.81 ± 0.33 (95 % CI) Mg ha⁻¹ in the 0–5 cm depth class to 1.36 ± 0.21 Mg ha⁻¹ in the 10–20 cm class. We approximated this pattern of cumulative FRB (W_c ; Mg ha⁻¹) with soil depth (d ; cm) incorporating all data, and the regression was given as $W_c = 7.45 \cdot (1 - 0.867^d)$. According to this non-linear regression and 999 bootstrap iterations, 94.2 (95 % CI, 88.9–97.6) % of the total FRB in the whole rooting depth was estimated as distributed within the 0–20 cm soil layer.

The number of trees, mean *dbh*, the estimates for AGB and CRB in each of the six subplots ranged from 275 to 600 trees ha⁻¹, 13.8 to 30.8 cm, 64 to 526 Mg ha⁻¹, and 12.2 to 58.0 Mg ha⁻¹, respectively (Table 1). Those variables of the stand structure did not differ substantially between the two plots. The mean value of FRB averaged for all samplings ($n = 66$) was 7.03 ± 0.65 Mg ha⁻¹. The FRB estimates differed six-fold among the samples, ranging from 2.25 to 14.5 Mg ha⁻¹, and the mean FRB value in each of the six subplots ranged from 5.13 to 9.39 Mg ha⁻¹ (Table 1). The relative proportion of the FRB against total biomass (i.e. the sum of AGB, CRB and FRB) ranged from 1.6 to 7.0 %, while the proportion of FRB against total roots (i.e. CRB plus FRB) ranged between 13.4 and 31.7 % (Table 1).

Local variation in FRB was high in the study site, and the variance components analysis showed that <0.0001, 25.6 and 74.4 % of total variance in the log-normalized FRB was accounted for between the plots, among the subplots in the plots, and within the subplots, respectively. This result suggests that the difference in FRB between the two plots is negligible, despite a difference in relative elevation between them of about 6 m. This result implies that the local scale differences the environmental conditions, such as soil moisture, between these plots did not have substantial influence on the FRB. Most of the variance in FRB was accounted for among and within a subplot spatial scale of less than 20 × 20 m. Regarding the influence of the stand structure (AGB, tree density) on FRB, there was a very weak positive correlation between the log-transformed FRB and AGB at the subplot scale ($\ln FRB = 0.211 \cdot \ln AGB + 0.743$; $p = 0.00398$, $r^2 = 0.122$), when all sampling data was pooled (Fig. 2). This result conforms to the results of previous studies, which indicate weak or no correlations between the basal area or AGB and FRB (e.g. Chen et al. 2004, Finér et al. 2011) at the stand level. The low correlation might be due to the effects from unmeasured factors such as the density of small trees less than 10 cm in *dbh* (Finér et al. 2011).

The FRB of Amazonian moist forests were estimated in different regions. Because the estimates of previous studies included dead fine root, we estimated the mean fraction of dead fine roots in the samples of total fine roots (i.e. both living and dead) as 23.1 % ($n = 12$). The reported total FRB values including dead fine roots at present are as follows: 12.2 Mg ha⁻¹ (<20 cm in soil depth; Sanford 1989) in the upstream region of the Negro River in

Fig. 2. Relationship between the fine root biomass of each sampling point and the aboveground biomass at each of the $6\ 20 \times 20\text{ m}$ subplots at the study site in São Gabriel da Cachoeira. Solid regression line indicates a log-linear relationship between them. See text for details.

Venezuela, 9.6 Mg ha^{-1} ($7.03 \pm 0.65\text{ Mg ha}^{-1}$ of the living biomass; $< 20\text{ cm}$; this study) in the upper Negro River basin in Brazil, $4.98\text{--}5.33\text{ Mg ha}^{-1}$ ($< 27\text{--}29\text{ cm}$; Klinge 1973) and 8.00 Mg ha^{-1} ($< 40\text{ cm}$; Powers et al. 2005) in the central Amazon, $2.01\text{--}2.96\text{ Mg ha}^{-1}$ ($< 10\text{ cm}$; Silver et al. 2005) and 2.34 Mg ha^{-1} ($< 10\text{ cm}$; Trumbore et al. 2006) in the eastern Amazon. Although the volume of research data remains quite limited, these comparisons show that fine root mass at the upper Negro River seems relatively large among the Amazonian moist forests.

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Appendix. Fine root biomass at each depth (0–5, 5–10, 10–20, and 0–20 cm) at each of the 72 measurement points at the study site in São Gabriel da Cachoeira.

Plot	Subplot	Fine root biomass (Mg ha^{-1})				Plot	Subplot	Fine root biomass (Mg ha^{-1})			
		0–5 cm	5–10 cm	10–20 cm	0–20 cm (Total)			0–5 cm	5–10 cm	10–20 cm	0–20 cm (Total)
1	1	2.691	2.002	1.734	6.426	2	4	4.420	1.212	1.100	6.732
		1.293	0.680	0.513	2.486			3.695	0.523	0.630	4.848
		1.336	2.263	0.395	3.993			5.132	0.465	0.954	6.551
		1.424	0.462	0.368	2.255			5.160	1.563	1.049	7.771
		3.221	1.360	1.230	5.812			5.091	1.218	1.277	7.586
		5.111	0.810	0.512	6.432			3.468	1.896	1.828	7.192
		2.034	0.664	0.636	3.334			3.079	0.703	0.581	4.363
		2.024	0.928	1.962	4.915			2.162	0.970	0.420	3.552
		3.397	2.456	1.361	7.214			2.266	0.234	0.548	3.048
		2.538	0.682	0.550	3.769			3.730	1.379	1.043	6.152
		4.697	1.432	1.046	7.175			5.218	0.508	0.398	6.123
		4.440	1.924	1.379	7.742			3.018	0.630	0.709	4.358
	2	2.779	3.426	0.568	6.773		5	2.870	0.863	0.785	4.518
		4.075	0.948	0.793	5.815			4.524	1.310	1.828	7.662
		2.067	1.180	0.812	4.059			3.745	1.931	1.262	6.938
		3.649	2.206	2.180	8.035			–	1.270	0.411	–
		6.159	3.075	1.800	11.034			5.465	–	0.732	–
		6.313	5.373	1.485	13.171			3.986	1.471	1.055	6.511
		3.963	3.931	1.222	9.117			5.133	3.690	–	–
		3.196	1.854	0.756	5.806			3.119	0.395	0.149	3.664
		4.191	2.509	0.373	7.073			3.882	2.540	1.320	7.742
		6.293	5.960	2.242	14.495			4.815	1.606	1.028	7.449
		5.095	4.422	4.783	14.300			4.916	2.662	1.682	9.259
		7.653	3.117	2.225	12.995			2.720	1.131	0.505	4.356
	3	4.088	3.839	2.485	10.412		6	5.025	1.887	1.272	8.184
		2.314	1.032	–	–			4.814	1.288	1.981	8.083
		3.194	1.582	1.319	6.095			1.815	4.009	2.675	8.499
		2.590	2.523	2.232	7.346			4.676	1.238	1.039	6.954
		4.580	2.490	1.275	8.345			3.718	1.881	1.869	7.467
		1.587	1.054	0.294	2.935			5.896	1.842	2.685	10.423
		4.247	1.554	–	–			6.337	1.495	2.384	10.216
		4.476	2.136	1.658	8.271			5.232	2.580	2.550	10.361
		4.536	2.990	1.756	9.282			4.074	1.350	1.597	7.021
		2.663	1.542	3.522	7.726			3.350	1.320	1.937	6.608
		2.336	–	0.615	–			0.694	1.754	3.054	5.503
		3.272	2.415	2.044	7.732			3.824	0.756	1.218	5.799