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ORIGINAL ARTICLE

Fine root biomass in gaps of 'Terra Firme' forest in eastern Amazonia

Massa de raízes finas em clareiras de floresta de terra firme na Amazônia Oriental

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ABSTRACT: Fine roots (< 5 mm) contribute to the uptake of water and nutrients by plants and play important roles in biogeochemical cycling. Nevertheless, little is known about the influence of logging on the production of these roots. The aim of this study was to evaluate the mass of fine roots in a 'Terra Firme' forest in the municipality of Moju, state of Pará, after natural and anthropogenic disturbance. Five gaps created by selective logging, five natural gaps caused by falling trees, and five undisturbed areas were selected. In each area, three replicates of soil samples were collected at different depths and all individuals with diameter at breast height (DBH) ≥ 5 cm were measured. The fine roots were separated into very fine roots (diameter < 1 mm), fine roots (diameter between 1-5), living and dead. Only the mass of live very fine roots was higher in intact forest compared to natural gaps and gaps formed by selective logging. The mass and necromass of roots decreased with soil depth. There was no significant relation between fine root mass and density of trees. Plots that underwent selective logging 14 years prior to the time of the study did not significantly recover the biomass of very fine and fine roots. Mass of very fine roots is more susceptible to forest disturbances.

RESUMO: *As raízes finas (< 5 mm) contribuem para a aquisição de água e nutrientes pelas plantas e exercem funções importantes para a regulação do ecossistema por meio da ciclagem biogeoquímica. Apesar disso, pouco se sabe da influência do impacto da exploração madeireira sobre a produção das raízes finas. O objetivo deste trabalho foi avaliar a massa de raízes finas em uma floresta de terra firme, localizada no município de Mojú, Estado do Pará, após perturbação natural e antrópica. Foram selecionadas cinco clareiras provenientes de exploração seletiva de madeira, cinco clareiras naturais provocadas por queda natural de árvores e cinco áreas não perturbadas. Em cada área, foram coletadas três repetições de amostras de solo em diferentes profundidades e foram mensuradas todas as árvores com DAP ≥ 5 cm. As raízes finas foram separadas em raízes vivas muito finas (diâmetro < 1 mm), finas, vivas (diâmetro entre 1 e 5 mm) e mortas. Somente a massa de raízes muito finas vivas foi maior em áreas de floresta não explorada do que em áreas de floresta explorada e áreas de clareiras naturais. A massa e a necromassa de raízes diminuíram com a profundidade do solo. A densidade de árvores não influencia na massa e na necromassa de raízes finas. Áreas que sofreram exploração seletiva de madeira havia 14 anos ainda não tinham recuperado de forma significativa a biomassa de raízes muito finas e finas. A massa de raízes muito finas é mais suscetível aos distúrbios florestais.*

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1 Introduction

Fine, non-woody roots of very small diameter constitute the main organ responsible for absorbing water and nutrients to plants (SILVER; MIYA, 2001). Some authors consider roots with diameter < 1 mm as fine roots (CASTELLANOS et al., 2001; TIERNEY; FAHEY, 2001); others classify as fine, roots with diameter < 2 mm (LEUSCHNER et al., 2006; LIMA; MIRANDA; VASCONCELOS, 2012); some others say fine roots are those with diameter < 3 mm (SUDARAPANDIAN; SWAMI, 1996); and finally, there are other authors that consider roots with diameter < 5 mm as fine roots; but these authors separate roots in different diameter classes, such as Cavelier, Estevez and Arjona (1996), Cavelier, Wright and Santamaria (1999), who classified fine roots according to diameter as < 1, between 1 and 2, and between 2 and 5 mm.

The production dynamics of fine roots can be influenced by several factors, such as availability of water and nutrients in the soil, physicochemical properties of soil (BLAIR; PERFECTO, 2001), seasonality (ZEWDIE; FETENE; OLSSON, 2008), type of vegetation, successional stage, and land use history (CAVELIER; WRIGHT; SANTAMARIA, 1999). Fine root biomass in soil can also be influenced by the formation of gaps caused by forest exploitation, resulting in increased annual net primary productivity; Sudarapandian and Swami (1996) reported that gaps formed by logging increase the productivity of fine roots, but other studies did not confirm this result (JONES et al., 2003; LEUSCHNER et al., 2006).

Reduced impact logging (RIL) is a forest management technique that aims to reduce damage to the remaining forest (VASCONCELOS; HIGUCHI; OLIVEIRA, 2009). The use of this technique causes smaller gaps, favoring the process of natural regeneration and plant growth (JARDIM; SENA; MIRANDA, 2008). The physical and chemical conditions of the soil are also favored by RIL. Few years after logging, the physical structure of soils in gaps no longer presents significant changes and may contain higher concentration of nutrients available in the soil than areas of primary forest intact (MELLO-IVO; ROSS, 2006).

The impact of logging on fine root biomass has never been investigated in Amazonia. This study aimed to assess the mass of live and dead fine roots in a Terra Firme forest located in the municipality of Moju, Pará state, after natural and anthropic disturbance. To this end, plots were used in areas of undisturbed primary forest, after natural disturbance (natural fall of trees), and after selective reduced impact logging (RIL), where the following hypotheses were evaluated: (1) Fine root mass in artificial gaps formed 14 years after RIL is smaller than that found in undisturbed primary forest areas and in natural gaps; (2) Fine root mass in a gap formed by RIL is smaller in its center than at 10 m away from the center; (3) Fine root mass in gaps formed by RIL is influenced by the directions North, South, East and West; (4) Fine root mass in natural gaps is greater in the crown area than in the areas of the trunk and roots of fallen trees; (5) Fine root mass decreases with soil depth; and (6) Fine root mass presents a direct relation with tree density.

2 Materials and Methods

The study was conducted in a Terra Firme forest located at the experimental field of Empresa Brasileira de Pesquisa Agropecuária - Embrapa, in the municipality of Moju, Pará state (2° 07' 30'' and 2° 12' 06'' S; 48° 46' 57'' and 48° 48' 30'' W). The area underwent selective RIL in October 1993.

The climate in the area is of Ami type according to Köppen classification, with average annual temperature between 25 and 27 °C and annual rainfall between 2000 mm and 3000 mm, irregularly distributed with occurrence of dry period. The study area presents plain relief with small slopes ranging from 0 to 3%. Yellow Latosol is predominant in the area, but Red-Yellow Argisol, Gleysol and Plinthosol are also present (SANTOS et al., 1985).

A plot of approximately 1059 ha, which underwent selective logging in 1993 and was observed for study in 2007, was selected in order to analyze the influence of gaps formed as a result of selective logging on fine root biomass. The study was carried out in a completely randomized experimental design, where five gaps formed by selective logging were selected; the gaps had their centers and cardinal directions (North, South, East and West) determined. The average size of the gaps investigated was 489 m^2.

A plot of 10 m^2 was established in the center of each gap and 10 × 20 m strips were installed around them, starting at the border of the gap into the forest, in the North, South, East and West directions; therefore, four strips were obtained per gap, covering an area of 900 m^2. Each strip was divided into square plots with 10 m sides. In each plot, three soil samples were randomly collected at three depths (0-10 cm, 10-20 cm and 20-30 cm), for a total of 91 samples per gap (Figure 1).

To compare the effect of natural gaps in the mass of fine roots, five natural gaps of approximately 203 m^2 formed after the natural fall of trees were randomly selected. In each gap, three samples of soil were randomly collected at four different

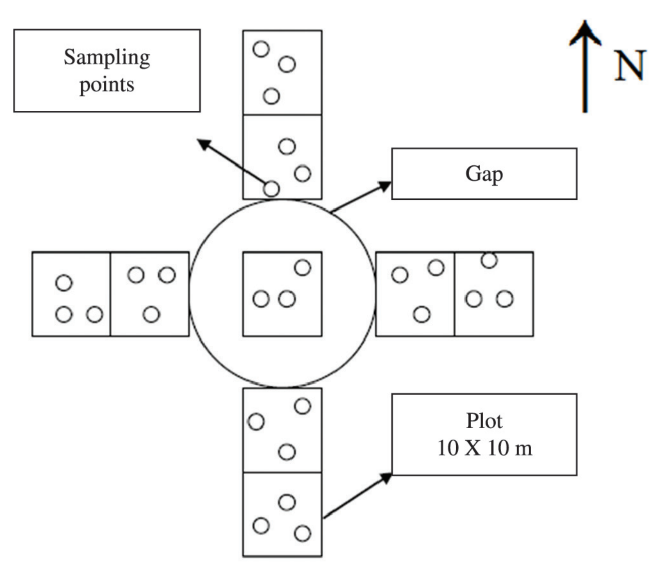

Figure 1. Schematic drawing of the distribution of plots and sampling points in relation to the gap in the municipality of Moju, Pará state.

depths (0-10, 10-20, 20-30 and 30-40 cm) in the region below the canopy, parallel to the trunk and inside the cavity caused by roots after the falling of trees, totaling 36 samples per gap, which in this case also correspond to the plot.

Five plots of 10 × 10 m were selected as control; they were randomly located in undisturbed areas, where three random soil samples were also collected at the same depths of those in the natural gaps, thus obtaining a total of 12 samples per plot.

Cylindrical soil samples (height: 10 cm, diameter: 5 cm, volume: 196.3 cm^{-3}) were collected using an auger (containing a volumetric ring inside); they were stored in plastic bags properly identified and kept under refrigeration at 4 °C in order to keep the roots alive in the soil block until their screening in the laboratory. The samples were washed with flowing water and sieved through 0.5 mm diameter mesh until only roots and organic fragments remained. The roots were manually separated from the organic fragments and categorized into very fine roots (diameter ≤ 1 mm), fine roots (1 mm < diameter ≤ 5 mm), and dead roots or necromass (dark and brittle). After separation, the roots were stored in paper bags and then dried at 70 °C to constant weight in a precision scale (0.0001 g) to obtain their dry weight.

The density of fine and very fine roots was obtained by the ratio between the mass and area of the cylinder (g m^{-2}). All data are presented as mean ± standard error. The Kruskal-Wallis test was used to verify the first five hypotheses. Comparison between the medians was performed by the Dunn test at 1% probability. Pearson linear correlation analysis was used for the last hypothesis. All tests were processed by the software package BioStat 5.0.

3 Results and Discussion

In this study, average fine root biomass ranged from 324 to 460 g m^{-2} (Table 1). These values are considered high for dense Terra Firme forests. This may have occurred because of the large amount of rain that occurs in the study area, providing greater availability of water in the soil. Similar results were verified by Cavelier, Wright and Santamaria (1999) in a dense Terra Firme forest in Barro Colorado Island, Panama (between 462 and 603 g m^{-2}), where rainfall values were very close to those found in this study. On the other hand, Sierra, Valle and Orrego (2003), in their study in a Terra Firme forest in Colombia, reported higher values of rainfall (above 3000 mm) and fine root biomass (1700 g m^{-2}).

No dead fine roots were found in the samples surveyed in all plots. This may have occurred because of the inefficiency of the sample volume (196.3 cm^{-3}) to include roots of larger diameters in the study area (SOUSA; GEHRING, 2010). The necromass of very fine roots ranged from 18 to 34 g m^{-2} (Table 1), similar to the result found by Espeleta and Clark (2007) in a primary forest in La Selva, Costa Rica (17 g m^{-2}).

The gaps formed as a consequence of reduced impact logging presented smaller very fine root biomass than the natural gaps and intact forest (Figure 2A). The necromass of very fine roots did not differ between gaps formed as a result of RIL, natural gaps and intact forest (Table 1). Fine root biomass also showed no difference between the areas

Table 1. Mass of very fine roots (≤ 1 mm), fine roots (1-5 mm), and necromass of very fine roots (≤ 1 mm) in IF = intact forest (n = 5), NG = natural gaps (n = 15), EF = exploited forest or forest that underwent selective logging (n = 45), in the municipality of Moju, state of Pará.

Size category	EF	NG	IF
	n=45	n=15	n=5
		(g m^{-2})	
≤ 1 mm	324.79±9.6	399.7±18.48	460±23.25
1-5 mm	325.39±53.17	348.62±50.17	413.09±57.14
Necromass ≤ 1 mm	23.01±3.92	34.52±6.52	18.98±2.88

Mean values followed by the standard error of the mean. n = number of plots.

of exploited forest, areas of natural gaps and areas of intact forest (Figure 2B).

Other studies have also found greater values of very fine root mass in undisturbed areas than in areas that have experienced anthropic actions, such as those by Sudarapandian and Swami (1996) and Leuschner et al. (2006). The fact that intact forests present greater mass of very fine and fine roots compared with logged forests can be attributed to better microclimatic conditions within intact forests, which is provided by greater canopy closure; unlike exploited areas, where there is a large increase in soil temperature during the day and decrease at night, impairing root respiration and diminishing the ability of mass accumulation by fine roots (LEUSCHNER et al., 2006). In addition, the inner rainfall is approximately 6% higher in exploited forest areas compared with intact forest areas, favoring an increase of rainwater, making the nutrients susceptible to displacement to deeper soil layers, therefore hindering the development of fine roots (FERREIRA; LUIZÃO; DALLAROSA, 2005).

The availability of nutrients in the soil may also have influenced the greater mass of very fine roots within the intact forest area. Leuschner et al. (2006) claim that exploited forests do not have the same production capacity of organic matter compared with intact forests, where a high density of dead matter is observed and where soil nutrient cycling is more constant and stable, thus encouraging the development of fine roots.

Gap size can directly influence fine root biomass, that is, gaps larger than 400 m^2, besides presenting wide variations in soil temperature, also present decreased soil humidity, interfering adversely in the stock of fine roots (LEUSCHNER et al., 2006). In gaps smaller than 200 m^2, the lateral growth of the crowns of the remaining trees ensures rapid canopy closure and prevents severe changes in the soil, allowing recovery of fine root biomass more rapidly, facilitated by their high plasticity (JONES et al., 2003; ZANGARO et al., 2007).

The natural gaps did not alter the biomass stock of very fine and fine roots and necromass compared with the intact forest, perhaps because they are small and with evidence of canopy closure due to lateral growth of the crown of trees near the gap; unlike the exploited areas in this study, where the increase of solar radiation was evident, resulting in increased temperature of the air and soil. Cavelier, Wright and Santamaria (1999) found smaller biomass of fine and very fine roots in natural

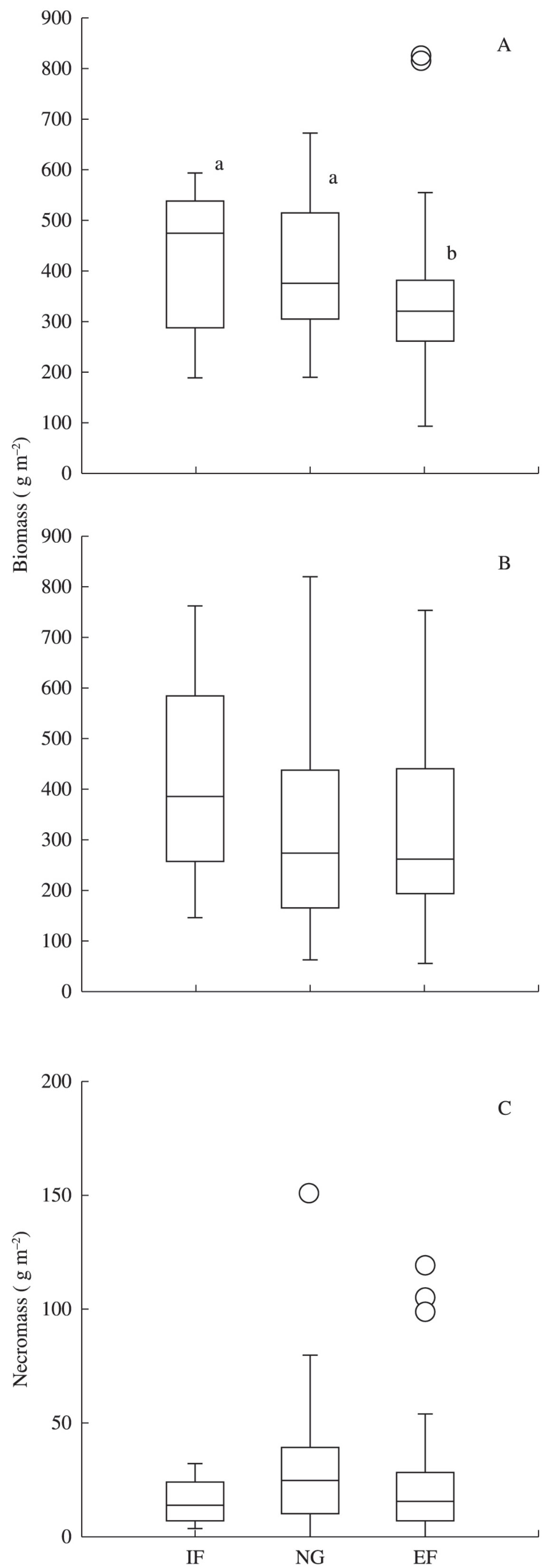

Figure 2. Biomass of very fine roots (A), fine roots (B), and necromass of very fine roots (C) in intact forest (IF, n = 5), natural gaps (NG, n = 15), forest that underwnet selective logging 14 years prior to the time of the syudy (EF, n = 45), in the municipality of Moju, state of Pará. Different letters denote statistical differences (Kruskal-Wallis, *p*<0.01).

gaps than inside the intact forest, but the gaps were much larger (400 m^2) than those of the present study (200 m^2).

In gaps formed by RIL, very fine root biomass was significantly higher in the center of the gap than on its border, or even 10 m away (center: 440.0±37.7 g m^{-2}; border: 303.8±14.9 g m^{-2}; 10 m away: 318.2±10.3 g m^{-2}) (Figure 3A). No difference was observed in biomass and necromass of fine roots between the center of the gap, the border, or at 10 m distance (Figure 3B).

The center of the gap presented greater biomass of very fine roots (440.0±37.7 g m^{-2}) compared with the plots located in the North (315.8±16.6 g m^{-2}), South (311±9.0 g m^{-2}), East (329.6±14.91 g m^{-2}), and West (278.8±23.8 g m^{-2}) directions, which in turn were not different among themselves (Figure 4A). Live and dead fine roots did not differ between the center of the gap and the adjacent regions (Figure 4B and C).

The larger stock of fine root biomass in the center of gaps of exploited forest can be related to canopy opening in some sites, especially in the north and west directions and at 10 m away from the border, caused by the recent natural fall of trees. These gaps favor the increase in the density of herbs, shrubs and lianas, whose roots intensify the competition with the remaining trees, negatively influencing the stock of fine roots (SUDARAPANDIAN; SWAMI, 1996).

The fact that only very fine roots present significant difference may be related to their sensitivity to respond rapidly to certain environmental changes; unlike fine roots, which have a much larger amount of structural chemical compounds such as lignin, cellulose, hemicellulose and tannin, thus ensuring greater resistance to small environmental changes (SILVER; MIYA, 2001).

In natural gaps, very fine and fine roots and necromass showed no significant differences between the crown, trunk and root regions of fallen trees - the mass of these roots was similar to that found in natural forests (Figure 5).

Equality of fine root biomass and necromass in the canopy, trunk and root regions of fallen trees were also observed by Cavelier, Estevez and Arjona (1996). This result may have occurred due to the recent falling of trees (residues of the crowns were not fully decomposed) in relation to the time of sample collection - probably the leaves of the canopy deposited on the soil, as well as to the fact that the dead roots of fallen trees still had not provided sufficient nutrients to attract the fine roots at that time (BLAIR; PERFECTO, 2001).

Very fine root biomass significantly decreased with soil depth, varying from 212.5±7.3 g m^{-2} in the top layer (0-10 cm) to 48.1±3 g m^{-2} at the 30-40 cm depth (Figure 6A). The same result was found for fine root biomass, which varied from 1957±10.9 to 41.34±7.8 g m^{-2} at the same depths, respectively (Figure 6B). The necromass was greater in topsoil (15.8±1.4 g m^{-2}) but the same at 10-20 and 20-30 cm depths, and greater at the depth of 30-40 cm, following the pattern of vertical distribution of fine roots in rainforests (ESPELETA; CLARK, 2007) (Figure 6C).

The greater biomass of very fine and fine roots and necromass of very fine roots in upper soil layers may be associated directly with the higher concentration of nutrients (TAPIA-CORAL et al., 2005) and dead matter in the first 10 cm of soil, which besides providing a favorable microclimate for

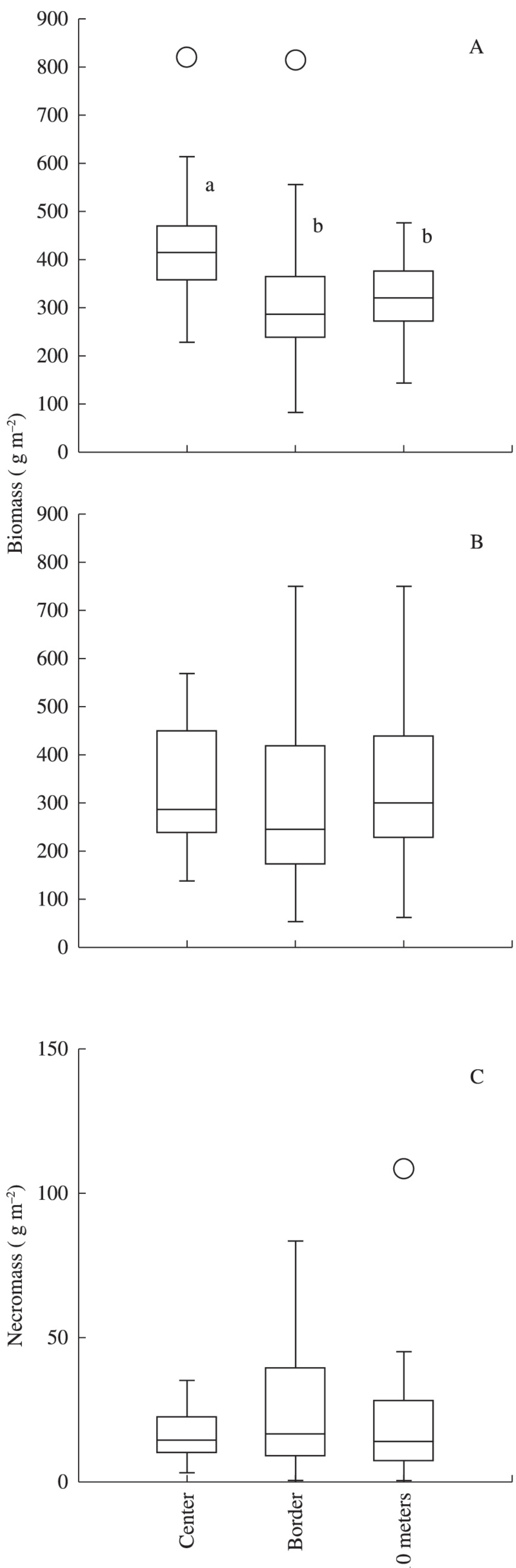

Figure 3. Mass of very fine roots (A), fine roots (B), and necromass of very fine roots (C) in the center (n = 5), border (n = 20), and 10 meters from the center of gaps (n = 20) in the municipality of Moju, state of Pará. Different letters denote statistical differences (Kruskal-Wallis, $p<0.01$).

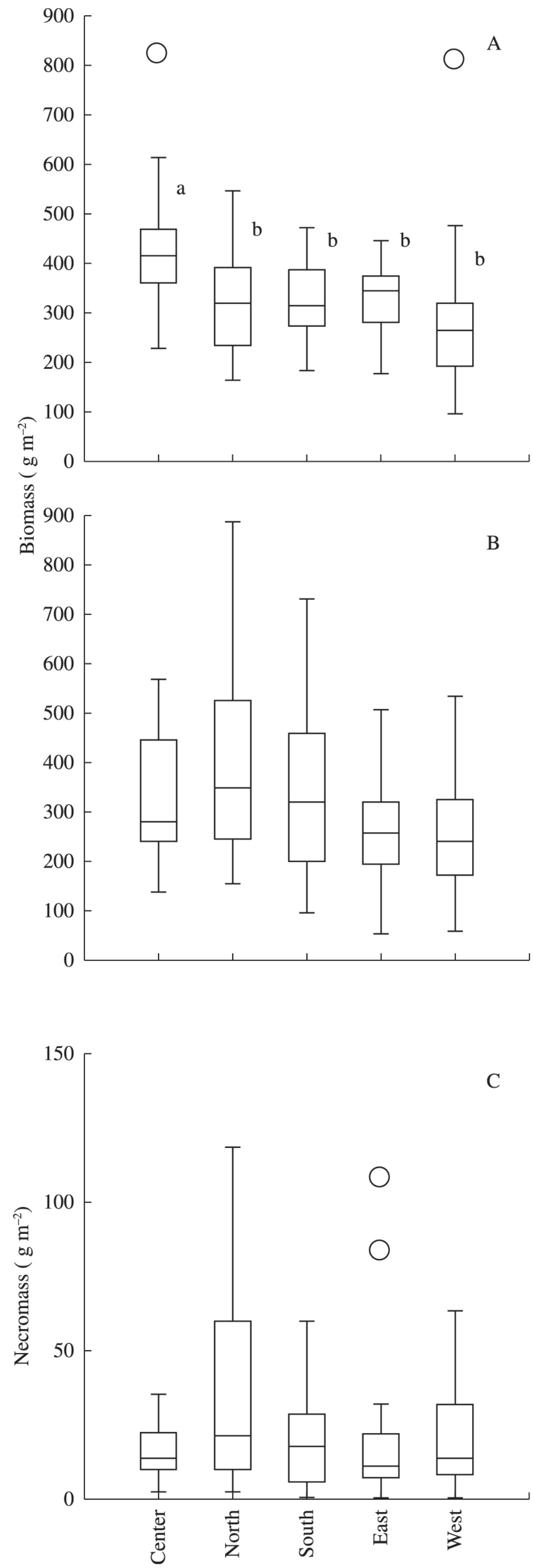

Figure 4. Mass of very fine roots (A), fine roots (B), and necromass of very fine roots (C) in the center of gaps (n = 5) and in the directions North (n = 10), South (n = 10), East (n = 10) and West (n = 10) of the gaps, in the municipality of Moju, state of Pará. Different letters denote statistical differences (Kruskal-Wallis, $p<0.01$).

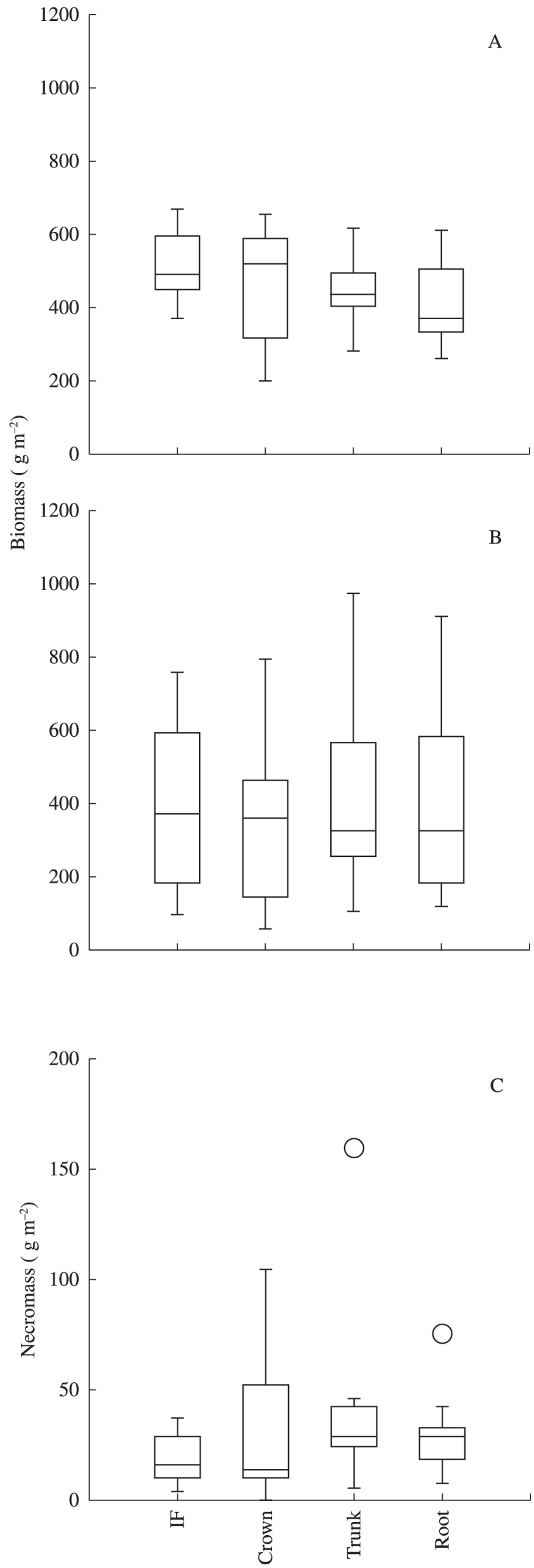

Figure 5. Mass of very fine roots (A), fine roots (B), and necromass of very fine roots (C) in the regions of IF = intact forest (n = 5), crown (n = 5), trunk (n = 5), and root (n = 5) of fallen trees in the municipality of Moju, state of Pará. Different letters denote statistical differences (Kruskal-Wallis, *p*<0.01).

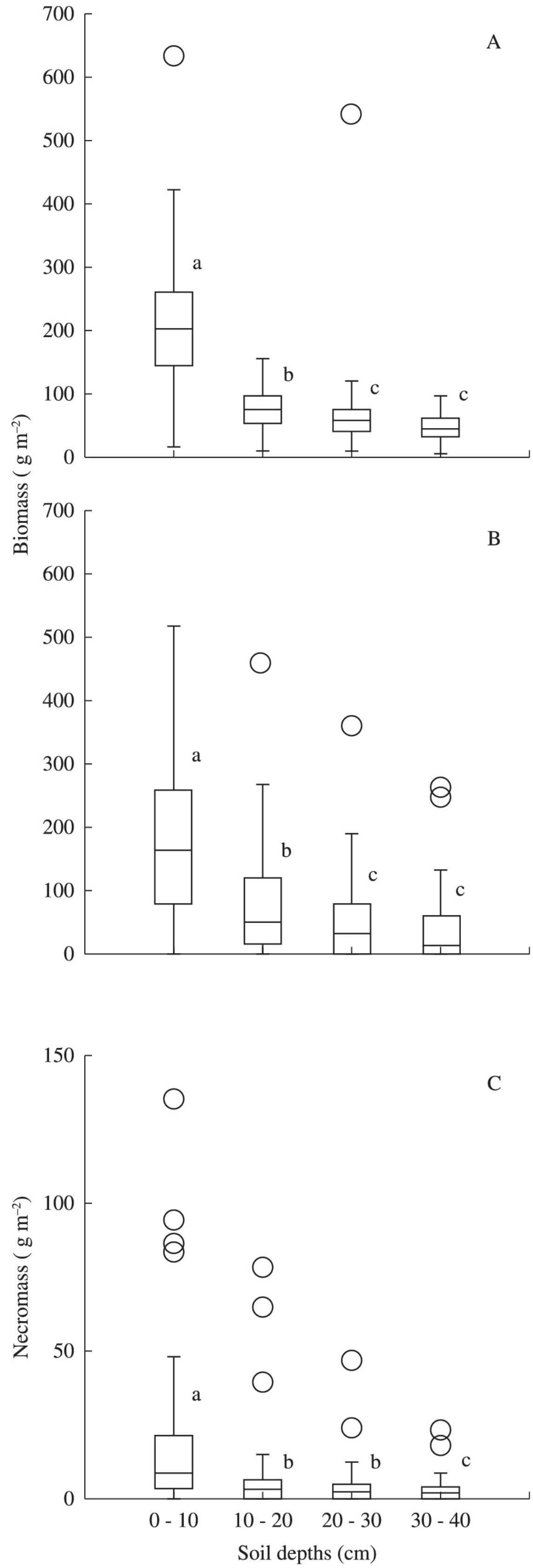

Figure 6. Mass of very fine roots (A), fine roots (B), and necromass of very fine roots (C) at different soil depths in a tropical rainforest in the municipality of Moju, state of Pará. Different letters denote statistical differences (Kruskal-Wallis, *p*<0.01).

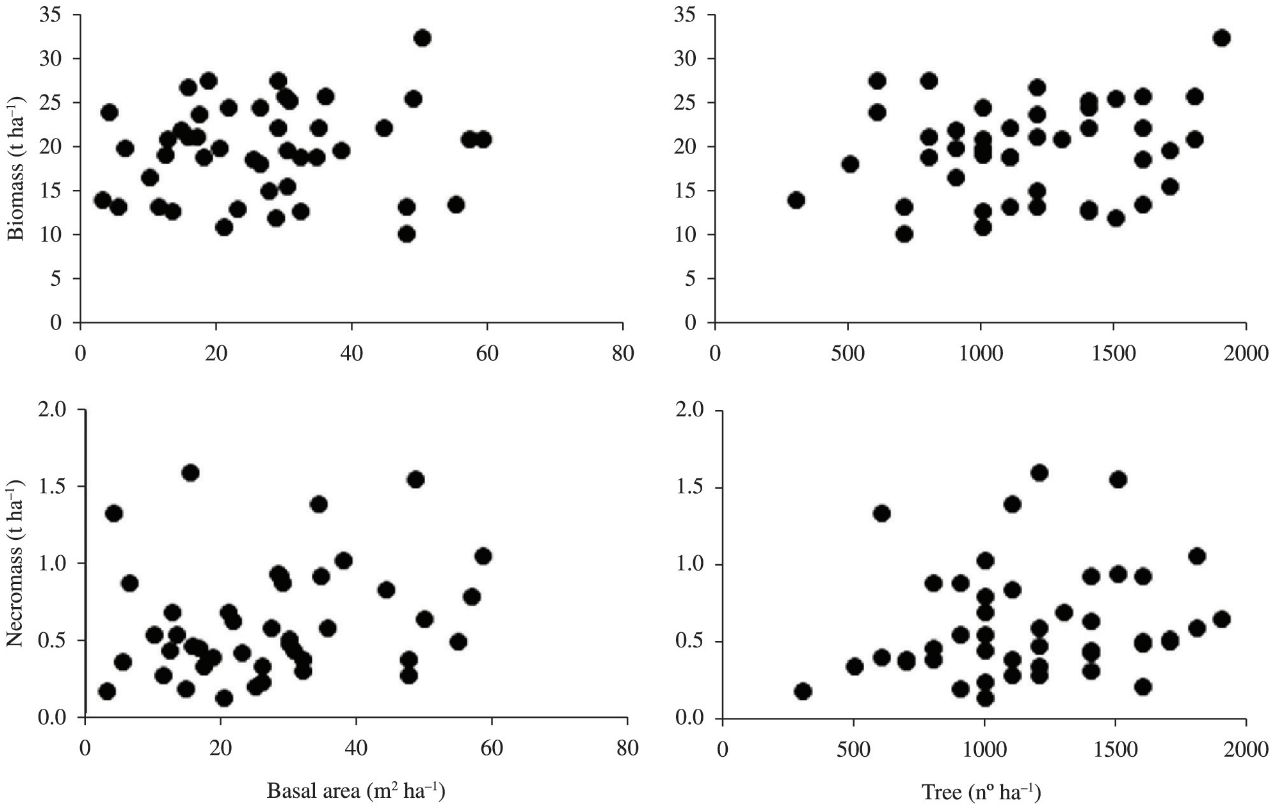

Figure 7. Relationship between basal area and number of trees with total biomass and necromass of fine roots at 30 cm depth (n = 46) in the municipality of Moju, state of Pará.

the growth of fine roots, also provides increased decomposition and, consequently, increases the cation exchange capacity of the soil, favoring the retention of nutrients by fine roots (MARQUES et al., 2004).

Fine root mass showed no significant correlation with tree density and basal area (Figure 7). Some studies show a relation between fine root mass and competition between trees (CAHILL; CASPER, 2000), but no study relates fine root mass with tree density. The lack of relationship found can be explained by some factors, including the heterogeneity of the physical and chemical attributes of soil (OLSTHOORN; KLAP; OUDE VOSHAAR, 1999). Plants change the distribution of fine roots according to the physical characteristics and, especially, to the availability of water and nutrients in the soil, which are not evenly distributed (JONES et al., 2003). More detailed studies are required to demonstrate the influence of heterogeneity of physical and chemical soil properties on the mass of fine roots.

Other factors that may have influenced the lack of correlation between fine root mass and tree density are the strategic characteristics of each species with respect to the uptake of water and nutrients (LEUSCHNER et al., 2004). Some species slow their growth when under stress and invest in the production of fine roots to become more competitive - it is a cost-benefit relation (CAHILL; CASPER, 2000); others react inversely (LEUSCHNER et al., 2004).

4 Conclusions

Unlike the forest areas under natural dynamic course, where the gaps formed by fallen trees did not influence the biomass, the areas that underwent selective logging 14 years prior to the time of the study did not significantly recover the biomass of very fine and fine roots. In the gaps that underwent RIL, the center showed greater very fine root biomass than the directions North, South, East and West, showing high sensitivity thereof to such modifications; unlike fine roots, which presented no alteration, as well as necromass of very fine roots. The sample volume surveyed did not consider the necromass of fine roots in any of the plots. The vertical distribution of the biomass of very fine and fine roots, and the necromass of very fine roots decreased with soil depth, with the same overall pattern of distribution of fine roots in the soil. It was also possible to verify in this experiment that tree density does not influence the mass of fine roots and very fine roots are more susceptible to sudden changes in the environment. It was also possible to verify in this experiment that tree density does not influence fine root biomass and that very fine roots are more susceptible to sudden environmental changes.

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