Soil Fertility, Mineral Nitrogen, and Microbial Biomass in Upland Soils of the Central Amazon under Different Plant Covers

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Amazon is the largest state in Brazil and majority of the state is covered by the largest tropical rainforest of the world. Most soils of the Amazon region soils are acidic and infertile. When the Amazon forest land is cleared for agricultural use by burning the vegetation, the efficient nutrient recycling mechanisms are disrupted. However, nutrient contents in the deforested burn land increased temporarily. The objective of this study was to evaluate the soil fertility, mineral nitrogen (N), and microbial activity of carbon (C), N, and phosphorus (P) resulting from the replacement of the primary forest with pasture (Brachiaria brizantha) and commercial plantations of rubber (Hevea spp.), cupuaçu (Theobroma grandiflorum), and citrus trees (Citrus sinensis) cultivated in Xanthic Ferralsol and secondary forest under Acrisols Dystric Nitosols. The results showed that ammonium-N predominates in the 0- to 10-cm soil depth in both primary forest and areas with secondary forest, citrus plantation, and pasture. There was no increase in soil fertility with management of the cultivated areas under the secondary forest, but in the pasture there was a significant increase in the stock of organic C and total N and high C/N ratios, the inverse of what occurred with the C of the microbial biomass. The primary forest had the greatest values of C and P of the microbial biomass and the lowest metabolic quotient. Of the successions studied, the rubber trees were the plant cover with the smallest changes in terms of quality of the organic matter in the soil.

Keywords Amazon forest, carbon cycle, nitrogen mineralization, pasture, plantation crops

Introduction

The Amazon region in South America has the largest tropical forest. In the Central Amazon, the natural vegetation is typically rainforest. The land use consists mainly of deforestation by logging the commercially valuable timber, slash and (in the case of mechanized agriculture) joining the remaining material, and then burning before the subsequent planting of annual and perennial crops and before formation of pastures (Andreux and Cerri 1989).
The soils and their parent materials have been subjected to intense weathering and leaching throughout much of geological history. Present-day soils are composed of low-nutrient clays, such as kaolinite, and sand washed in from the Brazilian and Guiana Shields (Jordan 1982). Jordan and Herrera (1981) have shown how the functioning of Amazon forests depends on nutrient-conserving mechanisms associated with the undisturbed forest. The removal of the original forest and subsequent burn-off breaks the processes of organic-matter cycling (Malavolta 1987), which functions as an important reservoir of plant nutrients. These nutrients operate thanks to the photosynthetic entrance of carbon (C) gas and the rapid and continuous decomposition of organic materials by the microorganisms in the soil.

When a primary forest is cleared for agricultural use, efficiency of the nutrient-recycling mechanism is disrupted, and nutrients released by burning the original vegetation may be rapidly leached (Schroth et al. 1999). As a consequence, multiple nutrient deficiencies develop early in annual crops grown on these soils (Cravo and Smyth 1997). Where the population density is too high for sustainable shifting agriculture, land-use systems with perennial crops and agroforestry systems that provide a permanent soil cover maybe considered more suitable for the condition than the soil with pasture. As the nutrient availability in the upland soil is increased by burning or fertilization, intensive rainfalls (average of 2,250 mm per year) may cause mobile nutrients, such as nitrate, two leach into the subsoil, despite the presence of the perennial root systems of the secondary forest and pasture (Schroth et al. 1999).

As the C content increases in the microbial biomass, its reserve in the soil also increases, meaning less potential for decomposing organic matter (Gama Rodrigues, Gama-Rodrigues, and Barros 1997). In contrast, the N in the microbial biomass constitutes a significant part of the potentially mineralizable element that will be available to plants. In addition, phosphorus (P) in the biomass plays an important role as a reservoir for that element in the soil, where it is released by the rupture of the microbial cells, which serve to protect the nutrient against fixation for prolonged periods in minerals in the soil (Paul and Clark 1996).

The objective of this study was to assess the impact on the soil fertility, mineral N, and microbial biomass as an indicator of the activity of C, N, and P in dystrophic Yellow Latosol (Xanthic Ferralsol) and Argissol (Acrisols Dystric Nitosols) in the Central Amazon, under primary forest cover and in areas where the original forest has been replaced by different vegetation successions. In addition, we compare the efficiency of microwave radiation (MR) and indirectly measuring the increase in the rate of respiration caused by adding glucose to the soil, employing an infrared gas analyzer (IRGA), to determine the C of the microbial biomass.

Materials and Methods

**Study Site Description**

The study was conducted on soil samples taken from plantations of 10-year-old citrus (*Citrus sinensis*), 10-year-old cupuaçu (*Theobroma grandiflorum*), and 10-year-old rubber trees (*Hevea brasiliensis*) grafted with a crown of (*Hevea pauciflora*); 5-year-old pasture (*Brachiaria brizantha*); primary forest growing on kaolinthic dystrophic Yellow Latosol; and secondary forest (10 years old) on kaolinthic dystrophic Argissol (Brazilian classification; Embrapa 1999), also called Xanthic Ferralsol and Acrisols Dystric Nitosols (FAO 1990). The areas are underlain by Quaternary sediments of the Alter-do-Chão Formation.
Table 1

Bimonthly minimum and maximum temperature and rainfall data of municipality of Manaus and Coari, Amazonas State, Brazil (2003)

<table>
<thead>
<tr>
<th>Months</th>
<th>Manaus</th>
<th></th>
<th>Coari</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature (°C)</td>
<td>Rainfall (mm)</td>
<td>Temperature (°C)</td>
<td>Rainfall (mm)</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>January/February</td>
<td>17.8</td>
<td>35.1</td>
<td>17.7</td>
<td>36.2</td>
</tr>
<tr>
<td>March/April</td>
<td>14.2</td>
<td>34.1</td>
<td>14.0</td>
<td>35.5</td>
</tr>
<tr>
<td>May/June</td>
<td>10.1</td>
<td>34.1</td>
<td>9.9</td>
<td>35.2</td>
</tr>
<tr>
<td>July/August</td>
<td>13.8</td>
<td>35.1</td>
<td>14.0</td>
<td>36.0</td>
</tr>
<tr>
<td>September/October</td>
<td>17.0</td>
<td>36.5</td>
<td>16.0</td>
<td>36.5</td>
</tr>
<tr>
<td>November/December</td>
<td>18.8</td>
<td>35.9</td>
<td>19.0</td>
<td>35.4</td>
</tr>
</tbody>
</table>

The chemical characteristics of the upland soils are shown in Table 1. In each of the areas, five subsamples were taken at a depth of 0–10 cm (Feigl et al. 1995) at the start of the rainy season (October and November). The first sample was taken from the center of the area in question, and the others were taken 25 m away in the four cardinal directions (Moraes et al. 1996). So that there would be no influence of fertilization in the areas with commercial covers, the samples were collected in the middle of paths outside the projection of the canopy (spacing with 400 plants per hectare). Periodically, the weed control was done manually. Except for the secondary forest, all the areas are adjacent to the primary forest.

The Xanthic Ferralsol is located near the geographic coordinates 3° 8’ 25’’ S and 59° 52’ W, in the municipality of Manaus, Amazon State, Brazil, and the Acrisols Dystric Nitosols is located at 4° 53’ S and 65° 11’ W, in the municipality of Coari, Amazonas. These soils are predominantly dystrophic, with exchangeable calcium (Ca) and magnesium (Mg) lower than 1.5 cmol, dm⁻³ (Moreira and Fageria 2009). In most of these soils, aluminum (Al) saturation is greater than 50%, and the base saturation is lower than 50%. The contents of bases [available potassium (K) and exchange Ca and Mg)] and available P are also less than the critical levels used in the interpretation of the soil analysis, which together with exchangeable Al, represent the largest difficulties for the root growth, negatively affecting the developments of plants. Malavolta (1987) reported that in Amazonian area, about 90% of the soils present low fertility. The P and K are the elements most limiting for crop yields.

The natural vegetation is a tropical rainforest. The predominant climate in both areas is humid tropical, classified as Afı by the Köppen system, with relatively abundant rainfall throughout the year (average of 2,250 mm). The rainfall during the dry months (July to September) is always more than 60 mm, and during the wet months (March to June) it is at least 320 mm (Table 1). The average temperature is approximately 26 oC during the same period (Vieira and Santos 1987).

Sample Collection and Soil Analyses

After collection, the soil samples were homogenized, placed in plastic sacks, and stored in a refrigerator for 5 days. Then the visible vegetable and animal remains were removed, and the soil samples were passed through a 4.0-mm mesh sieve. The moisture level to
standardize the samples was then determined by the gravimetric method after removing
the residues, and the mineral N was ascertained by the sum of the ammonium-N (N-NH4+) and
nitrate-N (N-NO3−), extracted with a solution of potassium chloride (KCl) 1.0 mol L−1
(Schroth et al. 1999).

Calculation of the C (Tate, Ross, and Feltham 1988), N (Brookes et al. 1985), and
P in the microbial biomass (Brookes, Powlson, and Jenkinson 1982) was done by irra-
diation and extraction (MR), as proposed by Ferreira, Camargo, and Vidor (1999) and
Mendonça and Matos (2005), in a microwave oven (127 V, 2450 MHz, and 1380 W).

For the C and N, four samples of fresh soil were weighed from each replicate, corre-
sponding to 25 g of dry soil from each plant cover. Half of the samples, in duplicates, were
irradiated for 10 min in the microwave oven (Ferreira, Camargo, and Vidor 1999). The
extraction was done by adding 100 mL of potassium sulfate (K2SO4) 0.5 mol L−1, and the
C was quantified by titration with ammonium ferrous sulfate, with diphenylamine barium
sulfonate as a marker (soil organic matter, SOM = C × 1.724). The N was determined by
the semi-Kjeldahl method, using boric acid as an indicator.

To determine the P, moist soil samples corresponding to 5.0 g of dry soil were used.
The extraction was done by adding 50 mL of sodium bicarbonate (NaHCO3) 0.5 mol L−1
(pH 8.5), and the P was then quantified using a colorimeter, with the addition of molyb-
date ascorbic acid. To correct for the fixation of part of the P adsorbed to the clays during
the extraction, we estimated the recovery rate at the same time with the same samples, by
adding 0.5 µg mL−1 of P (monopotassium phosphate; KH2PO4), which permitted correct-
ing the calculations by taking the difference between the soil irradiated for 10 min and the
control sample. To estimate the C, N, and P of the microbial biomass, we used KEC, KEN,
and KEP correction factors of 0.45, 0.54, and 0.40, respectively (Brookes, Powlson, and

We used another method to quantify the C of the microbial biomass (CMB): reading
the microbial respiration (Anderson and Domsch 1978) with the use of an infrared gas
analyzer (IRGA). This method is based on indirect determination from the increase in the
respiration caused by adding glucose to the soil. After determination in duplicate of the
induced respiration, it was transformed into the C of the microbial biomass by the formula:

\[
\text{Biomass in } \mu\text{g C g}^{-1}\text{ soil} = [\text{respiration induced in } \mu\text{L carbon dioxide (CO}_2\text{) min}^{-1}\text{g}^{-1} \\
\times 40.04] + 0.37
\]

Using the same apparatus, we obtained the basal respiration (µg g−1 day−1 C-CO2
soil) in the third sequential reading (slope), before adding 0.24 g of glucose and 0.50 g of
inert talcum, to reflect the microbial activity (Anderson and Domsch 1978). We defined the
flow of CO2 (mL min−1) by the mean of the 8th, 9th, and 10th readings. The glucose was
added to the soil samples after the 6th reading (slope). We obtained the metabolic quotient
(qCO2), which represents the quantity of CO2 released per unit of microbial biomass, by
dividing the basal respiration by the C of the soil’s microbial biomass and expressed the
values in (µg CO2/mg C min h−1) × 10−4.

After conducting the microbiological analyses, we air-dried the rest of the soil, sieved
it at 2 mm, and took it to the laboratory to determine the pH (1/2.5 ratio, v/v soil/water); C
(Walkley–Black method); P and K (extracted with Mehlich 1, 0.05 N HCl and 0.025 N
H2SO4, and determined with colorimeter and flame emission spectrophotometry, respec-
tively); Ca, Mg, and Al (extracted with KCl 1.0 mol L−1 and determined by atomic
absorption spectrophotometry); and total N (sulfuric digestion, Kjeldahl), according to the
methodology described by EMBRAPA (1997). Ten soil samples of the smaller pits before collected completely randomized at the same time were used to increase the number of replicates.

For the calculation of date’s stock per hectare, the bulk density of the soil was measured with volumetric cylinders in a soil pit to a depth of 0–10 cm. Five cylinders of 100 cm³ were collected. The mean bulk density of the Xanthic Ferrasol of different plant covers lay between 0.79 and 1.02 Mg m⁻³ (mean = 0.88 Mg m⁻³), without significant differences between species ($P \leq 0.05$). The mean bulk density in the Acrisols Dystric Nitosols was 1.24 Mg m⁻³.

**Statistical Analysis**

Because of similarity of soil fertility in the areas (Moreira and Fageria 2009), the six plant covers were compared in a separate analyses for a completely randomized complete design with 10 replicates. We submitted the data to variance analysis (ANOVA), the $F$ test at $P \leq 0.05$, and comparison of the means by the Tukey test at 5% probability (Pimentel Gomes and Garcia 2002). For the statistical analyses, we defined each point sampled as a replicate and considered each sample as the mean of the duplications. To compare the efficiency of the results of the C of the microbial biomass obtained by the IRGA and MR methods in soils with different plant cover, we computed the relationship at 5% significance.

**Results and Discussion**

The conversion of primary forest into the other types of plant cover studied here left the soil fertility little changed, with high acidity and exchangeable aluminum and low levels of available P, K, and exchangeable Ca and Mg (Table 2). These low values can be attributed to the highly weathered and nutrient-depleted condition of the soil’s material of origin, having low base values and little or no primary material, with the supply of nutrients coming basically from the organic matter in the soil (Carvalho 1986).

Except for the soil under pasture, the other plant covers did not differ significantly in the organic-matter content of the soil (Table 3). Nye and Greenland (1964) also found

<table>
<thead>
<tr>
<th>Plant covers</th>
<th>pH in water</th>
<th>P (mg kg⁻¹)</th>
<th>K (mg kg⁻¹)</th>
<th>Ca cmole kg⁻¹</th>
<th>Mg cmole kg⁻¹</th>
<th>Al cmole kg⁻¹</th>
<th>H⁺Al cmole kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary forest</td>
<td>4.28</td>
<td>2.59</td>
<td>20.70</td>
<td>0.17</td>
<td>0.17</td>
<td>1.41</td>
<td>7.18</td>
</tr>
<tr>
<td>Secondary forest</td>
<td>4.34</td>
<td>1.53</td>
<td>34.89</td>
<td>0.07</td>
<td>0.04</td>
<td>4.25</td>
<td>10.06</td>
</tr>
<tr>
<td>Rubber trees</td>
<td>3.79</td>
<td>3.09</td>
<td>26.75</td>
<td>0.15</td>
<td>0.10</td>
<td>1.24</td>
<td>7.75</td>
</tr>
<tr>
<td>Cupuaçu</td>
<td>4.40</td>
<td>4.51</td>
<td>41.39</td>
<td>0.47</td>
<td>0.32</td>
<td>1.13</td>
<td>7.28</td>
</tr>
<tr>
<td>Citrus</td>
<td>4.03</td>
<td>1.52</td>
<td>54.17</td>
<td>0.08</td>
<td>0.07</td>
<td>0.86</td>
<td>7.20</td>
</tr>
<tr>
<td>Pasture</td>
<td>4.23</td>
<td>2.04</td>
<td>17.63</td>
<td>0.20</td>
<td>0.12</td>
<td>1.09</td>
<td>7.00</td>
</tr>
</tbody>
</table>

*a*0- to 10-cm soil depth. $n = 20$ samples.

*b*Available P and K: Mehlich 1 extractant; exchangeable Ca, Mg, and Al: KCl 1.0 mol L⁻¹ extractant, exchangeable H⁺Al: calcium acetate 0.01 mol L⁻¹ (EMBRAPA 1997).
that with removal of the forest and its replacement with another culture, but without any disturbance in the physical characteristics, there is no change in the SOM content. In the case of pasture, Choné et al. (1991) reported that with the establishment of this type of cover, the stock of C remains stable and in some cases can be even greater than the content under original forest cover, a result also found by Moraes et al. (1996).

The lowest total N concentrations were observed in the soil under secondary forest and cupuaçu plantation (1.51 Mg ha\(^{-1}\) and 1.66 Mg ha\(^{-1}\)), while the greatest values were found in the pasture area (3.09 Mg ha\(^{-1}\)) (Table 3). The increase in N in soils under pasture can be due to the entrance of N from fixation by free-living bacteria (Azotobacters) associated with grasses and to a lesser extent by animal feces, because there was no application of N fertilizers (Fernandes 1999).

The soil from the primary forest and pasture presented the greatest C/N ratios (Table 3), when compared with that from areas under citrus, rubber, and cupuaçu trees and secondary forest. In primary forests, the increase in the C/N ratio generally occurs because of the rise in the number of leaves, twigs, and branches coming from different species with high (lignin + polyphenols) / N ratios. These species decompose slowly (Vieira and Santos 1987), a reflection of the low mineralization capacity of N (Gama Rodrigues, Gama-Rodrigues, and Barros 1997). In the case of pasture, despite the high quantity of total N, the grasses are C\(_4\) plants, characterized by their high efficiency in absorbing CO\(_2\) and in converting it into vegetable matter (Hopkins 1997). Consequently, with the continued entrance of a large quantity of this matter in the system, there is a proportionally lower rate of decomposition.

In the cupuaçu plantation soil, the concentration of nitrate N was greater than of ammonium N, representing 65.3% of the mineral N (Table 2). The presence of large quantities of pueraria (Pueraria phaseoloides) in the area sampled, associated with the smaller values of the C/N ratio, likely accelerated the process of converting N-NH\(_4^+\) into N-NO\(_3^-\) (Malavolta 1987). In other areas, ammonium N predominated. In the pasture, the proportion was 95.5% of the mineral N, while in the primary forest, secondary forest, and citrus plantation, the proportions of N-NH\(_4^+\) were 82.7%, 73.6%, and 64.6%, respectively.

To improve cropping systems for better nutrient use, there is a need to develop site- and species-specific fertilizer recommendations for different plant covers. Soil analyses must be the basis for fertilization, as significant amounts of previously applied fertilizer
nutrients may still be within the reach of the crop roots, especially in the case of older trees with well-developed root systems (Schroth et al. 1999).

The C values of the microbial biomass obtained by the MR and IRGA methods in the six plant cover areas varied on average from 169.91 to 652.84 kg C ha\(^{-1}\) and from 94.90 to 265.25 kg C ha\(^{-1}\), respectively, with the greatest values being observed in the forest soil (Table 4 and Figure 1), which represented, by the MR method, nearly 2.6% of the organic C of the soil in the 0- to 10-cm layer. In the pasture soil, this proportion was 0.4%, a figure well below the range of 1.7% to 3.3% reported by Grisi et al. (1998) in temperate and tropical soils. Besides the low microbial activity resulting from the biogeochemical equilibrium of the forest soil, the differences in the percentages of microbial C within the organic C also may be a result of the diversity of plant matter, favoring the development of microorganisms (Anderson and Domsch 1989), a fact that was not observed in the monocultures and secondary forest.

The adjusted equation between the MR and IRGA methods, without the data from this plant cover, presented a significant relationship (Figure 1) and corroborated the results of Moreira and Malavolta (2004), with the exception of the microbial C from the pasture soil. According to the equation, the mean factor for conversion was MR = IRGA × 2.96. However, it should be pointed out that, like with the chloroform fumigation extraction (CFE) method, the greater values obtained in irradiation and extraction can be related to the greater extraction power of the C of nonmicrobial origin from the soil by the K\(_2\)SO\(_4\) 0.5 mol L\(^{-1}\) (Badalucco et al. 1990), which does not occur with the IRGA method, because this is based on the addition of glucose in the soil, stimulating the release of CO\(_2\). Further studies are needed to quantify the contribution of methods from the soil microbial biomass to the pools of available nutrients in tropical rainforest soils. Although the MR method can be used on Amazonian soils, the IRGA was the most adequate procedure for C quantification with coefficient of variation lower (32.9%) than the MR (45.3%).

In the case of the secondary forest, the low CMB levels (222.18 kg C ha\(^{-1}\) for MR and 94.90 kg C ha\(^{-1}\) for IRGA) shown in Table 4 are possibly associated with the exhaustion of the minerals that favor growth of the microfauna, especially fungi, and mesofauna in

### Table 4

<table>
<thead>
<tr>
<th>Plant covers</th>
<th>CMB(^c) (kg ha(^{-1}))</th>
<th>NMB (kg ha(^{-1}))</th>
<th>PMB (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary forest</td>
<td>652.84 a</td>
<td>265.25 a</td>
<td>98.58 a</td>
</tr>
<tr>
<td>Secondary forest</td>
<td>222.18 d</td>
<td>94.90 d</td>
<td>43.84 c</td>
</tr>
<tr>
<td>Rubber trees</td>
<td>401.60 c</td>
<td>169.08 bc</td>
<td>102.06 a</td>
</tr>
<tr>
<td>Cupuaçu</td>
<td>495.83 bc</td>
<td>148.66 bc</td>
<td>77.34 b</td>
</tr>
<tr>
<td>Citrus</td>
<td>508.40 b</td>
<td>126.42 d</td>
<td>58.70 c</td>
</tr>
<tr>
<td>Pasture</td>
<td>169.91 d</td>
<td>183.20 b</td>
<td>71.24 b</td>
</tr>
</tbody>
</table>

\(^a\)0- to 10-cm soil depth. \(n = 10\) samples.

\(^b\)Values followed by similar letters in the same column are not significantly different at \(P \leq 0.05\) (Tukey's test).

\(^c\)Methods of microwave radiation (MR) and indirectly measuring the increase in the rate of respiration caused by adding glucose to the soil, employing an infrared gas analyzer (IRGA).
Figure 1. Relationship among C microbial biomass determined by infrared gas analyzer (IRGA) and microwave radiation (MR) under six plant covers. An asterisk (*) denotes significance at the 5% probability level.

the soil. In many cases, the growth of this plant cover occurs in degraded soils, succeeding subsistence crops such as corn and manioc, as well as in abandoned pastures. Because of the management employed, the CMB of the soil obtained from the citrus, cupuaçu, and rubber groves presented intermediate values (Table 4).

The type of plant cover (Table 4) affected the N of the microbial biomass (NMB) significantly. The greatest values were found in the primary forest (98.58 kg ha$^{-1}$) and rubber grove (102.06 kg ha$^{-1}$). Gama Rodrigues, Gama-Rodrigues, and Barros (1997) found a negative relationship between the NMB and mineral N, indicating that the greater the mineralization is, the lower its accumulation will be in the microbial biomass, a fact also verified in this work. Since the rubber tree, a native of the region, basically exports hydrocarbons—long polyisoprene chains (Moreira et al. 2009)—the restoration of nutrients to the soil occurs predominantly by falling leaves, twigs, and fruits, just as in the primary forest. The annual accumulation of these materials under rubber trees ranges from 5 to 7 metric tons of litter per hectare per year. For the cupuaçu, citrus, and pasture, the cycling is lower, because nutrients are exported from the fruits and cattle, respectively.

The quantity of P in the microbial biomass (PMB) of the soil at a depth of 0–10 cm varied from 2.01 kg ha$^{-1}$ in the cupuaçu plantation to 5.46 kg C ha$^{-1}$ in the primary forest (Table 4). These values indicate that the microbial biomass in the Amazon ecosystem is the main reservoir of P, in some cases presenting amounts greater than the available P in the soil (Table 2). The greater amounts of PMB in the primary forest, rubber grove, and pasture agree with Brookes, Powlson, and Jenkinson (1984), who found that systems with less soil perturbation over the years manage to maintain greater levels of P in the microbial biomass.

The soil samples from the secondary forest showed less respiratory activity (basal respiration of 1.19 µg g$^{-1}$ day$^{-1}$ of C-CO$_2$ in the soil), differing statistically from the
Table 5
Basal respiration flow of CO₂, metabolic quotient (qCO₂) and Cmic/Corg ratio under different plant covers in western Amazonia

<table>
<thead>
<tr>
<th>Plant covers</th>
<th>Basal respiration (µg g⁻¹ dia⁻¹ C-CO₂)</th>
<th>Flow of CO₂ (mL min⁻¹)</th>
<th>Metabolic quotient (µg CO₂/µg Cmin h⁻¹ × 10⁻⁴)</th>
<th>(Cmic/Corg) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary forest</td>
<td>1.39 b</td>
<td>494.99 a</td>
<td>2.18 e</td>
<td>2.63 a</td>
</tr>
<tr>
<td>Secondary forest</td>
<td>1.19 b</td>
<td>415.77 ab</td>
<td>5.22 cd</td>
<td>1.40 b</td>
</tr>
<tr>
<td>Rubber trees</td>
<td>1.60 b</td>
<td>432.76 ab</td>
<td>3.94 d</td>
<td>1.70 b</td>
</tr>
<tr>
<td>Cupuaçu</td>
<td>3.23 a</td>
<td>420.44 ab</td>
<td>9.05 a</td>
<td>2.04 ab</td>
</tr>
<tr>
<td>Citrus</td>
<td>1.57 b</td>
<td>374.38 b</td>
<td>5.17 cd</td>
<td>2.58 a</td>
</tr>
<tr>
<td>Pasture</td>
<td>3.16 a</td>
<td>385.327 b</td>
<td>7.19 b</td>
<td>0.40 c</td>
</tr>
</tbody>
</table>

*a* 0- to 10-cm soil depth. *n* = 10 samples.

*Values followed by similar letters in the same column are not significantly different at P ≤ 0.05 by Tukey’s test.

cupuaçu grove and pasture, whereas the soils under the citrus grove had the lowest flow of CO₂ (Table 5). The lower release of CO₂ in the secondary forest ecosystem indicates less biological activity, except in soils with high SOM levels, which did not occur in this condition (Table 3), because it is directly related with the C of the organic matter (Fernandes 1999).

Moreira and Costa (2004) and Moreira and Malavolta (2004), in the same edaphoclimatic conditions, also found that the metabolic quotient (qCO₂) is lowest in soil under primary forest cover in the Central Amazon. The basal respiration per unit of microbial biomass declines in more stable ecosystems (Balota et al. 1998), but with the replacement of the plant cover there is faster decomposition of the plant residues, increasing the metabolic quotient (Ocio and Brookes 1990). These results demonstrate the inverse relation between the qCO₂ and the microbial biomass, showing that with greater C levels there is reduced metabolic activity and increased microbial biomass (Balota et al. 1998).

The CMB and organic C ratios (Cmicr/Corg) showed statistical differences in function of the succession of cultures, varying from 0.40% in the pasture to 2.63% in the primary forest (Table 5). Brookes, Powlson, and Jenkinson (1984) reported that for permanent monocultures the average values for the rubber, cupuaçu, and citrus plantations are within or near the range of 1.8–2.1%. These variations also reflect the efficiency of the conversion of microbial C, the losses of C from the soil, and the stabilization of organic C by the soil’s mineral fraction (Sparling 1992; Balota et al. 1998). This ratio can indicate the level of imbalance of the C in the dynamic of the soil’s organic matter (Anderson and Domsch 1989).

The C content show small differences under primary forest, but the removal of the original vegetation for different plant cover can be associated with significant changes in SOM that resulted in an increase of level of C in pasture. The activity of microbial biomass (C, N, and P) of SOM dynamics provided important results about the turnover rate of the SOM on areas converted to other plant cover. Results obtained in this study may be useful for further study of C fluxes in Amazonian ecosystem.
Conclusions
The Amazon is the largest tropical forest in the world, and the major part of this forest is located in Brazil. Improved agriculture and animal husbandry practices are required in the region for sustainable production and conservation of forest. Knowledge of soil fertility is an important aspect to achieve this objective. In the soil under primary forest as well as those under secondary forest, citrus trees, and pasture, N-NH$_4^+$ predominates in the 0- to 10-cm soil depth. In the cultivated areas and in the secondary forest, there was no increase in soil fertility. The introduction of pasture significantly increases the stock of organic C, total N, and the C/N ratio of the soil, the opposite of what occurs with the C of the microbial biomass. The primary forest has the greatest levels of C and P of the microbial biomass and the lowest metabolic quotient. Of the successions studied, rubber trees are the plant cover causing the smallest change in terms of quality of the organic matter in the soil. Systems with perennial plants with well-developed root systems may increase the conditions for the cycling of nutrients in Amazon soils. The coefficient of variation in the soil samples submitted to IRGA was lower and may be considered the most adequate procedure for C quantification in soil biomass under edaphoclimatic conditions of the Amazon.

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References


Fernandes, S. A. P. 1999. *Soil properties in a conversion of forest into underfertilized and fertilized with phosphorus pasture in the Amazon (Rondônia)*. PhD thesis, Center of Nuclear Energy in Agriculture, University of São Paulo, Piracicaba.


