CARBON AND NITROGEN IN SOILS AND HUMIC FRACTIONS OF DIFFERENT PEDOFORMS IN THE ATLANTIC FOREST BIOME

Marcos Gervasio Pereira[1*], Victória Maria Monteiro Mendonça[2], Gilsonley Lopes dos Santos[3], Marisa de Cássia Piccolo[4]

[1*] Federal Rural University of Rio de Janeiro, Soils Department, Agronomy Institute, Seropédica, Rio de Janeiro, Brazil - e-mail: mgervasiopereira01@gmail.com
[2] Federal Rural University of Rio de Janeiro, Graduate Program in Environmental and Forest Sciences, Seropédica, Rio de Janeiro, Brazil - e-mail: viic_monteiro@hotmail.com
[3] Federal Rural University of Rio de Janeiro, Graduate Program in Environmental and Forest Sciences, Seropédica, Rio de Janeiro, Brazil - e-mail: leylopes85@hotmail.com
[4]University of São Paulo, Nuclear Energy Center in Agriculture, Piracicaba, São Paulo, Brazil - e-mail: mpiccolo@cena.usp.br

Received for publication: 31/12/2018 – Accepted for publication: 02/07/2019

Resumo

Carbono, nitrogênio e das frações da matéria orgânica do solo em diferentes feições de relevo no bioma mata atlântica. O relevo é um fator de formação do solo que pode modificar a distribuição das frações da matéria orgânica no solo (SOM) em uma paisagem. Este estudo teve como objetivo avaliar a influência do relevo sobre as frações da SOM, quanto à sua distribuição em diferentes posições topográficas, segmentos (S), em dois tipos de pedoforma (côncava e convexa), sob cobertura florestal do bioma Mata Atlântica. Foram selecionadas duas pedoformas, uma côncava e outra convexa, em áreas adjacentes, sendo essas divididas em S quanto à variação topográfica. Foram realizadas avaliações da origem do carbono e nitrogênio em estratos até 100 cm de profundidade. Amostras de terra foram coletadas nas profundidades de 0-5, 5-10 e 10-20 cm para a caracterização química e fracionamentos (granulométrico e químico) da SOM. Para o cálculo do estoque foi determinada a densidade nas profundidades de 0-5 e 5-10 cm. Na composição isotópica foi verificado predomínio do ^{13}C (carbono 13). Os maiores valores de carbono orgânico e carbono particulado ocorreram na pedoforma convexa. Na distribuição das frações húmicas foi verificado que a maior parte do carbono humificado foi encontrado na fração humina. As frações humina e ácidos fúlvicos apresentaram maiores valores na pedoforma convexa. Quanto aos estoques de carbono, de maneira geral, o maior valor foi verificado na pedoforma convexa, sendo esse decrescente em profundidade no solo, já para o estoque de nitrogênio não foram verificadas diferenças. Os maiores teores de carbono e nitrogênio foram verificados na pedoforma convexa e na região inferior da pedoforma côncava.
Palavras-chave: matéria orgânica particulada, substâncias húmicas, topografia, feição côncava, feição convexa.

Abstract

Relief is a soil formation factor that can modify the distribution of soil organic matter (SOM) fractions in a landscape. The objective of this study was to evaluate the effect of the relief on SOM fractions, considering their distribution in different topographic positions, segments, in two pedoforms (concave and convex) in areas covered with forest in the Atlantic Forest biome. The two pedoforms were selected in adjacent areas and divided into segments considering the topographic variation. The carbon and nitrogen origins were evaluated in the extract up to 100 cm of depth. Soil samples from the 0-5, 5-10, and 10-20 cm layers were collected for chemical characterization and fractioning (granulometric and chemical) of the SOM. The soil density in the 0-5 and 5-10 cm layers was determined to calculated the carbon stocks. The isotopic composition showed predominance of ^{13}C. The highest organic carbon and particulate carbon contents were found in the convex pedoform. The distribution of humic fractions showed that the larger part of the humidified carbon was in the humin fraction. The humin and fulvic acid fractions were higher in the convex pedoform. The carbon stocks were, in general, higher in the convex pedoform, decreasing as the soil depth increased; and nitrogen stocks presented no differences. The higher carbon and nitrogen contents were found in the convex pedoform and in the lower region of the concave pedoform.
Keywords: particulate organic matter, humic substances, topography, concave form, convex form.

INTRODUCTION

Soil organic matter (SOM) transformations are essential to improve or maintain the soil attributes in tropical forests. The SOM promotes processes that maintain the soil productive capacity due to its effects in the edaphic attributes (MARTINS *et al*., 2015).

The different topographic forms, also known as pedoforms, cause variations in soil and landscape attributes. They affect pedogenetic processes and the diversity of plant species by affecting the distribution of water (transport and storage), sediments, dissolved matter, light incidence, and soil moisture, determining horizontal and vertical distribution of soil attributes and the dynamics of SOM fractions (GODINHO *et al*., 2013).

Sanchez *et al.* (2009) found that the relief affects soil attributes in the landscape, and concave pedoforms present higher variations in soil attributes than linear and convex pedoforms.

Micro-relief is important for the study on convex, rectilinear, and concave pedoforms and for decision making for soil management and intensity and frequency of agricultural management practices, since they affect soil water intensity and flow direction (ARTUR *et al.*, 2014). Oliveira *et al.* (2013) evaluated Cambissolos (Incpetisols) of calcareous origin and found higher clay contents and deeper soils in a concave pedoform, indicating higher effect of pedogenesis on this area due to convergent water flows; and that the higher sand contents and shallower soils in the convex surface indicate a lower effect of pedogenesis and a higher intensity of selective erosion process.

The hypothesis considered in the present work is that relief forms affect the dynamics of SOM fractions. Thus, the objective of this study was to evaluate the effect of relief on SOM fractions, considering their distribution in different topographic positions, segments, in two pedoforms (concave and convex) in areas covered with forest in the Atlantic Forest biome.

MATERIAL AND METHODS

The study was conducted at the Ribeirão Cachimbal sub-basin of the Paraiba do Sul River, Mid-Paraiba do Sul Valley, Pinheiral, Rio de Janeiro, RJ, Brazil (22°29'03"S to 22°35'27"S, and 43°54'49"W to 44°04'05"W) (Figure 1). The region is in the Atlantic Forest biome, whose original vegetation is termed Submountain Semi-Deciduous Seasonal Forest. The climate of the region was classified as Am, a tropical rainy climate with a dry winter; and as Cwa, a temperate climate with a dry winter and rainy summer; the mean annual temperature is 21°C, and the mean annual rainfall is 1,300 mm (DINIZ *et al.*, 2015).

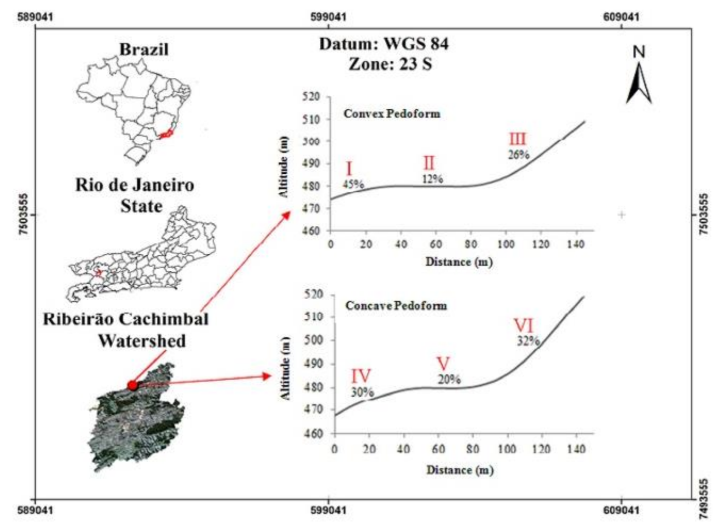

Figure 1. Sub-basin of Ribeirão Cachimbal, Pinheiral-RJ. Legend: I, II and III - S with variation of the topographic gradient and slope in the convex pedoform; IV, V and VI - S with variation of the topographic gradient and slope in the concave profile.

Figura 1. Sub-bacia do Ribeirão Cachimbal, Pinheiral-RJ. Legenda: I, II e III - S com variação do gradiente topográfico e da declividade na pedoforma convexa; IV, V e VI - S com variação do gradiente topográfico e da declividade na pedoforma côncava.

Two pedoforms were selected in a forest fragment at secondary stage of regeneration and classified as convex and concave. Each pedoform was segmented into three environments according to their topographic gradient and slope, which were termed segments (S) (Figure 1), totaling six segments. Three of them were in the convex pedoform, namely S-I (lower; mean altitude: 520 m; mean slope: 45%; width: 20 m; length: 33 m), S-II (intermediate; mean altitude: 530 m; mean slope: 12%; width: 20 m; length: 30 m), and S-III (upper; mean altitude: 550 m; mean slope: 26%; width: 20 m; length: 72 m); and three were in the concave pedoform, namely, S-IV (lower; mean altitude: 485 m; mean slope: 30%; width: 20 m; length: 45 m), S-V (intermediate; mean altitude: 590 m; mean slope: 20%; width: 20 m; length: 30 m), and S-VI (upper; mean altitude: 500 m; mean slope: 32%; width: 20 m; length: 72 m).

The vegetation cover of the study area presented arboreous physiognomy, with emerging trees, differentiated sub-forest formed by shade-tolerant species, diverse woody species with high heights and high breast diameters, and abundance of lianas and epiphytes (MENEZES *et al.*, 2010).

The soils in both pedoforms were classified as Cambissolo Háplico tb Distrófico típico (Inceptisol) (MENEZES *et al.*, 2010). Soil samples were collected in each segment in March 2013 and subjected to quantification of soil ^{13}C, ^{15}N, total organic carbon, total nitrogen, and organic matter fractions. All samples were air dried, crushed, and passed through a 2.00-mm mesh sieve before the analyses.

Soil sampling and analysis

Isotopic analysis of soil ^{13}C and ^{15}N

Three trenches were opened in the pedoforms, one per segment, with 100 cm of depth and soil samples were collected from the layers 0–5, 5–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–80, and 80–100 cm.

The soil ^{13}C, total N, and ^{15}N contents and isotopic composition were determined by mass spectrometry (Finnigan Mat, Delta Plus) at the Center for Nuclear Energy in Agriculture (CENA/USP) in Piracicaba, SP, Brazil. The values of $\delta^{13}C$ of samples were estimated considering Pee Dee Belemite (PDB) as standard reference, using the equation:

$$\delta^{13}C\ or\ {}^{15}N\ (‰) = 10^3\ x\ (R_{sample} - R_{standard})/R_{standard}$$

where R_{sample} is the isotopic ratio $^{13}C\backslash^{12}C$ or $^{15}N/^{14}N$ of the sample, and $R_{standard}$ is the isotopic ratio $^{13}C\backslash^{12}C$ or $^{15}N/^{14}N$ of the standard.

Soil total organic carbon (TOC) and total nitrogen (TN)

Composite soil samples from the 0-5, 5-10, and 10-20 cm layers were collected in the segment. The collection points were systematically distributed for better representation of the environmental conditions.

TOC and TN were determined on dry basis, using 250 mg of soil sample. The soil was macerated in a porcelain mortar, passed through a 100-µm mesh sieve, and subjected to oxidation at 900 ºC (CHN-600 Carlo Erba EA-1110, Italy).

Undisturbed samples were collected in the 0-5 and 5-10 cm layers using a Kopeck ring to determine the soil density (TEIXEIRA *et al.*, 2017). The bulk density and carbon and nitrogen contents and stocks were calculated using the equation:

$$C\ or\ N\ stock\ (Mg\ ha^{-1}) = (C\ or\ N\ x\ Bd\ x\ e)/10$$

where *C* is the carbon content in the layer (g kg^{-1}); *Bd* is the bulk density (Mg m^3); and *e* is the layer thickness (5 cm).

Fractioning of the soil organic matter (SOM)

The granulometric fractioning of the SOM was carried out using the method proposed by Cambardella and Elliot (1992), quantifying particulate organic carbon (OC_P) and more recalcitrant carbon forms associated with clay and silt fractions, termed mineral-associated organic carbon (CO_{MA}). The chemical fractioning was carried out using the differential solubility technique of Swift (1996), as adapted by Benites *et al.* (2003), quantifying the carbon fulvic acid (C-FAF), humic acid (C-HAF), and humin (C-HUM) fractions, and establishing the ratios C-HAF/C-FAF, HUM/(C-HAF+C-FAF), and C-HAF+C-FAF+HUM/C-TOTAL (CANELLAS and SANTOS, 2005). The carbon quantifications in the granulometric and chemical fractioning followed the technics proposed Yeomans and Bremner (1988).

Statistical analysis

TOC, TN, OC_P, CO_{MA}, C-HAF, C-FAF, and C-HUM data were tested for normality of errors (Shapiro Wilk test at $p \leq 0.5$) and homogeneity of variance (Levene test at $p \leq 0.5$). When these assumptions were met, the data were subjected to parametric analysis (Tukey's test at $p \leq 0.5$). When these assumptions were not met, non-parametric analysis was used (Kruskall-Wallis test at $p \leq 0.5$).

RESULTS

Soil isotopic composition (^{13}C and ^{15}N) in the pedoforms and different segments

The distribution patterns of ^{13}C and ^{15}N contents in the pedoforms and segments were similar in the environments (Figures 2 and 4), with increasing contents as the soil depths increased up to 30 cm, which stabilized from this depth up to 100 cm.

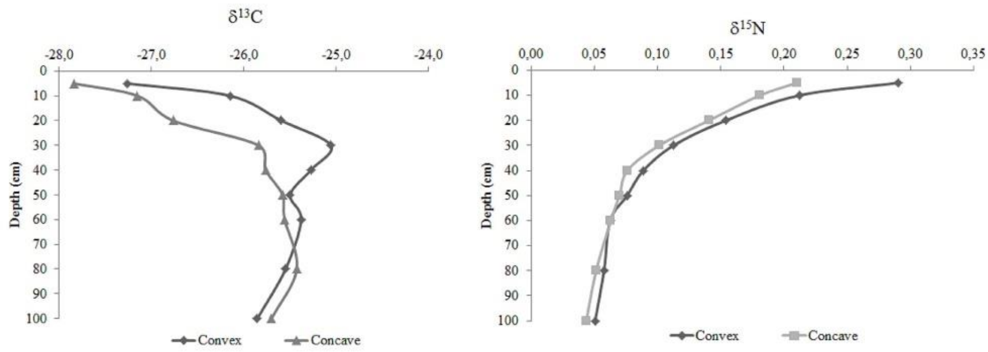

Figure 2. Natural abundance of 13C and 15N in the different pedoforms in depth.
Figura 2. Abundância natural de ¹³C e 15N nas diferentes pedoformas em profundidade.

The ^{13}C and ^{15}N contents found in the segments (Figure 3) showed that both pedoforms were covered by C3 plants, since the ^{13}C contents were between -28 and -24, indicating few or absence of C4 species in the environments and that the segments present predominance of C3 plants.

The distribution of ^{15}N throughout the pedoforms and their respective segments was also similar for the environments (Figures 2 and 3). The contents decreased up to 100 cm depth and were the highest contents found in the segments of the convex pedoform, with intermediate found for S-III.

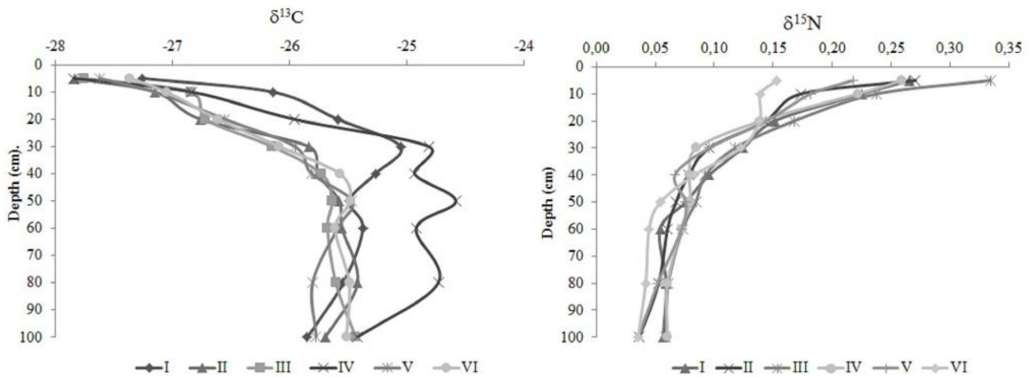

Figure 3. Natural abundance of ^{13}C and ^{15}N in the different S in depth.
Figura 3. Abundância natural de ¹³C e 15N nos diferentes S em profundidade.

Total organic carbon (TOC) contents were higher in the convex pedoform and decreased as the soil depth increased. The pedoforms showed no significant differences for total nitrogen (TN) (Table 1).

The granulometric fractionating showed that COMA contents were higher than OCP contents and decreased as the soil depth increased. The highest means were found in the convex pedoform in all layers, except 0-5 cm (Table 1). The OCP fraction was significantly different in the 0-5 cm layer; the lowest OCP was found for the concave pedoform (Table 1).

Table 1. Mean values of total organic carbon, total nitrogen and carbon fractions in the different pedoforms.
Tabela 1. Teores médios de carbono orgânico total, nitrogênio total e das frações do carbono nas diferentes pedoformas.

Study Area	TOC	N	OC_P	CO_{MA}	C-HAF	C-FAF	C-HUM
	g kg⁻¹						
Depth (cm)							
0-5							
Convex	27,00 **a**	1,56 a	7,28 **a**	19,72 **a**	2,26 **a**	2,21 **a**	18,36 **a**
Concave	24,65 **b**	1,72 a	5,13 **b**	21,52 **a**	1,74 **a**	2,82 **a**	15,64 **a**
CV%	22,97	29,46	49,08	32,83	64,30	60,13	30,03
5-10							
Convex	20,19 **a**	1,24 a	3,57 **a**	16,62 **a**	2,00 **a**	2,31 **a**	13,45 **a**

Concave	16,75 **b**	1,26 a	4,17 **a**	12,58 **b**	1,29 **b**	2,53 **a**	12,82 **a**
CV%	6,85	21,43	16,32	28,62	48,76	39,26	31,11
				10-20			
Convex	15,44 **a**	0,97 a	2,24 **a**	13,20 **a**	1,66 **a**	2,38 **a**	11,53 **a**
Concave	12,43 **b**	0,94 a	2,89 **a**	9,54 **b**	0,81 **b**	2,24 **a**	9,30 **b**
CV%	2,67	24,47	5,85	37,44	58,05	39,58	29,08

*Values followed by different letters in the column for each pedoform differ (p <0.05), according to the Tukey test. Values in parentheses: coefficient of variation (CV%).

The chemical fractioning of the SOM showed that humic fractions presented high variation in the 0-5 cm layer, and no pattern (Table 1). The 5-10 and 10-20 cm layers had humic fractions above 50% of TOC (Table 1). These results denote that most TOC was found in more humified forms in both pedoforms.

The humic fraction distribution in the pedoforms and soil layers showed that most humidified carbon was in the C-HUM fraction (77.17% for the convex, and 76.76% for the concave pedoform) (Table 1), followed by the C-FAF (12.29% for the convex and 15.43% for the concave pedoform), and C-HAF (10.54% for the convex pedoform and 17.86% for the concave pedoform) fractions (Table 1).

The C-HAF decreased as the soil depth increased, with significant differences for the 5-10 and 10-20 cm layers. The lower C-HAF values were found in the concave pedoform (Table 1). No significant differences (ANOVA) were found for the C-FAF fraction for any soil layer. The 10-20 cm layer showed differences for the C-HUM fraction, with higher values for the convex pedoform.

The C-HAF/C-FAF and C-HUM/(C-HAF+C-FAF) ratios decreased as the soil depth increased (Table 2). All soil layers showed C-HAF/C-FAF ratio (more soluble fractions) lower than 1.0 (Table 2) in both pedoforms; the 0-5 cm layer presented significant difference and values closer to 1.0.

Table 2: Index of the chemical fractionation of soil organic matter (MOS) in the different pedoforms (convex and concave).
Tabela 2: Índices do fracionamento químico da matéria orgânica do solo (MOS) nas diferentes pedofprmas (Convexa e Côncava).

Study Area	C_{HAF}/C_{FAF}	$C_{HUM}/(C_{HAF}+C_{FAF})$	$C_{HAF}+C_{FAF}+C_{HUM}/C_{TOTAL}$
	Depth (cm)		
	0-5		
Convex	0,94 **a**	19,34 **a**	86 % **a**
Concave	0,74 **b**	6,19 **b**	79 % **a**
CV %	55,35	47,81	31,09
	5-10		
Convex	0,66 **a**	9,88 **a**	88 % **a**
Concave	0,50 **a**	3,60 **b**	103 % **a**
CV %	63,74	72,43	26,77
	10-20		
Convex	0,38 **a**	2,70 **a**	97 % **a**
Concave	0,19 **a**	2,64 **b**	108 % **b**
CV %	53,46	43,97	28,97

Legend: C-HAF/C-FAF - indicator of condensation of soluble organic matter; C-HUM/(C-HAF + C-FAF) - indicates structural stability of organic matter; C-HAF + C-FAF + C-HUM/C-TOTAL - degree of evolution of organic matter in the soil; CV% - coefficient of variation.
*Values followed by different letters in the column for each pedoform differ (p <0.05), using the t test.

The C-HUM/(C-HAF+C-FAF) ratio was higher in the convex pedoform in all depths. Contrastingly, no significant differences were found for the recovery rate (C-HAF+C-FAF+C-HUM/C-TOTAL) in any of the layers (Table 2).

The TOC and TN distributions in the segments were different, and decreased as the soil depth increased (Table 3). The TOC in the 0-5 and 5-10 cm layers were higher in the segments of the convex pedoform and the lower third segments of the concave pedoform. Similar results were found for TN (Table 3). The TOC in the 10-20 cm layer was higher in the S-III, the upper third of the convex pedoform; the segments showed no significant differences for TN in this layer (Table 3).

Table 3. Average TOC and total nitrogen and soil organic matter fractions in the different S.
Tabela 3. Teores médios de COT e nitrogênio total e das frações da matéria orgânica do solo nos diferentes S.

Study Area	TOC	N	OC_P	CO_{MA}	C-HAF	C-FAF	C-HUM
	g kg-1						
	Depth (cm)						
	0-5						
I	26,95 **ab**	1,67 **abc**	8,35 **a**	18,60 **a**	2,25 **a**	1,88 **a**	17,74 **a**
II	25,47 **ab**	1,54 **abc**	7,41 **a**	18,06 **a**	2,30 **a**	2,35 **a**	16,84 **a**
III	29,53 **a**	1,52 **bc**	6,09 **a**	22,50 **a**	2,23 **a**	2,39 **a**	20,51 **a**
IV	31,05 **a**	2,47 **a**	4,66 **a**	25,96 **a**	2,33 **a**	3,17 **a**	15,91 **a**
V	26,49 **ab**	1,92 **ab**	4,70 **a**	22,68 **a**	1,81 **a**	3,33 **a**	18,35 **a**
VI	20,54 **b**	1,24 **c**	6,03 **a**	15,91 **a**	1,09 **a**	1,96 **a**	12,66 **a**
CV %	0,24	21,33	52,77	34,12	68,88	59,34	30,87
	5-10						
I	18,10 **ab**	1,18 **bc**	2,38 **a**	15,72 **ab**	2,34 **a**	2,52 **a**	12,14 **ab**
II	17,97 **ab**	1,12 **bc**	3,81 **a**	14,15 **ab**	1,95 **a**	2,82 **a**	10,44 **b**
III	24,99 **a**	1,32 **abc**	4,52 **a**	19,98 **a**	1,71 **a**	1,60 **a**	17,76 **a**
IV	17,37 **b**	1,53 **a**	5,80 **a**	11,25 **b**	1,29 **a**	2,41 **a**	10,53 **b**
V	17,52 **ab**	1,42 **ab**	3,97 **a**	13,82 **b**	1,22 **a**	2,62 **a**	12,69 **ab**
VI	15,25 **b**	1,04 **c**	2,73 **a**	12,68 **b**	1,34 **a**	2,56 **a**	15,25 **ab**
CV %	7,29	16,66	16,33	29,33	57,03	40,52	31,13
	10-20						
I	14,22 **b**	0,94 **a**	2,39 **a**	11,82 **ab**	1,67 **ab**	2,01 **a**	11,95 **a**
II	13,63 **b**	0,84 **a**	1,94 **a**	11,69 **ab**	0,89 **bc**	2,53 **a**	9,16 **ab**
III	19,70 **a**	1,05 **a**	2,38 **a**	16,09 **a**	2,41 **a**	2,60 **a**	13,47 **a**
IV	11,03 **b**	1,02 **a**	4,43 **a**	8,89 **b**	0,67 **bc**	1,87 **a**	7,17 **b**
V	12,52 **b**	1,09 **a**	1,49 **a**	10,72 **b**	1,02 **bc**	2,21 **a**	9,25 **ab**
VI	12,02 **b**	0,82 **a**	2,74 **a**	9,02 **b**	0,75 **c**	2,65 **a**	11,49 **ab**
CV %	2,92	21,27	6,04	40,27	67,39	40,36	30,44

Legend: S: segment; I, II and III - S with variation of the topographic gradient and slope in the convex pedoform; IV, V and VI - S with variation of the topographic gradient and slope in the concave pedoform; CV% - coefficient of variation (%).*Values followed by different letters in the column for each pedoform differ ($p < 0.05$), according to the Tukey test.

The segments showed no significant differences for the OC_P and CO_{MA} fractions in the 0-5 cm layer (Table 3) and decreased as the soil depth increased. The segments presented different CO_{MA} contents in the 5-10 and 10-20 cm layers in both pedoforms (Table 3), with the higher contents for S-I, II, and III.

The chemical fractioning (Table 3) showed significant differences for the C-HAF fraction in the 10-20 cm layer, with higher contents in S-III. The C-HUM fraction was significantly different in the 5-10 and 10-20 cm layers, which presented higher C-HUM contents in the S-III, followed by S-VI (Table 3). No significant differences were found for the C-FAF fraction.

The highest organic carbon stocks were found, in general, in the convex pedoform, with decreasing values as the soil depth increased; the pedoforms showed no significant differences for nitrogen stocks (Table 4).

Considering the carbon stocks in the granulometric fractions, the pedoforms showed significant difference for CO_{MA} fraction in the 5-10 cm layer (Table 4). The pedoforms presented no significant differences for humified fractions (C-FAF, C-HAF, and C-HUM) (Table 4).

Table 4. Stocks of total organic carbon, total nitrogen and fractions of organic matter in the different pedoforms.
Tabela 4. Estoques de carbono orgânico total, nitrogênio total e das frações da matéria orgância nas diferentes pedoformas.

Study Area	TOC	N	OC_P	CO_{MA}	C - HAF	C - FAF	C - HUM
	Mg ha-1						
	Depth (cm)						
	0-5						
Convex	14,98 **a**	0,84 **a**	3,98 **a**	10,86 **a**	1,26 **a**	1,30 **a**	10,03 **a**
Concave	13,16 **b**	0,91 **a**	2,76 **a**	11,55 **a**	0,92 **a**	1,50 **a**	8,41 **a**
CV%	22,23	21,03	54,66	33,30	65,12	51,54	30,70
	5-10						

Convex	11,94 **a**	0,69 **a**	2,04 **a**	9,52 **a**	1,15 **a**	2,15 **a**	7,70 **a**
Concave	9,26 **b**	0,71 **a**	2,40 **a**	6,96 **b**	0,72 **a**	2,53 **a**	7,10 **a**
CV%	24,02	22,30	71,67	23,52	48,91	43,77	31,11

*Values followed by different letters in the column for each pedoform differ between themselves (p <0.05), by the t test.

The segments presented no significant differences for carbon stocks in the soil surface layer (0-5 cm); and the layer of 5-10 cm showed the highest carbon stocks for the segments of the convex pedoform (Table 5). The highest N stocks were found in S-IV and V for all soil layers (Table 5).

Among the stocks of the granulometric fractions distributed in the segments, only CO_{MA} showed significant difference for the 5-10 cm layer, with the highest contents found for S-I, II, and III (Table 5). The segments showed no significant differences for stocks in humic fractions (Table 4 and Table 5).

Table 5. Stocks of total organic carbon, total nitrogen and fractions of organic matter in the different S.
Tabela 5. Estoques de carbono orgânico total, nitrogênio total e das frações da matéria orgânica nos diferentes S.

Study Area	TOC	N	OCP	COMA	C - HAF	C - FAF	C - HUM
				Mg ha^{-1}			
				Depth (cm)			
				0-5			
I	14,97 **a**	0,92 **abc**	4,55 **a**	10,42 **a**	1,29 **a**	2,24 **a**	9,89 **a**
II	14,73 **a**	0,89 **abc**	4,24 **a**	10,48 **a**	1,37 **a**	2,28 **a**	9,78 **a**
III	15,11 **a**	0,77 **bc**	3,15 **a**	11,66 **a**	1,12 **a**	1,46 **a**	10,52 **a**
IV	15,32 **a**	1,22 **a**	2,24 **a**	13,08 **a**	1,16 **a**	1,90 **a**	7,80 **a**
V	15,19 **a**	1,05 **ab**	2,62 **a**	12,57 **a**	1,00 **a**	1,75 **a**	10,40 **a**
VI	12,42 **a**	0,69 **c**	3,41 **a**	9,01 **a**	0,60 **a**	0,75 **a**	7,03 **a**
CV%	22,69	20,45	53,18	34,00	72,29	51,34	31,93
				5-10			
I	21,46 **ab**	0,70 **bc**	1,40 **a**	9,32 **ab**	1,39 **a**	1,84 **a**	7,20 **a**
II	21,66 **ab**	0,68 **bc**	2,25 **a**	8,57 **ab**	1,19 **a**	1,64 **a**	6,24 **a**
III	23,07 **a**	0,69 **bc**	2,46 **a**	10,66 **a**	0,86 **a**	1,28 **a**	9,66 **a**
IV	20,42 **ab**	0,93 **a**	3,48 **a**	6,73 **b**	0,77 **a**	1,01 **a**	6,34 **a**
V	18,98 **ab**	0,78 **ab**	2,23 **a**	7,26 **b**	0,67 **a**	0,93 **a**	6,72 **a**
VI	16,73 **b**	0,57 **c**	1,48 **a**	6,88 **b**	0,72 **a**	0,99 **a**	8,24 **a**
CV%	25,72	19,35	80.48	27,48	56,64	45,28	31,13

Legend: S: segment; I, II and III - S with variation of the topographic gradient and slope in the convex pedoform; IV, V and VI - S with variation of topographic gradient and slope in the concave pedoform. *Values followed by different letters in the column for each pedoform differ (p <0.05), according to the Tukey test.

DISCUSSION

Many plants species in tropical forests have C3 photosynthetic cycle. These species absorb less ^{13}C and more ^{12}C and, therefore, they are poorer in ^{13}C, presenting values between -20‰ and -34‰. This carbon isotope absorption pattern has been used to study changes in soil isotopic carbon due to changes in forest cover (DORTZBACH *et al.*, 2015).

The study area was under a succession process that increases the number of C3 plants and decreases C4 plants. The convex pedoform showed predominance of N-fixing arboreous species of the Fabaceae family, increasing the soil N contents. The N contents found were similar to those reported in other studies in the Atlantic Forest (DORTZBACH *et al.*, 2015; PINHEIRO *et al.*, 2010) and other biomes (VIANI *et al.*, 2011). The pedoforms and segments showed differences for ^{15}N. The highest ^{15}N contents were found for the segments of the convex pedoform, which are related to the presence of N-fixing species.

The higher ^{13}C contents in deeper layers found for the pedoforms and segments were related to the organic matter decomposition and humification process in the soil, which is affected by the decomposition of organic substrates, climate variations, higher older TOC contents, and higher humification rate, which are factors responsible for increases in ^{13}C contents in deeper soil layers (DORTZBACH *et al.*, 2015).

TOC, TN, and physical and chemical soil fractions

The highest TOC contents in the convex pedoform and in the soil surface layer are related to litterfall deposition and decomposition processes, which are more intense in these environments because of a high light incidence and high temperatures.

Santos *et al.* (2016) evaluated soil physical and chemical attributes in different reliefs of the same area and found higher litterfall deposition and decomposition rates in convex reliefs, showing that the high carbon contribution of the litterfall increased soil TOC contents.

Higher CO_{MA} than OC_P contents were found in the convex pedoform, which may be due to the higher mineralization rate; the OC_P fraction is associated with o more labile carbon forms, i.e., easily mineralizable (LOSS *et al*., 2014). According to Figueiredo *et al.* (2010), OC_P is negative correlated to CO_{MA}, i.e., areas with high CO_{MA} contents should have high organic matter decomposition, which will be associated with soil clay minerals. This denotes a higher stabilization of soil carbon forms, because they are connected to clay and silt fractions and, consequently, are more protected from the decomposition process. The curvature and slope of the convex pedoform resulted in higher light and wind incidences and water flow rate, which is a favorable environment to transformation of the organic matter added to the soil (SANTOS *et al*., 2016).

The occurrence of lower rainfall depths in dry periods retard the decomposition of the organic matter deposited in the convex pedoform, which explains the higher mean CO_{MA} in the soil surface layer (0-5 cm) in the concave pedoform. In these periods, concave reliefs favor soil moisture because of the slower water flow and the convergent direction, maintaining the SOM decomposition and contributing to increase TOC contents in this pedoform (SANTOS *et al*., 2016; OLIVEIRA *et al*., 2013).

The lower OC_P contents found in the concave pedoform (Table 1) may be due to the collection of samples in the dry period, which presented higher decomposition of plant matter in the concave pedoform (SANTOS *et al*., 2016) and, consequently, higher mineralization. The topographic characteristics of the concave pedoform favors soil moisture maintenance, contributing to the activity of organisms that decompose the SOM (DINIZ *et al*., 2015), decreasing OC_P contents. The CO_{MA} contents in the concave pedoform denote the negative correlation between these two fractions (Table 1).

Lin *et al.* (2016) model properties in deep soil layers in slopes areas with pasture in California, USA, using the LiDAR (Light Detection and Ranging) digital elevation model and found higher carbon contents in convex locations, despite concave locations present higher mass accumulation values.

The humified fractions showed predominance of humin (C-HUM), which is a more stable product of the SOM, with higher contents in the convex pedoform. According to Long and Espínola (2000), the predominance of the C-HUM fraction indicates low solubility and resistance to biological degradation, and a constant contribution of plant matter. The concave pedoform showed lower C-HAF contents, which may be related to the lower humification rate and slower organic matter mineralization in this pedoform.

C-HAF/C-FAF (more soluble fractions) ratios higher than 1.0 indicate higher condensation of the soluble organic matter (CANELLAS and SANTOS, 2005). Contrastingly, ratios lower than 1.0, as found for all soil layers and pedoforms (Table 2), denote predominance of the C-FAF fraction (CANELLAS and SANTOS, 2005).

According to Canellas and Santos (2005), recovery rates (C-HAF+C-FAF+C-HUM/C-TOTAL) between 65% and 92%, as found for the convex pedoform in all soil layers, are normal and characterize a constant SOM transformation with normal humification rates. The 5-10 and 10-20 cm layers in the concave pedoform showed values above this range, indicating poor soils, which is probably due to a slower transformation occurring in this pedoform (MENDONÇA *et al*., 2019).

The TOC and TN found throughout the segment (Table 3) showed similar pattern to that reported by Santos and Salcedo (2010), who evaluated soil relief and fertility in different forest extracts and found increases in C and N contents in the agriculture-forest direction, resulting in higher litterfall deposition, which is subjected to decomposition process and contributes to increases in C and N contents in the soil.

The distribution of the CO_{MA} fraction (Table 3) showed two significantly different layers, with the highest means found for the segment III (upper third of the convex pedoform), which is an area with higher water surface runoff, rainfall and wind mechanic actions, solar radiation incidence, favoring the addition and formation of litterfall and the decomposition speed (MENDONÇA *et al*., 2019).

S-I and II were higher in points of the slope subjected to higher removal of the SOM added, making it difficult its accumulation and subsequent transformation. Artur *et al.* (2014) evaluated the spatial variability of soil chemical attributes associated with micro-reliefs and found significant effect of micro-reliefs on water drainage and horizontal and vertical movements in the soil profile, which accelerate chemical reactions and promote the transport of solids and soluble compounds.

The highest C-HUM contents found in the S-III and VI (Table 3) were probably related to the position of these environments on the landscape, because both segment were in the upper third of the pedoforms, thus they were more exposed to factors that contribute to SOM decomposition, increasing the C-HUM fraction, which is a more stable form of SOM (MENDONÇA *et al.*, 2019). Canellas *et al.* (2000) studied humified SOM fractions in a toposequence in Rio de Janeiro, Brazil, and found higher percentage of C-HUM in soil profiles in the upper third of the slope.

The C-HAF fraction decreased as the soil depth increased; the 10-20 cm layer was significantly different, presenting higher C-HAF contents for S-III, followed by S-I, both in the convex pedoform (Table 5). Different pattern was found by Canellas *et al.* (2000), who reported lower C-HAF contents for the upper third of the relief.

Soil organic carbon and nitrogen stocks

Organic carbon stocks were, in general, higher in the convex pedoform, and decreased as the soil depth increased; the pedoforms showed no significant differences for nitrogen stocks (Table 4). Gatto *et al.* (2010) found effect of regional edaphoclimatic conditions on carbon stocks in eucalyptus plantations; the altitude, water deficit, and clay and Al contents were the factors responsible for the highest variation found. Nitrogen stocks in the soil surface layer (0-5 cm) were higher in segments in the lower and medium thirds of the convex and concave pedoforms. It decreased as the soil depth increased, and in the upper regions of the pedoforms (Table 5). The higher nitrogen content in segments in the lower and medium regions of the pedoforms may be attributed to the presence of legumes, which are N_2-fixing species, thus the N_2 will be returned to the soil through the litterfall.

The highest CO_{MA} contents were found in segments of the convex pedoform (Table 4 and 5); it can be attributed to the lower stability of the OC_P fraction, which is rapidly decomposed because of the topographic characteristics of this pedoform, resulting in a relative increase in the organic matter fractions that are associated with clay and silt (CO_{MA}).

CONCLUSIONS

- The highest carbon contents were found in the convex pedoform and in the lower region of the concave pedoform.
- Soil organic matter fractions are affected by the micro-relief.
- The highest results for granulometric (particulate organic carbon and mineral-associated organic carbon) and humic (fulvic acid and humin) fractions were found for the segments in the convex pedoform;
- The slope conditions and topographic gradient affect the dynamics of the soil organic matter transformation.

ACKNOWLEDGEMENTS

The authors thank the Foundation for Research Support of the State of Rio de Janeiro (FAPERJ); and the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES; Financing code 001) for the financial support.

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