Research article

Soil organic carbon forms with different uses in the Department of Magdalena (Colombia)

Formas de carbono orgánico en suelos con diferentes usos en el Departamento del Magdalena (Colombia)

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Abstract

Fractions of soil organic matter (SOM) labile and humified, can be affected by use and management practices, but the impact of these changes has not been evaluated in soils of tropical environments. The present study investigated the contents and some forms of soil organic carbon (SOC) in five warm tropical climate zones of the Department of Magdalena (Colombia), and the effect of the cropping practices on these forms of organic carbon in cultivated soils, associated with Coffee (*Coffea arabica*), Banana (*Musa* sp.), African palm (*Elaeis guineensis*), Aloe (*Aloe vera*) compared to natural forest soils. Significant differences ($P < 0.05$) were not found between zones neither between soil. The study areas had low average values of SOM and, the forest soils had higher contents of total carbon than cultivated soils. Forest soils had an total carbon accumulation average of 42.4 mg/ha at 20 cm, compared to 33.8 mg/ha in the cultivated soils, this equals to an average loss of 23% total C by the effect of crop management in these soils. Values of humified C (C extracted with sodium pyrophosphate), are very low in cultivated soils and almost zero in forest soils, but forest soils had a higher number of stable forms of C (Cnox). In the soil cultivated with bananas, Total Carbon corresponds to fully oxidized forms of C, however in the soil cultivated with African palm, C stable forms represented 83% of total carbon.

Key words: Agricultural soils, biogeochemical cycling, Carbon, Colombia, humus, Magdalena, plant nutrition.

Resumen

Las fracciones de materia orgánica del suelo (MOS) lábiles y humificadas pueden ser afectadas por las prácticas de uso y manejo; sin embargo el impacto de estos cambios no se ha evaluado en suelos y ambientes tropicales. El presente estudio tuvo como objetivo evaluar los contenidos y algunas formas de carbono orgánico del suelo (COS) en cinco zonas de clima cálido tropical (0 - 1110 m.s.n.m.) del departamento del Magdalena (Colombia) y el efecto que sobre ellas han tenido las prácticas asociadas a suelos cultivados con café (*Coffea arabica*), banano (*Musa* sp.), palma africana (*Elaeis guineensis*) y sábila (*Aloe vera*), comparados con suelos de bosques naturales. No se encontraron diferencias ($P < 0.05$) tanto entre zonas como entre usos del suelo, se presentaron valores medios a bajos de MOS en las zonas de estudio y contenidos de carbono total (Ct) mayores en suelos de bosques que en suelos cultivados, así los suelos de bosques presentan una acumulación media de Ct de 42.4 mg/ha a 20 cm, frente a 33.8 mg/ha en los suelos cultivados, esto equivale a una pérdida media de Ct del 23% por efecto del manejo de los cultivos. En relación con el carbono extraíble con pirofosfato sódico altamente relacionado con las fracciones humificadas de la MOS (Cp) se observaron valores muy bajos en los suelos cultivados y casi nulos en suelos de bosques; sin embargo estos últimos presentan mayor contenido de formas de carbono no-oxidables o estables (Cnox) determinado por diferencia entre Ct - carbono oxidable (Cox). En el suelo cultivado con banano, el Ct corresponde en su totalidad a formas de Cox; mientras que en el suelo cultivado con palma africana las formas estables Cnox representaron 83% del carbono total.

Palabras clave: Carbono, ciclo biogeoquímico, Colombia, humus, Magdalena, nutrición de plantas, suelos agrícolas.

Introduction

Stevenson (1994) divides the soil organic matter (OM) in two fractions ("pools") based on their reactivity: labile or active material and stable organic material. The active fraction includes the macroscopic organic matter even in the soil surface (litter). The light fraction is composed by the remains of living organisms in different stages of decomposition, the microbial biomass and the non-humic organic compounds. Therefore, the stable fraction is the humus or complex colloidal fraction which has experienced different degrees of stabilization. The soil organic carbon (SOC) is an important component of the global C cycle, occupying 69.8% of the organic C in the biosphere (FAO, 2001). Soil can act as a source or reservoir of C, depending on its use and management (Lal, 1999; Lal, 2005). It has been estimated that from the incorporation of new land for agriculture to intensive farming systems, COS losses occur between 30 and 50% of the initial level (Reicosky, 2002). The Kyoto Protocol requests an understanding of the stabilization of C in the soil because this represents the terrestrial reservoir with the largest capacity (Schlesinger, 1995, quoted by Madinabeitia, 2007). Then, any actions on the soil can lead to it to act as a sink or as a source of C to the atmosphere. Regarding this statement, Lal (2001) states that until 1970 the consequences of agricultural and forestry techniques have led to a higher loss of C to the atmosphere than those produced in the same period by industrial activities and transport. Despite improvements with the sustainable agriculture and good agricultural practices, the agriculture still accounts for 25% of emissions.

0.25% of global CO2 emissions are coming from Colombia. The 45% of greenhouse gases emissions is from agriculture and 9% of the total emission is produced by changes in land use and forestry (IDEAM –Ministry of Environment, Housing and Territorial Development, 2006). The county of Magdalena is no stranger to this reality, especially if it is considered its excellent agricultural vocation, with large areas of productive land devoted to these activities. Magdalena is represented by 215.512 ha in agriculture, 79.734 ha in agroforestry, 1,219,769 ha in livestock, 233.815 ha of forest and 416,941 ha in conservation (IGAC, 2002). In Colombia, especially in the Caribbean region, the storage of C has been poorly evaluated with respect to changes in the landscape. The landscape is an element of great importance because this element depends on the specific conditions of each site and, it needs sampling methods that take into account the changes of each site and the landscape to identify patterns of distribution. Moreover, agroecosystems can be managed to reduce C emissions and increase C pools, but choices should be based on knowledge of the soil storage capacity of a biome or agro-ecological region and their response to different uses (Carvajal et al., 2009).

In Colombia, soils with low organic matter (OM) are in the middle and upper Guajira, largely Aridisols. Soils with higher content of MO are Andisols which are in the cold climatic zone (Jaramillo et al. 1994). According to IGAC (1988) cited by Jaramillo (2004), in the Caribbean the organic carbon content is between 0.5% and 1%. Environmental issues associated with the living areas in this region, give limited contributions of biomass affecting soil OM content. Low values predominate (45% of the soil), followed by medium (30% of the soil) and very low (20% of the soil), while soils with high organic carbon percentages include only 5% of the region. Despite the low OM contents (65% of the soil), humus evolves according to the alternating seasonal precipitation and high temperatures (aridic and ustic schemes cover 65%) (Malagón-Castro, 2003).

From the statement above, this study assesses the changes in C stocks in different forms and uses of soils located at different altitudes of the Department of Magdalena considering that the CO in this region is affected by changes in land use, without neglecting the losses of C in soils traditionally devoted to intensive agriculture.

Materials and Methods

The research was conducted in the northwestern part of the Department of Magdalena in Santa Marta and the banana region, including the northwest part of the Sierra Nevada de Santa Marta (11 ° 36 '58 "- 8 ° 56' 25" N, 73 ° 32 '50 "- 74 ° 56 '45 "W), with a surface area of 23.188 km² (Figure 1).

Soil sampling. Five areas in the northwestern department of Magdalena were selected for this study (Table 1), two areas on the west side of the Sierra Nevada de Santa Marta, one on the farm of the University of Magdalena and the last two areas in the banana region. All selected areas had similar climate, topography and soil conditions. Given the inclusion of different land uses in each zone, the following sites were established at each place: cropland and forest land or fallow. Within each site a soil sample consisting of 10 subsamples were taken randomly in the field (Brady and Weil, 2002; ICA, 1992). In total 10 samples were taken to study the five zones.

Physical analysis. Munsell table was used to determine the color of wet and dry soils. Bulk density (Bd) was determined by two methods, graduated cylinder (samples 1, 2, 3, 4, 7 and 8), and waxy lump (samples 5, 6, 9 and 10) (IGAC, 2006).

Chemical analysis. The pH in H_2O and 0.1N of KCl were determined in a ratio of 1:2.5 respectively (IGAC, 2006). The exchangeable cations Ca^{+2}, Mg^{+2}, K^+, Na^+ were extracted with ammonium chloride and were determined by atomic absorption spectrophotometry. P was determined by the method of Olsen. C and total N were determined by a LECO analyzer (Model CHN-1000, LECO Corp., St. Joseph, MI). Oxidizable C (Cox) was determined by Walkley and Black technique (1934), cited by IGAC (2006). The SOM was calculated by multiplying Cox by the factor 1.724. The C bound to the soil humic fraction (C pyrophosphate, Cp) was determined according to the methodology described by Bascomb (1968), cited by Velasco (2006). Lastly, the non-oxidizable C fraction (Cnox) was calculated by the difference between Ct and Cox.

Analysis of results. As for the forms of C (Ct, Cox, Cp, Cnox) and C/N variables, the Kruskal Wallis test for independent samples was performed with Statgraphics Centurion

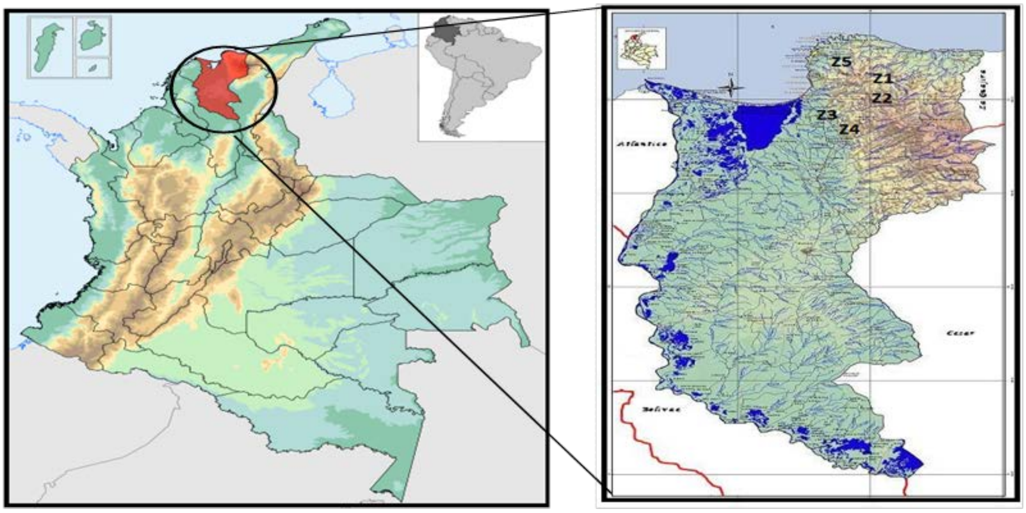

Figure 1. Location of sampling sites.

Source: IGAC, 2009.

Table 1. Land use and weather classification of the studied zones.

Sampling Zones	Samples	Land Use	Weather and altitude	Classification and climate regime	Landscape and parent material
1	1	Coffee crop	Warm Humid; Altitude 803 MASL; Precip. 1110 mm; 24°C	Haplic cambisol Typic Eutropepts Údic Isohyperthermic	Mountain landscape, hillside. Parent material schist
	2	Pasture and secondary forest	Warm Humid; Altitude 808 MASL.; Precip. 1110 mm; Tem 24°C	Haplic cambisol Typic Eutropepts Údico Isohyperthermic	Mountain Landscape, hillside, PM: schist
2	3	Coffee crop	Warm Humid; Altitude 610 MASL; Precip. 905 mm; Temp. 25°C	Haplic Phaeozem Typic Hapludolls Údic Isohyperthermic	Mountain Landscape, hillside, PM: quartz monzonite
	4	Secondary Forest	Warm Humid Altitude 616 MASL; Precip. 905 mm; Tem 25°C	Haplic Phaeozem Typic Hapludolls Údic Isohyperthermic	Mountain Landscape, hillside, PM:: quartz monzonite
3	5	African Palm Oil Crop	Warm Dry; Altitude 25 MASL.; Precip. 910 mm; Tem 27°C	Haplic Phaeozem Haplustolls Ústic Isohyperthermic	Plain Landscape. PM: colluvial-alluvial sediments
	6	Secondary Forest	Warm Dry; Altitude 25 MASL; Precip. 910 mm; Tem 27°C	Haplic Phaeozem Haplustolls Ústic Isohyperthermic	Plain Landscape. PM: colluvial-alluvial sediments
4	7	Banana Crop	Warm Dry; Altitude 20 MASL Precip. 970mm; Tem 27 °C	Haplic Phaeozem Haplustolls Ústic Isohyperthermic	Plain Landscape. PM: colluvial-alluvial sediments
	8	Secondary Forest	Warm Dry; Altitude 20 MASL; Precip. 970 mm; Tem 27 °C	Haplic Phaeozem Haplustolls Ústic Isohyperthermic	Plain Landscape. PM: colluvial-alluvial sediments
5	9	Aloe vera Crop	Warm Dry; Altitude 10 MASL; Precip. 600 mm; Tem 28.5 °C	Aric Regosol Typic Ustipsamments Ústic Isohyperthermic	Plain Landscape. PM: -alluvial sediments
	10	Tropical dry Forest	Warm Dry; Altitude 10 MASL.; Precip. 600 mm; Tem 28.5 °C	Haplic Regosol Typic Ustipsamments ÚsticIsohyperthermic	Plain Landscape. PM: -alluvial sediments

XVI, 2011.

Based on similarity ranges and with the purpose of complying with the "map" or set of samples over the content of Ct (in a specific number of dimensions), a non-metric multidimensional scaling analysis (MDS) was performed following the procedure adopted by the first program routine V. 6.1.6 (Clarke and

Warwick, 2001). Other physicochemical variables were analyzed taking into account the descriptive statistics. The stress estimated for this analysis was 0.07, which if not an excellent representation of P <0.05, provides a good data management without adding the information from the group structure when examined with three or more dimensions.

Results and discussion

Physical and chemical results of soils in this study are displayed in table 2. A range of colors between 10YR 4/2 and 10 YR 5/4 represent dark yellowish red as the typical surface horizons influenced by the presence of small quantities of OM. The pH values are in the range of slightly acid to moderately alkaline. Zones 1 and 2 showed the lowest values of pH, marked by the difference in altitude, rainfall and topography, which agrees with Rubiano et al. (1995) cited by IGAC (1995) and the General Soil and Land Zoning Survey of Magdalena County (IGAC, 2009) for soils in warm weather mountains located at the foothills of the Sierra Nevada de Santa Marta. Zone 5 showed a moderate alkalinity condition that clearly indicates an important evapotranspiration which exceeds the average annual rainfall (Vasquez and Baena, 2009). Zones 3 and 4 have low organic C in the first horizon and high natural fertility. These zones correspond to soils developed from alluvial deposits formed by the rivers that descend from the Sierra Nevada and have higher content of Ca. According IGAC (2009), the physi

Table 2. Soil properties of the studied zones.

Properties	**Cultivated Soils**					**Forest Soils**				
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**
	1	**3**	**5**	**7**	**9**	**2**	**4**	**6**	**8**	**10**
Color S[1]	10YR 4/2	10YR 5/4	10YR 5/4	10YR 5/4	10YR 5/2	10YR 5/3	10YR 5/2	10YR 5/2	10YR 4/2	10YR 5/3
Color H[1]	10YR 2/3	10YR 3/3	10YR 3/3	10YR 3/2	10YR 2/3	10YR 3/3	10YR 3/2	10YR 3/2	10YR 2/3	10YR 3/3
BD (gr/cm^{-3})	1.20	1.3	1.4	1.3	1.5	1.1	1.2	1.3	1.2	1.3
pH $_{H2O}$	6.10	5.9	7.2	6.7	8.3	5.9	5.8	6.2	6.9	8.2
pH $_{KCl}$	5.40	4.8	5.7	5.3	7.4	4.9	4.7	5.2	6.0	7.4
Ca^{+2} (cmol(+)/kg)	14.0	7.1	7.4	10.7	20.2	8.0	8.5	8.4	11.9	23.9
Mg^{+2} (cmol(+)/kg)	1.60	1.2	3.0	3.9	4.0	1.7	1.2	2.3	4.0	6.8
Na^{+} (cmol(+)/kg)	0.10	0.1	0.1	0.1	0.3	0.1	0.1	0.2	0.2	0.3
K^{+} (cmol(+)/kg)	0.20	0.2	0.2	0.3	1.2	0.2	0.2	0.4	0.3	1.7
CICE (cmol(+)/kg)	15.90	8.6	10.8	15.0	25.8	10.0	10.0	11.3	16.4	32.7
% Ca Sat.	88.30	83.0	68.8	71.2	78.4	80.0	85.4	74.5	72.8	73.2
% Mg Sat.	10.20	14.0	28.0	25.9	15.5	17.3	11.6	20.4	24.3	20.8
% K Sat.	1.00	1.8	1.9	1.9	4.8	1.9	1.9	3.1	1.7	5.1
% Na Sat.	0.50	1.2	1.3	0.9	1.3	0.8	1.1	2.0	1.2	0.9
P $_{(Olsen)}$ ppm	14.00	4	12	20	34	4	6	21	8	15
% Total N.	0.100	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2

[1] S= Dry; H= wet

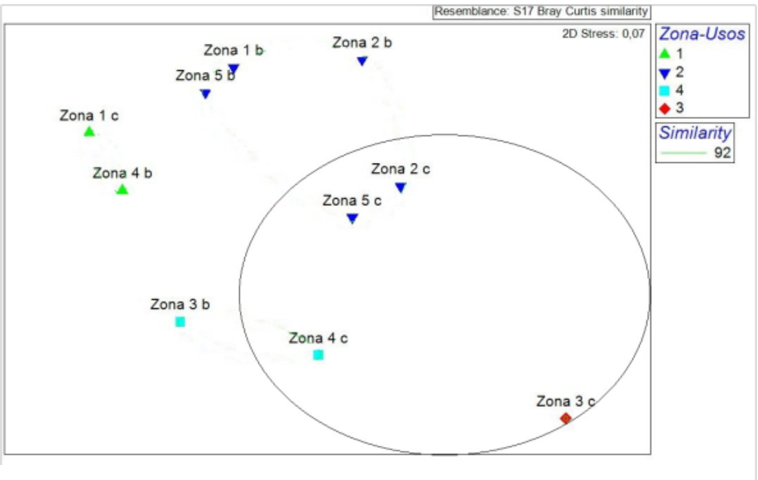

Figure 2. Ordering of non-metric multidimensional scaling (MDS) of the zones and land uses (zones 1, 2, 3, 4 and 5 - uses: crop = c, b = forest), based on the similarity of Bray Curtis (stress = 0.07) (Clarke y Warwick, 2001).

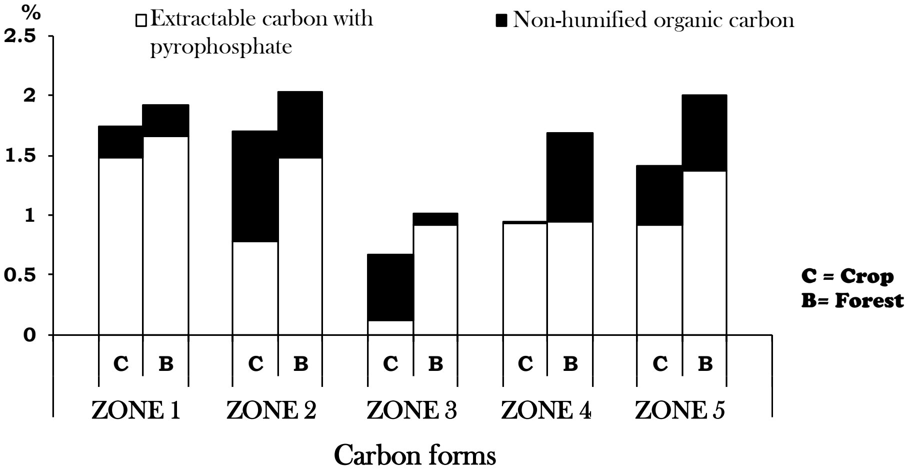

Figure 3. Distribution of carbon extractable by pyrophosphate and humified organic carbon of soil organic matter.

cal soil properties of these areas show compaction processes with BD values reaching 1.7 g/cm3, which is not reflected in the soils of this study.

According to the criteria of the Colombian Agricultural Institute (ICA, 1992), in general, all areas have a high content of Ca^{2+}, due to its dominant position in the exchange complex. Mg^{2+} content is low in zone 2, followed by zone 1 with medium and high levels in other areas. Except for high values in zone 5, moderate level of K^+ is in all areas of study.

Na^+ levels are low and the CEC (10-20 Cmol$(^+)$/kg) is moderate for all areas. P content is low in forest areas and moderate in cropping areas, probably due to the high fixation of this element that occurs in many of the soils in dry warm climate of the department of Magdalena. Total N content shows moderated values for crop and forest areas despite the high doses of nitrogen fertilizers applied in the region to coffee, banana and palm crops, and its low efficiency.

No significant difference ($P < 0.05$) was found nor between zones neither between

Table 3. Percentage of carbon and C/N ratio of the studied soils.

Zone	Soils	Use	C. Total	C. Oxi	C. Piro	O.M.	C. nox	C/N
1	1	Coffee	1.75	1.49	0.12	2.6	0.26	12.6
	2	Forest	1.92	1.67	0.12	2.9	0.26	11.3
2	3	Coffee	1.70	0.77	0.06	1.3	0.93	10.6
	4	Forest	2.03	1.49	0.37	2.6	0.54	10.5
3	5	Palm,	0.67	0.11	0.00	0.2	0.55	10.1
	6	Forest	1.01	0.91	0.00	1.6	0.10	11.8
4	7	Banana	0.94	0.93	0.00	1.6	0.01	10.7
	8	Forest	1.68	0.94	0.12	1.6	0.74	12.4
5	9	Aloe vera	1.42	0.92	0.12	1.6	0.50	10.8
	10	Forest	2.01	1.37	0.00	2.4	0.64	11.7

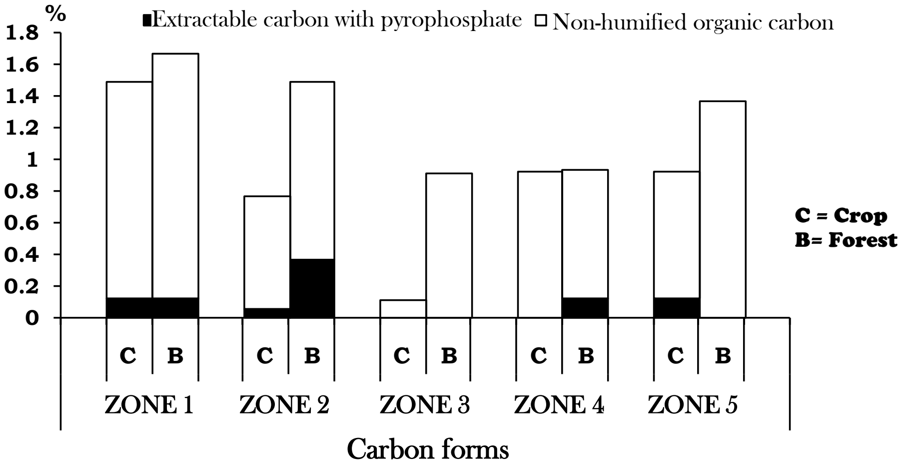

Figure 4. Distribution of the organic carbon forms from the extracted organic matter of each zone

land uses. However, evaluating the distance based on sample similarity (92%), it is important to highlight how even though, there are no differences in Ct contents between land use, there is a clear trend to get clusters of crop soils in the similarity graph (Figure 2) which noticeable, has lower Ct than forest soils, with only one exception on the crop soil of zone 1. This is caused by the climatic conditions that benefit CO accumulation in soils including higher altitude over the level of the sea, higher precipitation and lower temperatures.

To sum up, Ct contents are higher in forest soils than in crop soils for all zones (Figure 3). These results confirm Moreno and Lara (2003) studies who worked in Inceptisols and Entisols from Antioquia in Colombia. They found that the CO in the primary forest soils was higher than in soils of secondary forests and disturbed areas. On the other hand, Carvajal et al. (2009) showed a different trend for many profiles (0 – 30 cm) with a gain in soil C storage at the Colombian Andean landscapes. The C accumulation was principally from natural vegetation cover (forest relicts) that became crops, mainly coffee and bananas. The opposite occurs when crops became pastures with significant reductions of C.

Table 4. Relationship between the different carbón forms content in the studied soils.

Zone	Soil	Use	Cox/Ct	Cnox/Ct	Cp/Ct	Cp/Cox
1	1	Coffee	0.85	0.15	0.07	0.08
	2	Forest	0.87	0.13	0.06	0.07
2	3	Crop	0.45	0.55	0.04	0.08
	4	Forest	0.73	0.27	0.18	0.25
3	5	Palm	0.17	0.83	0.00	0.00
	6	Forest	0.90	0.10	0.00	0.00
4	7	Banana	0.99	0.01	0.00	0.00
	8	Forest	0.56	0.44	0.07	0.13
5	9	Aloe vera	0.65	0.35	0.08	0.13
	10	Forest	0.68	0.32	0.00	0.00

Table 5. C accumulation in the first 20cm of soil depth (mg/ha).

Zone	Soil	Use	Ct	Cox	Cp	Cnox
1	1	Coffee	41.2	35.1	2.8	6.1
	2	Forest	43.1	37.3	2.7	5.8
2	3	Coffee	43.6	19.8	1.5	23.8
	4	Forest	49.6	36.3	9.0	13.2
3	5	Palm	18.8	3.2	0.0	15.6
	6	Forest	25.7	23.2	0.0	2.5
4	7	Banana	24.0	23.8	0.0	0.2
	8	Forest	40.7	22.8	2.9	17.9
5	9	Aloe vera	41.2	26.8	3.5	14.4
	10	Forest	53.0	36.2	0.0	16.9

Cox values were low in all zones, except for the zone 1 (Table 3). Zone 4 presented most of the Ct content as Cox form in the cultivated soil. The above statement was possibly due to the composition of the waste, the great return of crop residues to the soil by agricultural management associated with banana crop, and also due to the climatic conditions of the area. Cp values were very low or almost zero (Figure 4). The lowest values of Cp were found in forest soils, however their Cnox values are high, and present stable forms due to the inherent stabilization process of C in these soils. The C/N ratio was between 10.1 and 12.6 which favors mineralization processes (Table 3).

The relation between different types of C, regarding the total C content (Ct), shows how the highest percentage of Ct is composed of liable forms, except for crop areas in zones 2 and 3 (Table 4). These areas show mainly recalcitrant and stable C forms, which represent 83% of Ct on the soil with African palm cultivation. A further evaluation should be made with more repetitions in the same area and cultivar in order to rule out the influence of a particular management in that site. Cp is related with different intensity in each of the studied C fractions (Table 4). In general, the ratio Cox/Ct is higher in forest soils than in cultivated, being the highest ratio in zone 3 (73%), and lowest in zone 5 (3%). The Cox/Ct ratio was higher in the soils cultivated with Zone 4 cultivated with banana, with a difference of 43% between the forest soil and the cultivated soil.

Table 5 shows the accumulation of different shapes C to 20 cm deep from the top of the soil. This accumulation is estimated from the concentration of C and bulk density (Bd) of the soil (Malagón, 2001). The average accumulation of the studied C forms was higher in the forest soil than in cultivated soils, except for the Cnox form. In the same table, forest sites in zone 5 (10 MASL, 29°C) shows that Cox values are similar to those of zones 1 and 2 (600 and 800 MASL, 24°C and 25°C, respectively). it is possibly due to the condition of secondary forest in zones 1 and 2 vs. the primary forest in zone 5, plus the effects of erosion due to topographic conditions in zones 1 and 2. Cultivated soils showed low or zero values of Cp showing little evolution of OM to humified forms, possibly due to the effect of agronomic practices and perhaps by the low microbial activity on the Cnox forms.

The analysis within each area allows observing the percentage of Ct losses in relation to land use, assuming that the original condition of Ct is determined by the forest soils. Moreover, the major losses of Ct (41%) occur in cultivated soils where banana crop was planted in zone 4, here, the entire Ct is the Cox form described above. The percentaje of Ct losses in other areas were 4, 11, 26 and 23 for zones 1, 2, 3, and 5, respectively. Calvo de Anta (1992), cited by Macías et al. (2004) found that soil C losses are between 26% to 49% in cultivated soils compared to forest soils at the province of La Coruna (Spain). Bayer (2002) found that labile and humified CO forms are more stable in light planting systems in Hapludox soils in the southern Brazil and, as a consequence, those soils are less vulnerable to mineralization.

Conclusions

- The use and management of cultivated soils compared to forest soils in each of the studied areas from the hot thermic floors in the Magdalena region, influence the content of the different forms of C.
- The total C content showed no statistically significant differences due to the height above sea level for the areas studied. In this case the values ranged between 0.7% to 2%, being lower in cultivated land and higher in forests soils.
- The fraction of Cox represents more than 50% of the total C in all the studied areas, while forms of Cnox do not differ between cultivated and forest soils.
- The humified fraction (extractable with pyrophosphate) is not representative for the organic C in the studied areas. Their values were not above 13% of the oxidizable C in cultivated soils while 25% was for forest soils.

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