RESEARCH

Soil organic carbon storage and dynamics after C_3-C_4 and C_4-C_3 vegetation changes in sub-Andean landscapes of Colombia

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The soil C capture capacity and organic matter turnover rate vary according to photosynthetic pathways; therefore the evaluation of C at sites suffering changes from C_3 to C_4 vegetation and vice versa, is important to identify impacts of land use change on C cycle. This study aims to evaluate C storage under different land uses, and soil C dynamics using the ^{13}C technique to identify the origin of soil C. In the Municipality of Alcalá, Department of Valle del Cauca, Colombia, the natural abundance of $\delta^{13}C$ was estimated, and data on land use history were gathered to calculate the organic matter turnover rate. The contribution of each type of vegetation to total percentage organic C and to storage at 0.30 m was estimated at sites suffering changes from C_3 to C_4 vegetation and vice versa. Average $\delta^{13}C$ ranged between -25.79 and -20.72‰ at the three depths evaluated. Over a period of 13 yr, mature fallow lands replaced more than 70% of the C fixed by pastures over a period of 60 yr, whereas paddocks, over a period of 17 yr, only managed to replace 37.9% of the C fixed by associated coffee plantations during a period of 50-100 years. We conclude that the use of ^{13}C avoided that C storage would have been attributed to current land uses when they are actually fixed by previous vegetation; and that C deposit from C_3 vegetation is recalcitrant, while that corresponding to C_4 vegetation has a relatively fast turnover rate.

Key words: Carbon stable isotope, ^{13}C, land use change, organic matter, turnover rate.

INTRODUCTION

Although it is estimated that 44% of the world's organic C is found in the first top meter of tropical soils (1500 Gt), the residency time of these deposits is shorter due to the combination of climatic factors and anthropogenic interventions that affect the entry of phytomass into the system as well as the thickness of the soil's protective porous layer (López-Ulloa et al., 2005; Tan and Lal, 2005).

Rates of C cycling are affected by the type, magnitude, severity, and frequency of anthropogenic interventions and, if the C cycle changes, they influence, in the long term, the isotopic signals that could serve as potential indicators to identify transformations in ecosystems according to change patterns generated by human disturbance (Boeckx et al., 2006). Estimates of C stocks and turnover rates are fundamental to understand the dynamics of terrestrial C. Furthermore, isotopic techniques are important because they can be applied in time scales that range from a few years to several hundreds of years (Oelbermann and Voroney, 2007).

The use of ^{13}C allows C deposits derived from original vegetation to be differentiated from those of recent vegetation, provided that C_3 plants predominate in one of these plant communities and C_4 plants in the other (Lemma et al., 2006), thus serving as a valuable tool to confirm changes produced by the conversion of rainforests into paddocks (Lima et al., 2006).

Urban development and agriculture industrialization escalated during the second half of the 20th century in the Colombian Coffee Belt, located in the Andes. Starting in 1920, migrant farmers turned the slopes of this landscape into arable land and pastures and, as of 1940, sugarcane (*Saccharum officinarum* L.), cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* (L.) Merr.), and maize (*Zea mays* L.) crops extended throughout the valleys, pushing livestock production toward the fragile volcanic slopes and intensifying the demand for land (Feijoo et al., 2007). In the La Vieja river watershed, where the municipality of Alcalá is located, land use has changed significantly over the past 10 yr, triggered mainly by the coffee crisis. Traditional and modernized coffee crops were eradicated to plant plantain, citrus fruits, and pastures, mainly African star grass to produce meat and milk. The inappropriate management of intensive livestock production systems has had negative impacts on the environment such as deforestation, soil compaction and erosion, water contamination, loss of biodiversity, and changes in plant coverage and landscape (CRQ et al., 2008).

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Based on the aforementioned changes, this study aims to evaluate soil C storage under different land uses and soil C dynamics, using the stable isotope technique (^{13}C) to identify the origin of C at sites presenting changes in vegetation from C_3 photosynthesis as coffee plantations (*Coffea arabica* L. var. Colombia) and mature fallow lands (*Ocotea macropoda*, *Piper* spp., *Sauravia scabra*, *Trichanthera gigantea*, *Miconia aeruginosa*) to C_4 photosynthesis as pastures (*Cynodon nlemfuensis* Vanderyst) and sugarcane crops, and vice versa. The proposed hypothesis is that natural plant coverage such as mature fallow lands has a greater capacity to stabilize soil C than pastures, and that despite the fact that coffee crops have been replaced by pastures and sugarcane crops in the Municipality of Alcalá, most of the C stored in the soil was fixed by C_3 plants and it has been conserved even after 17 yr of change in land use.

MATERIALS AND METHODS

Study site

The study was carried out in the Municipality of Alcalá, located in the Department of Valle del Cauca, Colombia, at altitudes between 1150 and 1600 m a.s.l. This municipality is located on the western slope of the Central Cordillera (4º43'18.25" N, 75º51'22.91" W and 4º38'56.85" N, 75º42'11.94" W), an intermediate thermal floor (1000-2000 m a.s.l.) with an annual average temperature of 18-24 °C, annual precipitation of 1350-2400 mm, relative humidity between 65-80%, and bimodal climate with two dry seasons (December-February and June-August) and two rainy seasons (March-May and September-November) (Alcaldía Municipal de Alcalá, 2003).

Three altitudinal strata were defined: (1) between 1150 and 1300 m a.s.l.; (2) between 1301 and 1450 m; and (3) between 1451 and 1600 m. Two grids were constructed in each stratum, formed by 16 points projected every 200 m, for a total of 96 sampling sites. Grids 1 and 2 were located in the highlands of the La Cuchilla, El Congal, and Maravélez rural communities; grids 3 and 4 in the mid-altitude area of the La Polonia and Bélgica rural communities; and grids 5 and 6 in the lowlands corresponding to the El Higuerón rural community (Figure 1). Soils belong to two units of volcanic ash (Malabar and Chinchina) but differ in texture, base saturation, fertility, structure, and internal drainage (Table 1) (Alcaldía Municipal de Alcalá, 2003; Cenicafé, 2007).

Natural abundance of ^{13}C

The natural abundance of ^{13}C ($\delta^{13}C$), which is the ratio of $^{13}C/^{12}C$ based on international Vienna-Pee Dee Belemnite (V-PDB) standard (Peterson and Fry, 1987), was determined using the formula:

$$\delta^{13}C = \left(\frac{(^{13}C/^{12}C)\ sample}{(^{13}C/^{12}C)\ V-PDB} - 1 \right) x\ 1000$$

Samples were collected in the 0-10, 10-20, and 20-30 cm depths using a metallic cylinder (98.12 cm^3). Wet

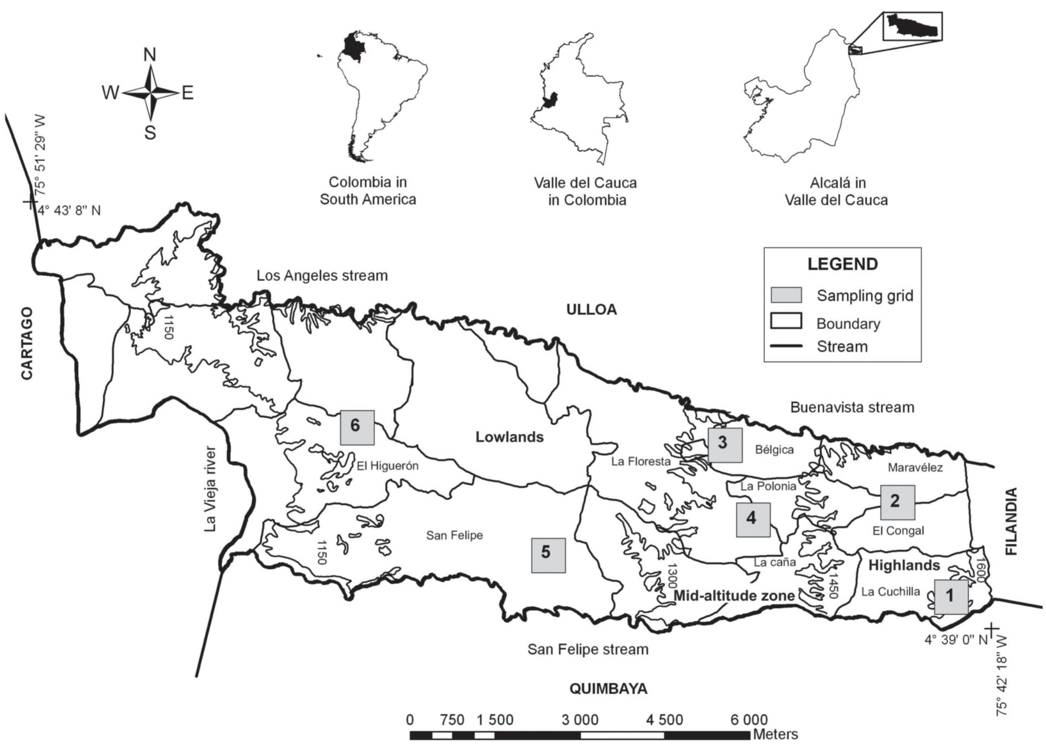

Figure 1. Location of sampling grids in three altitude zones of the Municipality of Alcalá.

Table 1. Characteristics of the soils of the study area (Municipality of Alcala, Valle del Cauca, Colombia).

Parameter	Malabar unit	Chinchiná unit
Soil order	Alfisol	Andisol
Taxonomic classification	Argiudolls Endoaqualfs	Melanudands Fulvudands Hapludands
Altitudinal range, m a.s.l.	900-1250	1250-1600
Origin	Volcanic ashes	Volcanic ashes
Texture	Clay loam-Clay	Loam
Fertility	Intermediate-high	Low
Base saturation, %	40-50	20-35
Cationic exchange capacity, mEq 100 g^{-1} soil	18-20	11-30
Organic matter, %	1-10	1-15%
Color	Dark brown to dark yellowish brown	Black to yellowish brown
Structure type	Subangular blocky and crumby	Angular and subangular blocky
Class structure	Intermediate to fine	Fine
Degree structure	Moderate to strong	Moderate to strong
Internal drainage	Slow	Rapid
External drainage	Rapid	Rapid
Presence of pores	Abundant and fine	Abundant and fine
pH	5.0-6.2	4.2-6.0

weight (W1) was recorded, soil samples dried, and the dry weight (W2) used to determine the bulk density (BD) with the formula: BD (g cm^{-3}) = (W1-W2)/internal volume of cylinder. Carbon contents were calculated as follows:

$$\text{Soil C (t ha}^{-1}) = \%C \times BD \times T \times A \times 100$$

where, %C is percentage C, BD is bulk density (g cm^{-3}), T is thickness of sampling layer (10 cm), A is area considered (1 ha).

At those sites where vegetation type changed from C_3 photosynthesis (coffee plantations and mature fallow lands) to C_4 photosynthesis (pastures and sugarcane crops) and vice versa, the contribution of each type of vegetation to the total percentage organic C was calculated using the formulas:

$$C_{C3} = \left(\frac{(\delta^{13}C_{SC3} - \delta^{13}C_{SC4})}{(\delta^{13}C_{VC3} - \delta^{13}C_{SC4})} \times \%C \right)$$

$$C_{C4} = \left(\frac{(\delta^{13}C_{SC4} - \delta^{13}C_{SC3})}{(\delta^{13}C_{VC4} - \delta^{13}C_{SC3})} \times \%C \right)$$

where C_{C3} is C derived from C_3 vegetation, C_{C4} is C derived from C_4 vegetation, $\delta^{13}C_{SC3}$ is natural abundance of ^{13}C measured in soil with C_3 vegetation, $\delta^{13}C_{SC4}$ is natural abundance of ^{13}C measured in soil with C_4 vegetation, $\delta^{13}C_{VC3}$ is natural abundance of ^{13}C in C_3 vegetation (-26‰), $\delta^{13}C_{VC4}$ is natural abundance of ^{13}C in C_4 vegetation (-12‰).

After calculating the contribution to the percentage total organic C, C storage fixed by each type of vegetation was estimated as follows:

$$\text{Stored C derived from } C_3 \text{ vegetation (t ha}^{-1}) = \%C_{C3} \times BD \times D$$

$$\text{Stored C derived from } C_4 \text{ vegetation (t ha}^{-1}) = \%C_{C4} \times BD \times D$$

where $\%C_{C3}$ is percentage C derived from C_3 vegetation, $\%C_{C4}$ is percentage C derived from C_4 vegetation, BD is bulk density (g cm^{-3}), and D is sampling depth (cm).

Data analysis

Information on the land use history of each sampled field was gathered to identify changes over time and then calculate organic matter turnover rates (% yr^{-1}), relating the $\delta^{13}C$ to the establishment time of each system.

Nonparametric ANOVA-the Kuskal Wallis test for independent samples- was used to determine the natural abundance of ^{13}C, using the SPSS program version 10.0 (SPSS, 1999). This allowed significant differences ($p < 0.05$) between sampling strata or areas, between sampling depths, and between land uses to be determined.

RESULTS

Variation of C with changes in land use and altitude above sea level

Altitude above sea level affects the organic carbon retained in the soil. The largest total storage of C (0-30 cm) were found in the highlands of Alcalá (1450-1600 m a.s.l.), with values ranging between 102.67 and 123.64 t ha^{-1}; in the mid-altitude area these values ranged between 43.08 and 105.40 t ha^{-1} and in the lowlands, between 41.75 and 92.33 t ha^{-1}.

In terms of land use, the greatest accumulation of C occurred in plantain (137.97 t ha^{-1}), coffee-banana-cassava (134.90 t ha^{-1}), and giant bamboo (130.43 t ha^{-1}) in the upland area; mature fallow land (43.08 t ha^{-1}) in the mid-altitude area; and giant bamboo-cacao (41.75 t ha^{-1}) in the lowlands. Soils, despite having the same land use, modified the amount of C fixed depending on the altitude. Considerable reductions were recorded. For example, a difference of 59.59 t ha^{-1} accumulated C was observed between mature fallow land in the highlands and mature fallow land in the lowlands. This trend was also observed in the other land uses present in the evaluated strata. The lowest amounts of accumulated C occurred in the altitudinal range of 1150-1300 m a.s.l. (Table 2).

On the other hand, altitude above sea level did not affect the natural abundance of ^{13}C, presenting a low correlation coefficient (-0.2) and absence differences ($p < 0.05$) between sampling areas. The average values of abundance of this isotope ranged between -25.18 and -21.72‰ for all uses evaluated. None of obtained values were similar to those of tropical pastures (-12‰ on average), emphasizing the predominance of C_3 plants in C fixation in the soil.

Organic matter turnover rates

Of the 96 sampled sites, 27 presented changes from C_3 to C_4 vegetation and vice versa. The regrowth of vegetation was allowed at three upland sites that had been used as paddocks over a 60-yr period; the land transformed into mature fallow lands after 13 yr. Sugarcane crops that had been established for 2 yr were found at three lowland sites that had previously been planted to coffee. The remaining 21 samplings were performed in pastures, 1 to 17 yr old that have previously been planted to coffee.

The $\delta^{13}C$ of sites that had undergone a change in vegetation ranged between -25.31 and -18.82‰ for the depth of 0-10 cm; between -25.00 and -21.21‰ for the depth of 10-20 cm; and between -25.42 and -20.05‰ for the depth of 20-30 cm. Pastures and sugarcane crops conserved the C from the coffee plantations, whereas the mature fallow lands with $\delta^{13}C$ values close to those of C_3 vegetation (-26‰ on average) showed that, within a 13-yr period, they managed to replace the C derived from pastures over a 60-yr period.

The turnover rates of organic C in the soil at the three depths ranged between 0.3-20.9% yr^{-1}. The rapidness with which pastures stabilized C was evidenced in the three 1-yr pastures and in the three 2-yr sugarcane crops, decreasing over time until a minimal rate was found in the 17-yr-old pasture (Pa19).

The highest turnover rates were recorded in Pa3 at depths of 10-20 and 20-30 cm (20.1 and 19.3% yr^{-1}, respectively), attributable to root system architecture. High turnover rates were also observed at the three depths of several sugarcane samplings (Cn1, Cn2), presenting values of 16.5 and 16.2% yr^{-1} at 0-10 cm, 14.4 and 11.9% yr^{-1} at 10-20 cm, and 13.9 and 11.5% yr^{-1} at 20-30 cm (Table 3).

At seven sites corresponding to mature fallow land (Mfl1), cut-and-carry grass (Ccg) and pastures (Pa1, Pa4, Pa6, Pa7), the natural abundance of ^{13}C tended to increase with depth (less negative values), as well as the organic matter turnover rates, contrary to other mature fallow lands (Mfl3, Mfl4), pastures (Pa10, Pa15, Pa16, Pa17) and sugarcane (Cn2, Cn3).

Table 2. Average storage of C according to land use in upper 0-30 cm of soil.

Land use	n	Natural abundance of ^{13}C (‰) Average	SD	Storage of C (t ha^{-1}) Average	SD
Highlands (1450-1600 m a.s.l.)					
Mature fallow land	6	-23.74	1.41	102.67	15.29
Coffee var. Colombia	8	-23.99	0.79	120.32	15.41
Coffee-cassava	1	-23.60	-	114.78	-
Fallow land	3	-24.48	0.63	121.11	17.91
Plantain	1	-24.68	-	137.97	-
Coffee-plantain	4	-24.50	0.77	122.94	9.64
Pasture	2	-23.79	0.00	118.01	5.49
Coffee-plantain-cassava	1	-23.80	-	134.90	-
Giant bamboo	3	-25.18	0.52	130.43	8.51
Coffee under shade	2	-24.81	0.06	125.13	18.79
Coffee var. Caturra	1	-23.56	-	123.64	-
Mid-altitude area (1300-1450 m a.s.l.)					
Mature fallow land	1	-21.27	-	43.08	-
Coffee variety Colombia	6	-24.24	0.53	101.39	24.49
Fallow land	2	-24.30	0.33	105.18	7.69
Plantain	1	-24.21	-	78.15	-
Coffee-plantain	8	-24.52	0.60	89.79	28.02
Pasture	5	-22.85	1.36	82.52	22.35
Giant bamboo	1	-24.99	-	87.90	-
Fruit trees	1	-24.54	-	105.40	-
Coffee var. Caturra	4	-23.74	0.20	80.08	7.66
Cut-and-carry grass	1	-24.84	-	101.48	-
Coffee-plantain -citrus fruits	1	-23.88	-	85.14	-
Coffee-citrus fruits	1	-21.72	-	63.98	-
Lowland area (1150-1300 m a.s.l.)					
Fallow land	2	-24.12	0.70	62.18	16.30
Plantain	1	-23.94	-	45.48	-
Coffee-plantain	1	-24.48	-	68.28	-
Pasture	12	-23.01	1.00	64.53	13.28
Giant bamboo	3	-24.88	0.80	58.24	15.61
Coffee under shade	1	-24.96	-	61.58	-
Fruit trees	2	-24.37	0.20	57.85	6.21
Coffee var. Caturra	5	-23.93	0.80	92.33	22.46
Giant bamboo-cacao	1	-23.87	-	41.75	-
Heliconias	1	-24.40	-	83.28	-
Sugarcane	3	-22.13	1.10	80.31	30.60

SD: Standard deviation.

Origin of soil organic carbon

In mature fallow land, the total average % C ranged between 5.57 and 6.81%, and the highest proportion was derived from C_3 vegetation. Of the four sites evaluated, Mfl3 presented the highest percentage of C derived from C_4 vegetation (26.8%). Two more sites (Mfl1 and Mfl2), despite being geographically close and presenting similar land use histories, differed in the amount of C contributed by the vegetation, mainly because the turnover rates in Mfl3, at all three depths, were lower than those of the other three mature fallow lands.

Total C storage in fallow land ranged between 93.26 and 118.02 t ha^{-1}, the highest value corresponding to Mfl4 where 104.17 t ha^{-1} were derived from C_3 vegetation and only 13.85 t ha^{-1} from C_4 vegetation (Figure 2). A predominance of C fixed by C_3 plants, which ranged between 62 and 91.7%, was observed at sites where grasses were present. At sites presenting pastures in which vegetation changes had occurred over a period of 1 to 7 yr, the percentage of total C tended to be higher, decreasing with increasing time of establishment. The storage of C was higher in Pa7, where 101.57 t ha^{-1} were derived from previously existing coffee crops and only 20.31 t ha^{-1} from pastures with 7 yr of establishment (Figure 3).

Table 3. Organic matter turnover rates at sites with changes in vegetation from C_3 photosynthesis to C_4 photosynthesis or vice versa.

Site	Current use	Time (yr)	Prior use	$\delta^{13}C$ in soil (‰)			Organic matter turnover rate (% yr^{-1})		
				0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Mfl	Mature fallow land	13	Pasture	-25.08	-25.00	-24.11	6.3	6.3	5.9
Mfl2	Mature fallow land	13	Pasture	-23.70	-24.43	-23.76	5.7	6.0	5.7
Mfl	Mature fallow land	13	Pasture	-20.64	-22.65	-23.44	4.2	5.2	5.5
Mfl	Mature fallow land	13	Pasture	-23.54	-24.50	-25.42	5.6	6.1	6.5
Ccg	Cut-and-carry grass	1	Coffee	-25.31	-24.97	-24.24	4.3	6.5	11.1
Pa1	Pasture	1	Coffee	-24.79	-24.26	-24.25	7.6	11.0	11.0
Pa2	Pasture	1	Coffee	-23.40	-22.68	-23.18	16.3	20.9	17.8
Pa3	Pasture	1	Coffee	-23.99	-22.80	-22.94	12.7	20.1	19.3
Pa4	Pasture	3	Coffee	-24.28	-24.17	-21.46	3.6	3.8	9.5
Pa5	Pasture	4	Coffee	-22.68	-23.47	-23.22	5.2	4.0	4.4
Pa6	Pasture	4	Coffee	-24.13	-23.64	-23.59	2.9	3.7	3.8
Pa7	Pasture	7	Coffee	-22.85	-24.22	-24.29	2.8	1.6	1.5
Pa8	Pasture	9	Coffee	-23.55	-24.05	-20.05	1.7	1.4	4.2
Pa9	Pasture	9	Coffee	-22.01	-22.53	-21.82	2.8	2.4	2.9
Pa10	Pasture	9	Coffee	-21.21	-21.61	-22.37	3.4	3.1	2.5
Pa11	Pasture	9	Coffee	-19.90	-22.20	-22.09	4.3	2.7	2.7
Pa12	Pasture	9	Coffee	-22.96	-23.80	-23.80	2.1	1.5	1.5
Pa13	Pasture	9	Coffee	-23.11	-24.76	-24.67	2.0	0.9	0.9
Pa14	Pasture	9	Coffee	-24.51	-24.37	-23.77	1.0	1.1	1.6
Pa15	Pasture	9	Coffee	-21.97	-22.40	-23.67	2.8	2.5	1.6
Pa16	Pasture	9	Coffee	-21.69	-22.85	-23.44	3.0	2.2	1.8
Pa17	Pasture	10	Coffee	-18.82	-21.21	-22.05	4.5	3.0	2.5
Pa18	Pasture	10	Coffee	-21.14	-23.73	-23.60	3.1	1.4	1.5
Pa19	Pasture	17	Coffee	-25.16	-24.33	-24.36	0.3	0.6	0.6
Cn1	Sugarcane	2	Coffee	-23.72	-24.64	-21.61	7.2	4.3	13.8
Cn2	Sugarcane	2	Coffee	-20.76	-21.43	-21.58	16.5	14.4	13.9
Cn3	Sugarcane	2	Coffee	-20.85	-22.22	-22.36	16.2	11.9	11.5

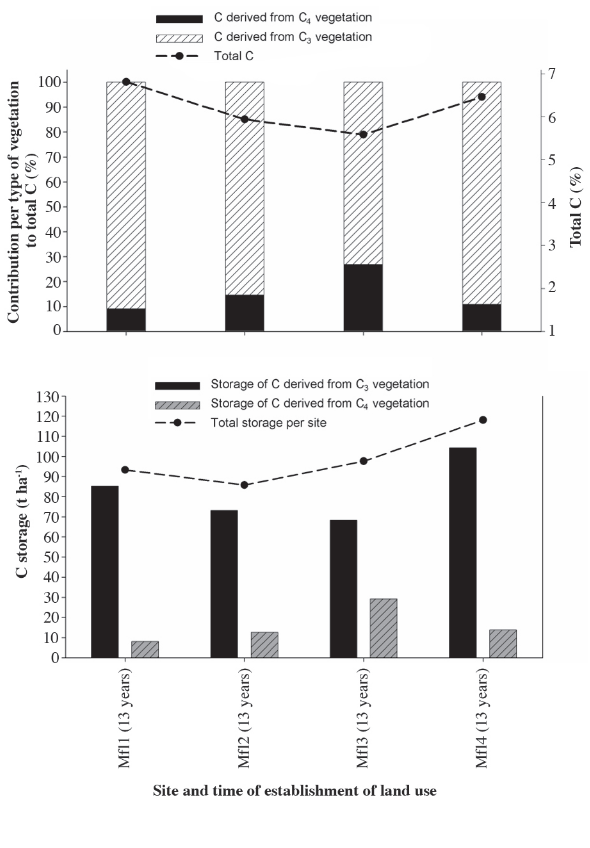

Figure 2. Origin and storage of C (0-30 cm) at sites presenting changes from C_4 vegetation to C_3 vegetation. Mfl: Mature fallow land.

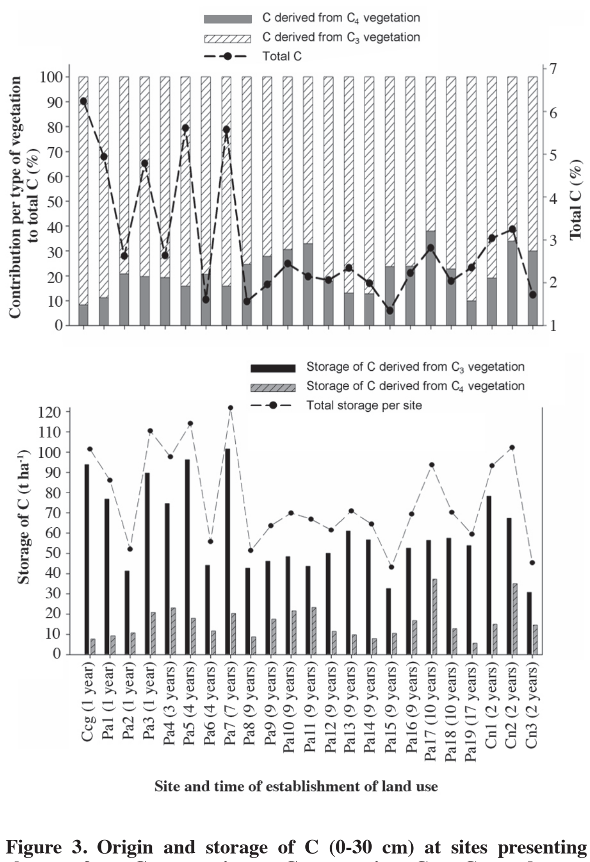

Figure 3. Origin and storage of C (0-30 cm) at sites presenting changes from C_3 vegetation to C_4 vegetation. Ccg: Cut-and-carry grass, Pa: pasture, Cn: sugarcane.

DISCUSSION

The estimation of soil C storage was complemented with the calculation of organic matter turnover rates, because according to Solomon et al. (2002) and Desjardins et al. (2006), the change in land use alters the speed at which the organic molecules oxidized, therefore affecting its accumulation and mineralization. Oelbermann and Voroney (2007) assert that those turnover rates are key to understanding the dynamics of terrestrial carbon and may even allow the C flow between soil and atmosphere to be calculated at a given moment. Therefore the ^{13}C technique is increasingly important in studies on soil C because it allows different time scales, which can range from 1 to several hundreds of years, to be evaluated (Bernoux et al., 1998). In the case of this study, the rates at sites with different land use histories, where changes of vegetation occurred over a period from 1 to 17 yr, were calculated. In addition, the use of stable C isotopes was a tool that prevented erroneous conclusions being made about the sites that had undergone changes in vegetation. If the evaluation had only taken into account the results obtained with the dry combustion method, then C storage would have been attributed to current land uses when they are actually product of the C fixed by previous vegetation.

Although tropical pastures contain C_3 grasses that make considerable contributions to isotopic signals, this study as well as that conducted by López-Ulloa et al. (2005) assumed that the highest contribution came from grasses, indicating the usefulness of identifying the C contributed by the pasture and evaluating the capacity of C_4 plants to stabilize and fix C.

Diels et al. (2001), on the other hand, recognize that the use of the technique to determine the natural abundance of ^{13}C has been limited to situations presenting an abrupt transition of C_3 vegetation to C_4 vegetation or vice versa. When combined with models to determine soil organic C such as CENTURY (Parton et al., 1987) or ROTHC (Jenkinson et al., 1992), the signals of this isotope could potentially be used to forecast changes in more complex situations where no drastic changes have occurred or in systems where both two types of vegetation are found mixed together.

At 24 of the 96 sites that were sampled, the type of photosynthesis of the vegetation changed when coffee plantations were replaced with pastures or sugarcane. The organic matter at these sites had not yet been stabilized because signals of ^{13}C fixed by previous vegetation were found. This is why it is important to relate the estimation of the natural abundance of ^{13}C with the farmers' knowledge of transformations in land use at each sampling site so as not to overestimate capacity of grasses to capture C.

The ^{13}C values in the three sampling areas were less negative at the depth of 20-30 cm; however, in relation to land use, the ^{13}C did not increase with depth in seven of them, whereas this trend was maintained in the remaining 11. Coffee-plantain, coffee under shade, and fruit trees presented differences ($p < 0.05$) in ^{13}C values between the depths of 0-10 and 20-30 cm, with variations above 1 unit (‰). The findings of Sisti et al. (2004) agree with the above results and indicate that soil organic matter at deeper depths has a higher humus content, which explains the higher ^{13}C values with increasing depth in the soil profile. Differences between 1 and 2 units (‰) are found between the surface layer and 100-cm depth. In this study, however, changes of this magnitude were also found between the surface layer and 30-cm depth. The same authors put forward that the factors responsible for these increases with depth could be related to the increased use of fossil fuels with low abundance of ^{13}C over the past 150 yr, decreasing by at least 1.3% the average ^{13}C in the atmosphere. Furthermore, soil organic matter is increasingly older with increasing depth, so it is possible that the C previously introduced into the soil via photosynthesis has higher ^{13}C values. Rao et al. (1994) indicate that another possible cause of this phenomenon could be the preferential decomposition in deeper soil layers, with components or molecules with low ^{13}C values being removed first.

Sites with pastures that are 9, 10, and 17-yr old yielded ^{13}C values that varied between -18.82 and -25.16‰ at the three depths, showing a predominance of C from coffee plantations (C_3). In an area with predominance of Oxisols and an average temperature of 26 °C (Carimagua, Colombia), Rao et al. (1994) found, on the contrary, that 12-yr-old pastures that presented a quick organic matter turnover rate with ^{13}C values ranging between -12.08 and -13.26‰, indicating that the C in these soils had been derived from pastures (C_4). The foregoing shows that soil type and temperature could affect the increase in organic matter turnover rate, indicating a regional effect on C dynamics and, as a result, greater susceptibility of soil C to land use changes in a given area.

Manfrinato et al. (2001) conducted a study on native tropical rainforest, a 20-yr-old pasture, and pastures that had been abandoned for 5 or 10 yr and found ^{13}C values of -27.74, -22.90, -25.10, and -26.49‰, respectively, at a depth of 0-10 cm. Results indicated the following: the area under native vegetation presented the highest values corresponding to C_3 vegetation; ^{13}C value of the 20-yr-old pasture had still not reached the values of C_4 vegetation (on average 14‰); and abandoned pasture colonized by shrub and tree vegetation tended to present more negative values similar to those of initial vegetation. Turnover rates in these areas were lower than those found in Alcalá, where pastures 9 and 10 yr old presented values of -19.90‰ (Pa8-lowlands), with an organic matter turnover rate of 4.3% yr^{-1}.

All sites were observed to have a high capacity to stabilize organic matter, contrary to that reported in sandy soils of South Africa, where soils have little potential for stabilization of organic matter (Lobe et al., 2005). In this study, in abandoned pastures presenting successive tree vegetation, ^{13}C values at all depths after 13 yr ranged between -20.64 and 25.42%, being closer to the average of C_3 vegetation (-26%) than to that of C_4 vegetation (-14%). Outliers were found at lowland sites Pa11 (0.3% yr^{-1}) and Pa13 (1.0% yr^{-1}). These values were lower than those found by Roscoe et al. (2001) in Brazil where pastures, 23 years after establishment, had only managed to replace 36% C from native vegetation, indicating a turnover rate of 1.6% yr^{-1}, which is regarded as fast and notably differs from rates found at sites such as Cn29 and Cn30, where transformation occurred at a rate 16.5 and 16.2% yr^{-1}, respectively.

The high percentage of C derived from C_3 plants at sites with pastures of several years, compared with that of fallow land in highlands with little C from C_4 plants, indicates that the C deposit from C_3 vegetation is recalcitrant, while that corresponding to C_4 vegetation has a relatively fast rate of return (Lemenih et al., 2005; Liao et al., 2006).

Michelsen et al. (2004) in Ethiopia as well as Krull and Skjemstad (2003) and Wynn et al. (2005) in Australia found that the abundance of ^{13}C increased —in other words, presented negative less values— from the surface downward to the deepest soil layers. These findings are consistent with the isotope theory that states that respiratory losses of isotopically-light C during decomposition cause that, with depth, the residual C (in other words, the oldest) is enriched with isotopes. The increase in ^{13}C in the lower layers also indicates the preferential loss of ^{12}C molecules through kinetic fractionation during biological transformation (Krull et al., 2006).

In the Brazilian Amazon region, Desjardins et al. (2004) found ^{13}C values ranging between -28.9 and -27.3‰ in natural forests; -28.0 and -25.8‰ in 4-yr-old pastures; -25.9 and -22.2 in 8-yr-old pastures; and -24.4 and -20.3‰ in 15-yr-old pastures. These results show the effect of pastures on the isotope over time. In Costa Rica, Oelbermann et al. (2006) conducted studies in both agro-forestry systems and monocultures, finding that fertilizer application or use of N-fixing plants as plant cover did not directly affect C turnover rates in the soil. Therefore the application of the ^{13}C technique indicated that changes in isotopic signals were directly related to the type of vegetation contributing plant residues to the soil surface.

CONCLUSIONS

The use of stable C isotopes was a tool that prevented erroneous conclusions being made about the sites that had undergone changes in vegetation. If the evaluation had only taken into account the results obtained with the dry combustion method, then C storage would have been attributed to current land uses when they are actually product of the C fixed by previous vegetation. Besides, we conclude that the knowledge of transformations in land use at each sampling site was a key factor to prevent overestimating the capacity of grasses to capture C.

In general, the soils of the Municipality of Alcalá have relatively fast turnover rates, showing a high capacity to stabilize organic matter, especially at sites where pastures were abandoned. On the other hand, the natural abundance of ^{13}C was a chemical property of the soil that was related to the predominant type of vegetation at sampling sites and not to biophysical factors, such as altitude above sea level. The values of this isotope increased with soil depth due to the age of the organic matter and to selective decomposition processes in which isotopically light C is degraded first.

Mature fallow lands were found to have a greater capacity to stabilize high C stabilization capacity, because within a period of 13 yr, these soils could replace more than 70% of the C that had been fixed by pastures over a 60-yr period; while the maximum C that these latter pastures could replace in periods of establishment up to 17 yr was 37.9% of the C fixed by coffee plantations over periods of 50-100 yr.

The last shows the importance of C_3 vegetation on C cycle, because it fixes great quantities of soil C and potentiates its storage during long periods. Therefore we conclude that C deposit from C_3 vegetation is recalcitrant, while that corresponding to C_4 vegetation has a relatively fast turnover rate.

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