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Soil organic carbon dynamics under different tillage systems in rotations with perennial pastures

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ABSTRACT

Physical fractionation and ^{13}C determinations are useful techniques for soil organic carbon (SOC) dynamics studies. Changes in SOC content, distribution and origin were assessed after 9.5-year crop-perennial (C3 species) rotation on a Uruguayan Mollisol under conventional tillage (CT) and no-tillage (NT). Soil samples were collected at depths of 0–6, 6–12 and 12–18 cm in 1994 and 2003. Determinations were made of total SOC, particulate organic matter C (POM-C) and mineral-associated organic matter C (MAOM-C). In addition, ^{13}C determinations were made on the total sample and the different particle size fractions. None of the studied variables were affected significantly by the tillage system. SOC levels in 2003 did not differ significantly from those of 1994 at any of the studied depths. However, changes were found in fraction distribution. Within 0–18 cm of the soil surface, POM-C decreased by 63%, whereas MAOM-C did not vary significantly. After 9.5 years, only 14.5% of SOC within 0–18 cm of the soil surface was young SOC. The largest proportion was incorporated within 0–6 cm of the soil surface and in the coarsest physical fractions of organic matter. Only 17% of the estimated C input from crops for the study period was retained by the topsoil. The estimated half-life of SOC within the upper 18 cm of soil was 28 years. Within this layer, the C half-life varied from less than 5 years for POM-C to more than 400 years for MAOM-C. These results suggest that agricultural rotation systems including perennial pastures are capable of maintaining SOC levels even under CT. However, C cycling and other ecosystem processes may be altered due to the significant loss of labile organic matter. The use of ^{13}C analysis enabled the estimation of parameters relevant to the modeling of SOC dynamics.

1. Introduction

The soil organic carbon (SOC) stock results from the balance between inputs resulting from the decomposition of plant and animal residues and outputs due to erosion and microbial oxidation (Alvarez and Steinbach, 2006a; Urquiaga et al., 2007). Residue decomposition rates depend largely on the physical and biochemical characteristics of each type of organic material, as well as on the interaction of the latter with the mineral fraction and microorganisms occurring in a particular soil type, in addition to the environmental conditions, mainly temperature and moisture (Urquiaga et al., 2007).

Traditionally, research into SOC dynamics has focused on determining the productive functions of soil. Over the past decades, however, the environmental potential of soil dynamics has also gained in importance, since soil can act as either a source or a sink of CO_2, a greenhouse gas (Balesdent and Mariotti, 1996; Urquiaga et al., 2007).

Not only may a certain soil management procedure result in net SOC gains or losses but it can also lead to changes in the composition of soil organic matter, even if no significant changes in SOC content are to be detected. Determinations of ^{13}C have been used in several SOC studies (Gregorich et al., 1995; Balesdent and Mariotti, 1996; Andriulo et al., 1999a; Collins et al., 1999; Urquiaga et al., 2007). This technique is based on the difference between the ^{13}C proportion of C_3 species and that of C_4 species (average $\delta^{13}C$: −27‰ and −12‰, respectively) and on the fact that SOC retains the $\delta^{13}C$ signal of vegetation. Thus, a change in the photosynthetic cycle of vegetation growing on a soil will be reflected in a change in the isotopic composition of SOC. Based on the above, the origin of organic matter may be traced, and the path and dynamics of its transformations studied (Balesdent and Mariotti, 1996).

The physical fractionation of soil organic matter (SOM) according to particle size or density has also been used in several SOC studies (Christensen, 2001; Urquiaga et al., 2007). Experimental physical fractionation efforts have been aimed at isolating SOM pools according to turnover rates. Those SOM fractions

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corresponding to the size of the coarsest soil particles (sand size), referred to as particulate organic matter (POM), consist of only partially decomposed plant material with a C/N ratio nearly as high as that of the starting plant material and a higher decomposition rate than that associated with silt and clay carbon (Christensen, 2001). The coarse fractions have been demonstrated to be more sensitive to changes associated with soil use and management (Cambardella and Elliot, 1992; Bayer et al., 2001; Morón and Sawchik, 2003; Galantini et al., 2004). The quantification of the progressive incorporation of new C into the different SOC fractions enables the elucidation of the transformation and stabilization paths of organic carbon (Balesdent and Mariotti, 1996).

Generally, ^{13}C determinations and physical fractionation methodologies have been used to assess the effect of vegetation changes (C_3 to C_4 species, or vice versa), based on monoculture studies. In contrast, crop-pasture rotation systems are commonly used for grain and livestock production in Uruguay (García Préchac et al., 2004). Traditionally, soil tillage has been used before each crop and at pasture planting. Over the past decades, the expansion of no-tillage systems has enabled a reduction in the amount of tillage, minimizing SOM losses due to mineralization and erosion. Although several studies have focused on how these systems contribute to changes in the SOC stock (Morón, 2003; Terra et al., 2006; Salvo et al., 2010), little has been reported on the contributions of new crop and pasture vegetation to the total SOC stock or its individual fractions.

Therefore, the objective of this study was to quantify the change in SOC content, distribution and origin after a 9.5-year crop-pasture (C_3) rotation under conventional tillage (CT) and no-tillage (NT) on a soil with a history of several cops under CT.

2. Materials and methods

2.1. Experimental conditions and management procedure

This study was conducted within the framework of an ongoing long term field trial iniciated 1993, at the Mario A. Cassinoni experimental station of Uruguay's Universidad de la República (Faculty of Agronomy). Located at a 10-km distance from the city of Paysandú (32°21′S 58°02′W), the Station is comprised within a sub-humid region with annual, winter and summer average temperatures of 17, 12 and 24 °C, respectively. The soil at this site is classified (USDA) as a fine, mixed, active, thermic Typic Argiudoll on a slope of less than 1% with an A horizon 18 cm deep, $pH_{(H2O)}$ 5.7 (soil water relation v:v = 1:2.5), and clay, silt and sand contents of 289, 437, 273 g kg^{-1}, respectively.

The framework experiment combines different crop-pasture rotations with CT and NT (Salvo et al., 2010). Among these rotations, that with the highest proportion of C_3 species during the period from 1994 to 2003 (treated under both CT and NT) was selected for this study.

In a distant past, the natural vegetation of the experimental site was a mixture of C_3 and C_4 species. The highest occurrence and abundance were observed, among C_4 species, for *Botriochloa laguroides* DC., *Paspalum dilatatum* Poir., *Paspalum notatum* Flűgge and *Setaria vaginata* Spreng, and, among C_3 species, for *Briza subaristata* Lam., *Bromus auleticus* Trin., *Bromus catharticus* Vahl., *Piptochaetium stipoides* Hack., *Stipa hyalina* Nees, *S. megapotamica* Spreng, *Sterculia setigera* Presl. (García et al., 2005). The soil cover prior to the commencement of this study may be characterized according to the following two periods. Over the 1970–1986 period, crop-pasture rotations under CT included C_3 and C_4 species. Then, the plot was planted with perennial pastures of C_3 species (*Festuca arundinacea* Schreb., *Lotus corniculatus* L. and *Trifolium repens* L.), which had progressively been invaded by *Cynodon dactylon* (a C_4 species) by the start of the experiment (1993).

Table 1
Crop sequences of crop-pasture rotations under CT and NT from 1993 to 2003.

Year	Winter crop	Summer crop
93/94	Barley	Sorghum
94/95	Wheat	Sunflower
95/96	Wheat with PP[a]	PP
96/97	PP	PP
97/98	PP	PP
98/99	Fallow	Corn
99/00	Wheat	Fallow
00/01	Wheat	Soybean
01/02	Fallow	Sunflower
02/03	Wheat with PP	PP
2003	PP	–

PP: perennial pasture (*Festuca arundinacea* Schreb., *Lotus corniculatus* L. and *Trifolium repens* L.).
[a] Pasture was sod together with wheat to reduce sawing costs. Wheat is harvested for grain, after which pasture is grazed.

The crop-pasture rotation used in the experiment consisted of three years of crops (two crops per year) and three years of livestock-grazed pastures (Table 1). A chisel plow and an excentric disk harrow were used for CT at a depth of 15–20 cm. On average, four plowing operations were used for soil preparation in winter, while two operations were used for summer crops. Agrochemical management (fertilizers, herbicides, insecticides and fungicides) was conducted according to the requirements of each tillage system.

Wheat (*Triticum aestivum* L.) (C_3) and barley (*Hordeum vulgare* L.) (C_3) were cultivated in winter, and sunflower (*Helianthus annus L.*) (C_3) and soybean (*Glycine max* L.) (C_3) in summer (Table 1). Pasture mixes included *F. arundinacea* Schreb., *L. corniculatus* L. and *T. repens* L., which were cultivated between 1995 and 1998 (first cycle) and from 2002 to 2003 (first year of the second cycle). Only two C_4 crops were seeded during the study period: sorghum in the 93/94 summer (South hemisphere) and corn in the 98/99 summer (Table 1). A randomized complete block design with three replications was used for the analysis. Plot size was 10 × 50 m.

2.2. Sampling and measurements

Soil samples were collected in January 1994 (summer in the southern hemisphere) before Sorgum harvest, for the two tillage types at depths of 0–6, 6–12 and 12–18 cm. At the end of the first year of pastures, in June 2003, the soil was sampled again at depths of 0–3, 3–6, 6–12, 12–18 cm. Prior to collecting each sample, aboveground crop residues were removed from the soil surface. Samples were composed of 20 cores per plot. At each soil depth, undisturbed samples were collected to determine bulk density. To such end, ring samplers 3 cm high and 5.4 cm wide were used, which were introduced vertically in the soil. Three replicates per plot were collected.

Soil samples for carbon analysis were sieved to less than 2 mm and physically fractionated according to Cambardella and Elliot (1992), separating coarse and fine particulate organic matter (POM-C > 200 μm, POM-C > 50 μm, respectively) from mineral-associated organic matter (MAOM-C; smaller than 50 μm). Carbon content and ^{13}C isotopic abundance were determined for each depth and size fraction by dry combustion (IRMS Thermo Finnigan Delta Plus coupled to a Flash EA 112 elemental analyzer). The C recovery from the three fractions averaged 90% of total SOC. MAOM-C was calculated as the difference between total SOC and POM-C.

Natural ^{13}C abundance, expressed in delta (δ) units, indicating the isotopic ratio of the sample relative to that of the Pee Dee