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Soil organic matter dynamics along a rice chronosequence in north-eastern Argentina: Evidence from natural ^{13}C abundance and particle size fractionation

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Abstract

We studied the consequences of rice cultivation and its subsequent abandonment for soil organic matter (SOM) dynamics in north-eastern Argentina. Two chronosequences, which included a pristine grassland with C4 vegetation as a control, and several stages of rice (C3) fields abandoned for 1, 2, 4, 6 and 15 years were selected, and soil samples from the first 10 cm were gathered from each plot. Natural ^{13}C abundance coupled with particle-size fractionation were employed to characterize SOM changes through time discriminated by SOM origin. Soil samples up to 50 cm were also collected throughout one chronosequence. Most changes in SOM occurred on the first 20 cm layer and, bulk density, carbon and nitrogen content, as well as $\delta^{13}C$ remained similar at greater depths. After the rice cropping, the bulk density was slightly greater than in the natural grassland, and remained stable after the abandonment. Carbon and nitrogen contents remained almost stable in the surface layer during the cultivation. $\delta^{13}C$ varied accordingly with the changes in vegetation cover with a C4 signature in the natural grassland and mainly a C3 signature in the rice fields. The abandonment of the rice cropping induced a decrease of the soil organic matter content, mainly of natural grassland origin, during the first 4 years. When the abandonment extended, the SOM content (from C4 origin) increased slowly and after 15 years, was almost the same as that of the natural grassland. The carbon turnover was greater in the coarser fractions than in the finer ones, confirming that soil organic carbon in the sand fraction was relatively labile. However, all the fractions were affected by inputs and outputs of C derived from rice and natural grassland. This fact could indicate that the former protected carbon could become less stable due to cultivation.

Keywords: Argentina; Natural grassland; Rice fields; Soil organic matter; Stable carbon isotope; Turnover

1. Introduction

Soil organic matter (SOM) plays an important role for soil fertility because it influences many soil properties which are vital for soil functioning (Feller and Beare, 1997). It is a source of energy for the soil biota and simultaneously a source and a sink for nutrient elements; it has charge properties which make it a site of ion exchanges, and its chemical and physical properties promote aggregation with mineral particles, governs the structure stability and influence soil water regimes (Swift and Woomer, 1993).

The level of organic matter in soil is determined by the equilibrium between the factors that determine its formation and those which promote its breakdown (Greenland and Nye, 1959). Among those factors, the influence of the abiotic conditions of the soil as well as the presence of key

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organisms related to decomposition processes have a paramount importance (Brussaard et al., 1997). The quality and quantity of the organic matter changes according to the aboveground vegetation, and this is commonly observed when natural vegetation is replaced by agriculture (Tilman et al., 2002). In fact, the change in land use also alters the speed at which the organic molecules oxidized, therefore affecting its accumulation and mineralization (Solomon et al., 2002). Comparisons of cultivated and uncultivated soils have demonstrated a reduction in soil organic matter with cultivation in most of the studies (Mann, 1986). However, the anaerobic conditions imposed in waterlogged soils, such as irrigated rice fields, lead in general to a delay in soil organic matter mineralization producing its accumulation (Neue et al., 1997).

SOM dynamics can be studied in several ways. For example, various chemical fractionation and characterization methods have been commonly used in the last decades (Stevenson and Elliot, 1989). However, since 1985, the use of ^{13}C natural abundance technique, coupled with particle-size fractionation allowed great progress in SOM turnover studies (Cerri et al., 1985; Sevink et al., 2005). These methods are well suited to study soil organic carbon dynamics over time when natural or anthropogenic changes of vegetations from different metabolic pathways (C3 and C4) occurred (Solomon et al., 2002). The method, based on the fact that plants with C3 and C4 photosynthetic cycles differ in their $\delta^{13}C$, has been extensively discussed in the literature (Balesdent et al., 1987; Boutton, 1996; Mariotti, 1991), and therefore will not be treated here.

In the subtropical region of North-eastern Argentina, in Corrientes Province, natural grasslands, characterized by C4 plants, have been used for cattle ranching since the last century. However, during the last decade, with the increasing availability of artificial water reservoirs, rice (C3 plant) production has become a common agricultural activity and, consequently, 20% of natural grasslands of that province have been converted into paddy rice fields. It is customary to cultivate rice for three or four consecutive cycles and later abandon these fields for several years, when the cost of fertilizers, used to compensate the decrease of fertility, became economically unfeasible. Work done in parallel to this has shown that paddy rice fields produce a reduction in soil porosity and an initial accumulation of SOM after the last rice harvest (Folgarait et al., 2003). It was also shown that this agricultural activity drastically changes the macrofauna community that colonizes the abandoned rice fields without recovering richness levels of control plots even after 15 years from the last rice harvest (Thomas et al., 2004).

The aims of this study were to evaluate the impact of rice cropping and abandonment on the quantity and turnover of soil organic matter in bulk soils and particle-size fractions by means of natural ^{13}C abundance measurements in north-eastern Argentina.

2. Materials and methods

2.1. Study site

The study was conducted in Mercedes Department, Province of Corrientes, Argentina (29°S, 58°W). The climate is wet sub-tropical, without a definite dry season; autumns (March and April) are rainy, springs (October and November) humid, and summers (December, January, and February) are hot and frequently wet; mean annual precipitation is 1270 mm and mean annual temperature is 20.1 °C (Fernández et al., 1993).

This study was performed on the farm "Aguaceritos" located north of Mercedes. This farm covers 21 000 ha mainly used for cattle ranching on pristine grassland vegetation dominated by *Andropogon lateralis* (Carnevalli, 1994). Around 1500 ha have been cultivated with rice and are now at different stages of abandonment. Additionally, every year several hundreds of hectares are being recultivated again in the same fields or in pristine grasslands. Rice is cultivated by flooding the field for three to four months during rice growth and then removing the surface water before harvesting. Generally the rice is cropped for 3 years then the field is abandoned.

Two chronosequences were selected. Each one consisted of a pristine natural grassland (NG), a rice field recently harvested (Ri) and rice fields abandoned since 1 (P1), 2 (P2), 4 (P4), 6 (P6) and 15 years (P15), respectively. The two chronosequences were chosen as replicates of each stage and the same sampling procedure was used in each one. The samples of the first and the second chronosequences were collected in July 2000 and in July 2002, respectively. The farthest away plots were approximately 10 km apart, whereas the closest were less than 1 km apart from each other. Part of the soil data corresponding to the natural grassland and the 2 years after rice harvest were published elsewhere (Folgarait et al., 2003); however, those are included in this paper to complete the chronosequence data.

A preliminary pedological survey was performed on several plots in this farm and the soil was characterized as alfisols (Soil Survey Staff, 1992). They are developed on a several meters thick clayey saprolite of calcareous sandstones. The main characteristics of the soils from natural grassland are given in Table 1. In plots after rice cultivation, large compact clods occurred in the ploughed layer and a distinct ploughpan appeared from 15 cm caused by mechanical farming. The following year, the whole topsoil appeared homogeneously compacted by cattle trampling and the upper limit of the ploughpan could no longer be macroscopically distinguished. Hydromorphy increased in cultivated plots relative to the natural grassland. As the period of abandonment increased, biogenic structures built by the macrofaunal activity appeared, the ploughpan became discontinuous and its thickness decreased.

Table 1
Main analytical characteristics of soil from natural grasslands

Depth (cm)	pH H_2O	CEC ($cmol_c\,kg^{-1}$)	Base sat. (% CEC)	Texture (%)		
				Sand	Silt	Clay
0–5	5.6	8.8	88.4	12.8	70.8	16.6
5–10	5.4	7.4	88.6	14.2	70.8	15.1
20–30	5.9	8.2	89.6	14.3	67.3	18.5
60–70	6.8	18.8	92.7	10.7	59.6	30.1

Data from Lesturgez (2000).

2.2. Total carbon and nitrogen content

Five composite samples of approximately 500 g corresponding to the 0–10 cm layer were collected manually from each plot. These samples were homogenized, air-dried and sieved at 2 mm.

Total soil organic carbon (C) and total nitrogen (N) were determined by dry combustion of an aliquot of the samples ground at 100 μm, using a «Fisons NA 1500CHN» autoanalyser. Results are shown in $mg\,g^{-1}$.

2.3. Particle-size fractionation

The fractionation method, adapted from Feller (1979) and Anderson et al. (1981) has been used on the five soil samples from the upper layer (0–10 cm) that were collected at each plot. Twenty grams of air-dried 0–2 mm sieved soil were first dispersed by mechanical shaking in 200 ml of water in the presence of 5 mm glass beads during 6 h. Sand-size plants fragments were separated simultaneously with sandy particles by wet-sieving. This procedure was used first for 200 μm and then repeated for 50 μm. Afterwards the 0–50 μm fraction was dispersed using a low-energy sonicator for 15 min. The 20–50 μm fraction was then separated by wet-sieving. Each of the 2–20 μm fractions and the 0–2 μm fractions were separated in water by sedimentation. Finally, all the fractions were oven-dried at 60 °C. The recovery of size separates ranged from 94% to 99% of the initial soil mass. By this method the soil was well but not totally dispersed: the sandy fractions amounted 20% of the soil (versus 13–14% by the mechanical analysis) and the clay fraction 11% (versus 15–17%). The carbon balance after fractionation was generally lower than 1 (0.97 ± 0.1).

2.4. Stable carbon isotopic analyses

C4 plants characterize natural grasslands in sub-tropical Corrientes Province whereas rice plants (*Oryza sativa*) have a C3 photosynthetic pathway. The change in plant cover due to the new agricultural activity offers a good opportunity to trace the fate of organic matter of different origins (Boutton et al., 1998; Deines, 1980).

The ^{13}C natural abundance of the CO_2 released by the CHN autoanalyser was measured with a mass spectrometer Fisons SIRA 10 Isotope Ratio MS (Girardin and Mariotti, 1991). Precision of the on-line procedure was better than ±0.2‰ for carbon isotope ratios. The ^{13}C natural abundance on each sample was expressed in δ units, by reference to the international standard PDB (Craig, 1957), according to the following equation:

$$\delta\,^{13}C‰ = 10^3 \times [(^{13}C/^{12}C)\text{sample} - (^{13}C/^{12}C)_{PDB}]/(13C/^{12}C)_{PDB}.$$

The total carbon content derived from C3 rice plants (Cr), and from C4 vegetation (natural grassland and invading grass on ex-rice field as Cng) was calculated for each soil layer or fraction as follows:

$$Cr = [(\delta - \delta_0)/(\delta_r - \delta_0)] \times Ct, \quad Cng = Ct - Cr,$$

where δ is the $\delta^{13}C$ of the soil sample in abandoned rice field, δ_0 the $\delta^{13}C$ of the soil sample under natural savanna and δ_r is the $\delta^{13}C$ of the rice grass. The $\delta^{13}C$ of the rice is not the ideal estimator of δ_r. However, as there was no soil covered by rice for a long time, it is the better estimator which can be used (Balesdent, 1991).

2.5. Statistical analyses

Results have been statistically analyzed using non-parametric statistics when data were not normally distributed and did not show homoscedasticity due to small sample sizes. When more than one treatment was compared we used Kruskal Wallis H test. In the case of two comparisons we used Mann–Whitney U tests (Siegel, 1974; Scherrer, 1984). When data were normally distributed and showed homoscedasticity, results were analyzed by one-way analysis of variance, and for comparisons of two groups, the Tukey test was used. Statistical analyses were performed using the SigmaStat statistical software (version 2.0, 92–97).

3. Results

First of all, we tested if the two chronosequences replicates differ from each other. As we did not find any significant difference (each comparison $p > 0.05$), we pooled the data for further analyses.

3.1. Total carbon and nitrogen content

We registered a pronounced change in carbon contents throughout the chronosequence (Table 2). Carbon content from natural grassland was significantly greater than for the rice fields (each, $p < 0.05$), except immediately after rice fields were harvested. The carbon content decreased up to 4 years after rice abandonment, but increased afterwards. Still after 15 years, the carbon content remained lower in comparison to the natural grassland, but not significantly ($p = 0.057$). For organic nitrogen content (Table 2) the variations along the chronosequence are less pronounced

Table 2
Mean with standard deviation of bulk density, C and N contents, C/N ratio and $\delta^{13}C$ values of the 0–10 cm soil layers of the chronosequence

Plots	Bulk density (g cm^{-3})	Carbon (mg g^{-1})	Nitrogen (mg g^{-1})	C/N	$\delta^{13}C$ (‰)
NG	1.20±0.10	17.68±1.75	1.45±0.17	12.3±0.8	−14.9±0.3
Ri	1.35±0.10	15.89±1.95	1.50±0.15	10.6±0.4	−18.0±0.7
P1	1.28±0.15	14.03±1.92	1.27±0.13	11.0±0.7	−19.0±0.6
P2	1.42±0.08	14.15±1.09	1.38±0.13	10.3±0.3	−20.1±1.1
P4	1.41±0.07	12.60±1.64	1.23±0.15	10.3±0.6	−18.2±0.8
P6	1.36±0.06	13.37±1.82	1.27±0.14	10.5±0.6	−16.5±0.6
P15	1.39±0.09	15.49±0.75	1.39±0.04	11.1±0.5	−15.7±0.3

than for C, and only the nitrogen level from the 4 years abandoned rice field was significantly lower than in the natural grassland and the recently harvested rice field. After 15 years of rice abandonment the N content did not differ from that typical of natural grasslands ($p>0.05$).

The C/N ratio changed throughout the chronosequence (Table 2) and was characterized by a significant decrease during rice cultivation. After rice was abandoned, we observed a trend for the C/N ratios to increase very slightly as time passed by.

3.2. $\delta^{13}C$ isotopic signature

$\delta^{13}C$ values from the natural grassland (−14.9‰) corresponded to a C4 vegetation (Table 2). The rice chronosequence has shown a marked decrease in the signature in the first stages of abandonment with an increase for later stages of the chronosequence. The lower value (−20.1‰) occurred after 2 years of rice abandonment. After 4 years of rice abandonment the $\delta^{13}C$ values increased significantly ($p = 0.001$), in comparison to previous stage, ending at 15 years old with an isotopic signature that did not differ from that of the natural grassland ($p>0.05$).

3.3. Particle-size fractionation

In the natural grassland, analysis of particle-size separates showed that a large proportion of SOM was associated with the silt fractions, comprising 41% of the total SOC and 44% of soil N. The sand fractions contained 35% of the total SOC and 25% of soil N. The organic matter associated with the clay fraction represented only 23% of SOC and 30% of soil N (Table 3). During rice cultivation the C and N contents of the fine sand fraction decreased significantly whereas in the clay the C content increased slightly and the N content significantly. During the first years after the abandonment of rice cultivation the C and N contents of the clay and fine and coarse silt fractions tended to decrease but after 4 years of abandonment this trend was reverted. After 15 years of abandonment the C and N contents of the particle size fractions did not show significant differences with the natural grassland (except for the C content of fine sand fraction).

The C/N ratio showed the same pattern for all the stages of the chronosequence, with a sharp decrease going from the coarse fraction (18.4–28.8) towards the fine fraction (7.7–9.4) (Table 3). The C/N ratio differed mostly between the natural grassland and each stage of the rice chronosequence, the difference being more pronounced for the coarse fractions. As time of abandonment progressed, the C/N ratio increased slightly, but this increase was significant only for the finest fractions (Table 3).

The $\delta^{13}C$ values of the different particle-size fractions exhibited different patterns along the chronosequence (Table 3). In the natural grassland, the differences among the fractions were small; however, the two finest fractions had $\delta^{13}C$ values higher than the coarser fractions. Across the rice chronosequence, all the particle-size fractions showed a decrease in the $\delta^{13}C$ values during the rice cultivation and in the first stages of abandonment and an increase in the later ones. These variations along the chronosequence were clearly more pronounced for the coarser fractions than for the finer fractions.

3.4. Carbon turnover from organic matter of different origins

The effects in change of vegetation (from C4, to C3 and again C4 from plants colonizing the abandoned plots) were reflected by the estimates of the carbon derived from the rice (Cr) and from the natural grassland (Cng) in the surface soils (0–10 cm) of the chronosequence (Fig. 1).

In the recently harvested rice field more than 21% (3.5 mg g^{-1}) of the carbon had a rice origin whereas here we registered a reduction of 30% in Cng in comparison to the natural grassland (from 17.7 to 12.4 mg g^{-1}). During the two first years of abandonment, the Cng continued to decreased, whereas the Cr increased. In the 2 years old abandoned rice field, more than 37% (5.3 mg g^{-1}) had a rice origin and in comparison to the natural grassland, 50% (8.8 mg g^{-1}) of the Cng was lost. During the latter stages of abandonment, the Cr decreased, whereas the Cng increased regularly. In the 15 years old abandoned rice field, only 5% (0.8 mg g^{-1}) of the C had a rice origin, whereas 95% (14.7 mg g^{-1}) was attributed to the C4 vegetation (present before and after rice cultivation).

The absolute quantities and relative proportions of soil organic carbon derived from the natural grassland and

Table 3
Soil organic carbon (SOC) and total nitrogen (NT) contents, C/N ratios and $\delta^{13}C$ values of the particle-size fractions from the 0–10 cm soil layers of the chronosequence (number are means ± standard errors)

Fraction (μm)	Plot	SOC (mg g^{-1}) soil	NT (mg g^{-1}) soil	C/N	δ ^{13}C (‰)
>200	NG	1.91 ± 0.46	0.07 ± 0.02	28.8 ± 5.6	−15.2 ± 1.2
	Ri	1.86 ± 0.61	0.10 ± 0.04	18.6 ± 3.2	−22.5 ± 0.7
	P1	2.14 ± 0.93	0.11 ± 0.04	18.9 ± 2.4	−22.7 ± 1.3
	P2	1.98 ± 0.56	0.11 ± 0.03	18.4 ± 1.8	−22.3 ± 1.9
	P4	1.58 ± 0.55	0.08 ± 0.03	19.4 ± 2.9	−19.3 ± 1.9
	P6	1.60 ± 0.76	0.08 ± 0.04	18.6 ± 1.6	−16.8 ± 1.2
	P15	1.53 ± 0.49	0.07 ± 0.03	22.4 ± 4.5	−16.2 ± 0.8
50–200	NG	4.35 ± 1.56	0.30 ± 0.13	14.9 ± 1.3	−15.0 ± 0.4
	Ri	2.30 ± 0.79	0.19 ± 0.06	12.3 ± 1.3	−19.3 ± 0.8
	P1	2.57 ± 0.56	0.19 ± 0.04	13.6 ± 0.4	−20.5 ± 0.7
	P2	2.48 ± 0.73	0.20 ± 0.06	12.6 ± 0.6	−22.1 ± 1.8
	P4	2.06 ± 0.62	0.16 ± 0.05	13.0 ± 1.5	−19.6 ± 1.0
	P6	2.46 ± 0.90	0.19 ± 0.07	12.9 ± 1.3	−17.3 ± 0.8
	P15	2.83 ± 0.92	0.21 ± 0.08	13.9 ± 2.3	−16.0 ± 0.6
20–50	NG	2.15 ± 0.93	0.18 ± 0.08	12.3 ± 1.1	−15.8 ± 0.5
	Ri	1.62 ± 0.44	0.14 ± 0.04	11.6 ± 0.8	−18.8 ± 0.9
	P1	1.22 ± 0.22	0.10 ± 0.02	12.1 ± 1.1	−19.9 ± 0.5
	P2	1.17 ± 0.38	0.10 ± 0.03	11.2 ± 0.5	−21.0 ± 0.9
	P4	1.26 ± 0.39	0.12 ± 0.04	11.1 ± 1.2	−19.9 ± 0.7
	P6	1.23 ± 0.37	0.11 ± 0.03	10.8 ± 0.9	−18.1 ± 0.7
	P15	1.55 ± 0.46	0.13 ± 0.04	11.6 ± 0.4	−16.7 ± 0.5
2–20	NG	5.18 ± 0.93	0.46 ± 0.07	11.2 ± 0.9	−14.7 ± 0.2
	Ri	5.30 ± 0.73	0.52 ± 0.07	10.3 ± 0.6	−17.0 ± 0.6
	P1	4.18 ± 0.74	0.40 ± 0.08	10.6 ± 0.9	−17.7 ± 0.6
	P2	4.63 ± 0.45	0.46 ± 0.05	10.2 ± 0.8	−18.9 ± 0.9
	P4	3.99 ± 0.60	0.41 ± 0.06	9.7 ± 0.3	−17.6 ± 0.8
	P6	4.20 ± 0.58	0.41 ± 0.07	10.3 ± 0.6	−16.3 ± 0.7
	P15	5.05 ± 0.49	0.47 ± 0.05	10.7 ± 0.3	−15.3 ± 0.5
0–2	NG	4.10 ± 0.88	0.44 ± 0.10	9.4 ± 0.8	−14.8 ± 0.4
	Ri	4.81 ± 1.02	0.56 ± 0.11	8.6 ± 0.5	−16.4 ± 0.6
	P1	3.91 ± 0.38	0.47 ± 0.05	8.3 ± 0.4	−17.5 ± 0.7
	P2	3.89 ± 0.52	0.50 ± 0.05	7.7 ± 0.5	−18.5 ± 0.8
	P4	3.71 ± 0.47	0.46 ± 0.06	8.1 ± 0.5	−17.3 ± 0.6
	P6	3.88 ± 0.38	0.48 ± 0.07	8.2 ± 0.6	−15.9 ± 0.4
	P15	4.53 ± 0.93	0.51 ± 0.10	8.9 ± 0.5	−15.3 ± 0.6

from the rice varied strongly with particle-size fractions and stages of the chronosequence (Fig. 2). In the recently harvested rice field Cr was present in all the fractions but the inputs decreased significantly from the coarser to the finer fractions (from 55% to 12%). In the 2 years old abandoned rice field, the quantities and proportions of Cr were significantly higher ($p<0.01$) for the fine silt and clay fractions, in comparison to the most recently abandoned rice field. In the latter stages of abandonment, the quantities and proportions of Cr continued to decrease in all the fractions. However, there were no statistical differences between the 6 and the 15 years old abandoned rice fields. In the latter stages of abandonment the quantities of Cng increased in all the fractions, indicating an input of Cng from the invasive C4 vegetation.

In the recently harvested rice field, the losses of carbon Cng occurred mainly in the coarser fractions, and no losses were observed in the clay fraction (Fig. 3). In the 1 and 2 years abandoned rice fields, the losses, observed in all the

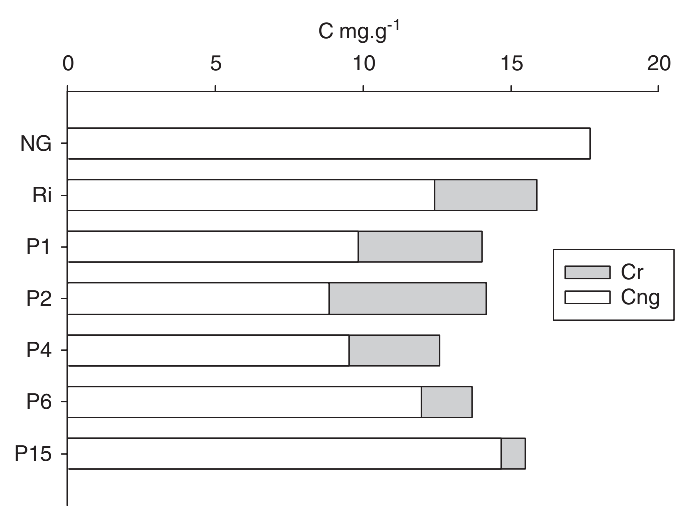

Fig. 1. Content of natural grassland- (Cng) and rice-derived (Cr) soil organic carbon in bulk soil from the 0–10 cm layer across the chronosequence.

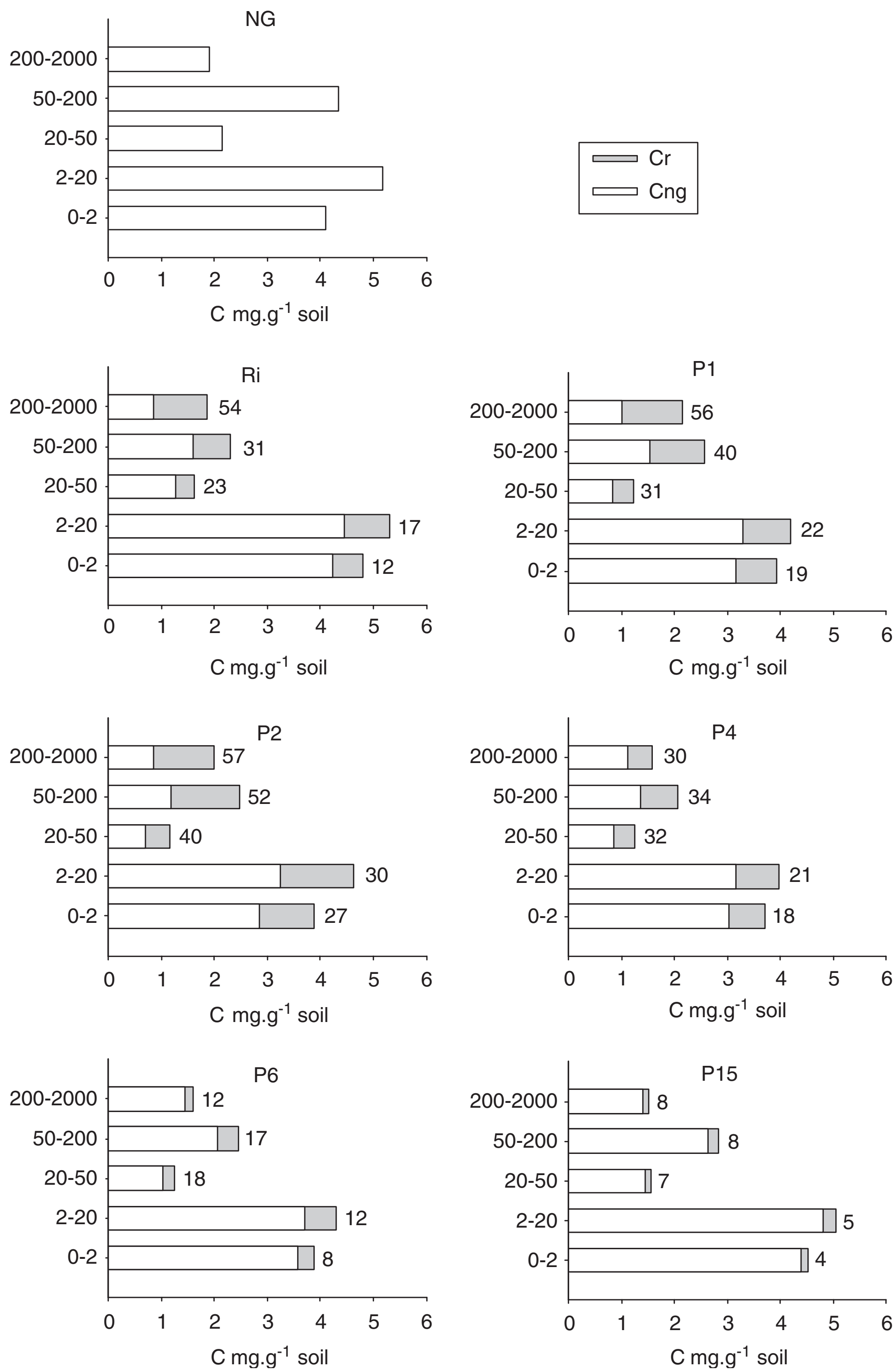

Fig. 2. Content of natural grassland- (Cdng) and rice-derived (Cdr) soil organic carbon for each particle-size fraction, expressed as mgC g^{-1} of soil, from the 0–10 cm layer across the chronosequence. The numbers in front of the bars indicate the rice-derived (Cdr) soil organic carbon expressed as % of total carbon for each particle-size fraction.

fractions, ranged from 47% to 73% for the sandy fractions and from 23% to 30% for the clay fraction.

4. Discussion

Our results represent the first study done on the dynamics of organic matter in abandoned rice fields in Argentina. Contrary to traditional views of the impact of agriculture, and in particular, paddy rice fields, we have observed that ex rice soils were able to mineralize very fast the soil organic matter, regardless it was from natural grassland or rice origin.

The evolution of the C and N contents along the chronosequence was a consequence of the vegetation

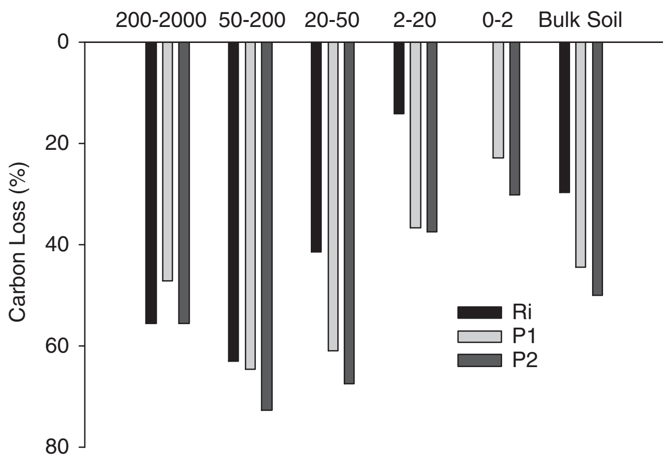

Fig. 3. Loss of natural grassland-derived carbon (Cng) in bulk soil and particle-size fractions from the 0–10 cm layer across the first stages of the chronosequence.

changes. First, we observed a slight (and not statistically significant) decrease of C and N contents in recently harvested rice fields in comparison to the natural grassland. This result may seem unexpected as the inputs of rice crops residues after 3 years of rice cropping were probably higher than the inputs of the natural vegetation, and because of the flooding conditions of the rice cultivation. However, these flooding conditions took place during only 4 months a year. The existence of 8 months of aerobic conditions and the alternance of wet–dry conditions could have induced a high biological activity leading to a high decomposition rate of the SOM. The decrease of SOM content in continuously cropped field could be attributed to cultivation which disrupts soil aggregates and thereby improves microbial accessibility to organic matter (Solomon et al., 2002). Second, at 2 years of the abandonment of the rice fields, we registered a decrease in the C and N content which could be, in part, explained by the fact that as the recolonization of the abandoned rice field by the natural grassland vegetation occurred at a slow pace, the (new) inputs of organic residues could have been very small during the first 2 years of abandonment. In addition, the return to continuous aerobic conditions could have stimulated the decomposer soil organisms and, therefore the mineralization rate of the SOM. Two years seem to be enough to allow the establishment of a working soil community (Folgarait et al., 2003). Third, as the abandonment extended, the inputs of organic residues from colonizing plants of natural grassland origin increased and the C and N contents of the surface layer were enhanced as well.

The distribution of SOC and N in size fractions in these soils was slightly different to the patterns observed in temperate (Amelung et al., 1998) and tropical soils (Desjardins et al., 2004; Koutika et al., 2000; Solomon et al., 2002). The proportions of C and N associated with the silty fractions were higher than those of most soils, because of the very high silt content (70%), confirming the influence of texture on organic matter incorporation (Desjardins et al., 2004). The C/N ratios of the size fractions decreased with decreased diameter, suggesting that microbial alteration of SOM was much higher in the finer size fractions than in the coarser ones, and that the clay fraction represented the main pool of humified SOM, similar to results from Amelung et al. (1998) and Solomon et al. (2000).

Even though the total C content in the recent harvested rice field was only slightly modified, as compared to that of the natural grassland soil, the changes in ^{13}C natural abundance were indicative of significant inputs and losses in C derived from the rice and from the natural grassland, respectively. After 3 years of rice cropping, the Cr represented more than 21% of the total carbon content in the 0–10 cm layer. This turnover is more rapid than those observed by Vitorello et al. (1989) in south Brazil for a sugarcane crop (on a forest soil) and for a maize crop (on a grassland soil) in central Argentina (Andriulo et al., 1999). This fact confirms that the rice cultivation produced a high quantity of organic residues, which were incorporated in the soil. Even after the abandonment of the rice cropping, organic rice residues remaining on the soil surface continued to be incorporated into the soil which could account for the high content of Cr (37% of the total C content) registered after the first 2 years of abandonment.

The proportion of the Cng lost during the 3 years of cropping amounted to 29%, which was higher compared to those observed by Andriulo et al. (1999) and by Martin et al. (1990) for a savanna in Ivory Coast (14% in 4 years and 59% in 16 years, respectively). This decrease of the Cng continued strongly until the 2 first years of abandonment (near to 50% of Cng lost), confirming that during the first stages of recolonization by the natural grassland vegetation, the inputs of C from C4 origin were small.

Isotopic methods clearly confirmed that particle-size fractions represent SOM pools of different turnover rates as already observed for other temperate (Balesdent et al., 1988), subtropical (Bayer et al., 2001) and tropical soils (Feigl et al., 1995; Sevink et al., 2005). Faster turnover and substitution of SOC derived from natural grassland by SOC derived from rice crop, and conversely after abandonment, of SOC derived from rice crop by SOC derived from C4 colonizing vegetation were observed in the sand fractions. The clay and the fine silt fractions retained the C derived from the previous vegetation for longer and more efficiently than the coarser fractions. However, the losses which had occurred in all the particle-size fractions suggest a destabilization of the SOM by the cultivation practices (Balesdent et al., 1998).

The inputs of Cr, quantified after 3 years of rice cropping, were registered in all the fractions. However, as observed in others studies (Balesdent et al., 1988; Desjardins et al., 1994; Feigl et al., 1995), the proportion of Cr varied strongly with particle-size fractions, decreasing progressively from the coarser to the finer fractions. When the rice cultivation ended, the inputs of fresh rice residues were stopped and the Cr content of the coarse sand fraction began to decrease. At the same time, the inputs of Cr in the others fractions continued to increase indicating a transfer of Cr from coarser to finer fractions. As expected, when the period of abandonment increased, the Cr content decreased in all the fractions; however, this output was more evident in the coarser fractions, as the Cr has been transferred from the coarser to the finer fractions. The Cr content continued to decrease up to 6 years after abandonment, afterwards, it remained constant as we observed in the 15 years of abandonment plot; this constancy could indicate a chemical or physical protection (Bayer et al., 2001).

Although the total amount of SOM decreased only slightly during the cultivation, the studied soil ecosystem appeared sensitive to the plant cover substitution. Particle-size fractionation and ^{13}C natural abundance measurements have shown qualitative changes, even after the end of cultivation. A period of 15 years of fallow did not seem sufficient to recover a soil ecosystem similar to the natural grassland. Thomas et al. (2004), studying the soil macrofauna of this chronosequence, showed that the community composition, 15 years after cultivation abandonment, was still different from the natural grassland soil. It appeared evident that even a short period of cultivation (3 years) induced new conditions of soil functioning for a longer period. Therefore, periods of fallow longer than 15 years seemed necessary to return to an ecosystem similar to the natural grassland, in terms of chemical and biological properties.

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