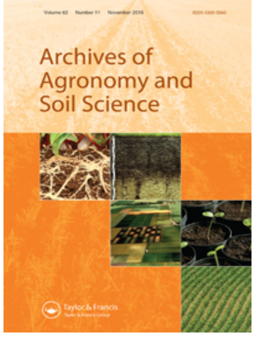

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Are active organic matter fractions suitable indices of management effects on soil carbon? A meta-analysis of data from the Pampas

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ABSTRACT

Active fractions of organic matter have been proposed as early indices of changes in soil organic carbon (organic-C) induced by management. We performed a meta-analysis of published results from 31 field experiments conducted in the Pampas in which tillage and rotation effects on organic-C, microbial biomass carbon (microbial-C), light fraction carbon (light-C), particulate carbon (particulate-C) and basal respiration (mineralized-C) were assessed. We compared the changes of organic-C and the four active fractions between management treatments sampled at the same date and depth within each experiment. Pooling all the experiments, active fractions-C varied on average 1.2- to 3.0-fold more than organic-C, depending on the fraction considered, but these average changes were significantly greater than organic-C changes only for particulate-C. This later fraction showed to be more sensitive to agricultural practices than organic-C. In experiments in which organic-C changes were lower than 15–25%, the four labile fractions may show opposite trends than organic-C. Above this threshold, changes of active fractions generally copied organic-C changes and were greater. Consequently, the active fractions may be used as indicators of changes in organic-C only when this latter variable has already suffered a huge change. In these cases, it will be easier to simply measure organic-C.

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KEYWORDS
Active fractions of organic matter; microbial biomass; light organic fraction; particulate carbon; basal respiration

Introduction

Organic matter is the soil characteristic most widely used as a quality and fertility indicator (Manlay et al. 2007). It has also been associated with soil productivity (Pan et al. 2009) and could be an important atmospheric carbon sink (Manlay et al. 2007). Because its changes are slow and difficult to measure under many environments (Goidts et al. 2009), much effort has been invested in developing early indices of changes in organic matter. The fractionation of organic matter into functional pools with different turnover allowed for the understanding of organic matter dynamics, its stabilization mechanisms and modelization (Von Lüzow et al. 2007). Success has been attained in isolating active organic fractions with fast turnover (Von Lüzow et al. 2007). Such active fractions, as microbial biomass carbon (microbial-C), light fraction carbon (light-C), particulate carbon (particulate-C) and basal respiration (mineralized-C), are more sensitive than total soil organic carbon (organic-C) to the effects of management (Xu et al. 2011). In short time periods, these fractions can

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change under contrasting management scenarios while organic-C remains unaffected, and after long time periods, these changes can be greater than those of organic-C (Xu et al. 2011).

Microbial-C has been proposed as an early index of changes in organic-C because it is much more sensitive to straw amendments (Powlson et al. 1987) and other management practices (Sparling 1992; Biederbeck et al. 1994) than organic-C. Light-C may also be more sensitive than organic-C to management (Dalal & Mayer 1986; Bremer et al. 1992; Gregorich et al. 2006) although it did not respond linearly to straw amendments in some cases (Gregorich et al. 2006). Variation of particulate-C under different land uses was greater than variation in organic-C (Poeplau & Don 2013) and its behavior under contrasting managements was much more similar to light-C (Gregorich et al. 2006). Finally, mineralized-C could change 10-fold more than organic-C in response to different agricultural practices (Bremer et al. 1992).

The Pampas is one of the most important grain production regions of the world because of its extension and grain potential (Satorre & Slafer 1999). During the recent decades, large changes in tillage system and crop rotation have occurred in this area (Alvarez et al. 2014) and many experiments have been performed to assess the impact of these changes on soils. In many of these experiments, organic matter and its active fractions were evaluated, usually applying similar techniques, offering the opportunity to use this information for determining whether active fractions are suitable tools for predicting future regional changes in organic-C. We performed a meta-analysis of published results from available experiments to fulfill this objective.

Materials and methods

Site description

The Pampas is a vast plain in Argentina of ca. 60 million hectares (28° S and 40° S and 57° W and 68° W) that developed under a humid and warm-temperate climate. The mean annual rainfall varies from 500 mm in the West to 1200 mm in the East and the mean annual temperature varies from 14°C in the South to 23°C in the North. The natural vegetation is grassland with graminaceous species (Hall et al. 1992). Mollisols formed on loess-like materials are the most common soils in the Pampas. The eolian origin of sediments from Southwest to Northeast and the West–East rainfall gradient promoted soil variation from sandy textured and shallow in the semi-arid West to fine textured and deep in the humid East (Alvarez & Lavado 1998; Berhongaray et al. 2013). Soil organic carbon follows the rainfall trend while pH usually varies between 6 and 7 in well-drained soils not following the climate gradient (Alvarez & Lavado 1998; Berhongaray et al. 2013). Higher pH values are found only in hydromorphic lands (Berhongaray et al. 2013). Acid soils are very uncommon in the region. In well-drained soils with annual rainfall above 600 mm rain-fed crops are cultivated. At present, ca. 50% of the Pampean area is being used as cropland, with soybean (*Glicine max* Merr.), wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) as the main crops (MinAgri 2015). The widespread adoption of no-till and fertilizer use has occurred since 1990 (Alvarez et al. 2014).

Data material

We compiled results from 31 field experiments performed in the humid–subhumid portion of the Pampas in which the effects of tillage systems and crop rotation on organic-C and some active fractions or organic matter were evaluated. The criteria for selection were: (1) all the experiments were performed by official institutions, usually at experimental stations; (2) data were published in international or local peer-reviewed journals available online; (3) experimental design and techniques were described in detail; (4) soil was uniform before the initiation of the experiment; (5) management treatments applied copied common farmers' production techniques; and (6) reported measurements were averages of three or more replications. Climate conditions of experimental sites were obtained from the published papers or from available local records (Table 1). Soils

Table 1. Climate, soil, and management conditions of the studied sites and sampling depth.

Reference	MAR (mm)	MAT (°C)	Experiments	Soil type[a]	Sand (g kg^{-1})	Silt (g kg^{-1})	Crop rotation[b]	Tillage system[c]	Years of the experiment[d]	Depth (cm)	Paired data
Abril et al. (2005)	750	17.2	1	THs, EHs	146	687	S-S, C-S, S/CC-S, S/CC-C	CHT, NT	5 to 10	0–10	12
Alvarez et al. (1995a)	950	16.5	1	TA	160	570	C- W/S	PT, CHT, NT	12	0–5	3
										5–10	3
										10–15	3
										15–20	3
Alvarez et al. (1995b)	950	16.5	1	TA	140	640	W/S	PT, HT	2	0–5	2
										5–10	2
										10–15	2
										15–20	2
Alvarez et al. (1995c)	950	16.5	1	TA	140	660	W/S	PT, HT	1 to 2	0–15	5
Alvarez et al. (1998a)	950	16.5	1	TA	170	560	U, C-C-C-S	PT, NT	4	0–5	3
										5–10	3
										10–15	3
Alvarez et al. (1998b)	1100	16.0	1	TA	160	570	C- W/S	PT, NT	15	0–5	2
										5–10	2
										10–15	2
										15–20	2
Benintende et al. (1995)	1005	18.2	1	AA	104	620	C-C, C-W/S	PT, CHT, NT	12	0–7	6
Casanovas et al. (1995)	870	13.7	1	TA	398	337	GC, GC-P	PT	6 to 14	0–15	15
Chagas et al. (1995)	900	17.0	1	TA	100	650	S-S	PT, CHT, NT	17	0–5	3
										5–10	3
										10–15	3
Ciampitti et al. (2011)	924–950	17.0	4	EHs, TA, TH, AA	31–566	354–789	C-W/S, C-S-W/S	NT	6	0–5	8
										5–10	8
										10–20	8
Costantini et al. (2006)	924	17.0	1	TA	60	689	C-W/S-S	CHT, NT	10	0–5	6
										5–10	6
										10–20	6
Cozzoli et al. (2010)	870	13.7	1	TA, PP	411	358	GC-P	PT, NT	9	0–20	7
Diovisalvi et al. (2008)	870	13.7	2	TA, PP	411	358	GC	PT, NT	7 to 8	0–5	4
										5–20	4
Divito et al. (2011)	870	13.7	1	TA, PP	410	360	C-S-W/S	NT	7	0–5	3
										5–20	3

(*Continued*)

Table 1. (Continued).

Reference	MAR (mm)	MAT (°C)	Experiments	Soil type[a]	Sand (g kg^{-1})	Silt (g kg^{-1})	Crop rotation[b]	Tillage system[c]	Years of the experiment[d]	Depth (cm)	Paired data
Dominguez et al. (2009)	952	14.1	1	TA, PP	411	358	C-C-C-Su-W	PT, NT	4,7	0–5	4
										5–20	4
Echeverria et al. (1993)	614–960	13.7–15.0	4	TA, PP	227–332	283–405	GC, P	PT	2	0–20	6
										20–50	6
Eiza et al. (2005)	870	13.7	1	TA, PP	411	358	GC-P	PT, NT	9	0–5	7
										5–20	7
Fabrizzi et al. (2003)	846–928	13.5–13.7	2	TA, PP			U, GC	PT, CHT, NT	4 to 7	0–7.5	10
										7.5–15	10
Ferreras et al. (2009)	928–1000	17–18.3	3	TA, AA	30–96	689–745	U, GC, GC-CC, GC-P	CHT, NT	7 to 13	0–7.5	13
Palma et al. (2000)	924	17.0	1	TA	60	689	U, C-C, S-C	PT; NT	15	0–10	5
Wyngaard et al. (2012)	870	13.8	1	TA	410	360	C-S-W/S	PT, NT	7	0–5	14
										5–20	14

[a] THs, Typic Haplustoll (Haplic Kastanozem); EHs, Entic Haplustoll (Haplic Kastanozem); TA, Typic Argiudoll (Luvic Phaeozem); AA, Aquic Argiudoll (Luvic Phaeozem); TH, Typic Hapludoll (Luvic Phaeozem); PP, Petrocalcic Paleudoll (Kastanozem on calcrete). Soil classification is given using Soil Taxonomy (USDA 2003) and WRB equivalences in brackets (Lal 2005).

[b] S, soybean; C, corn; CC, cover crops; W/S, wheat-soybean doubled crop; U, uncropped; GC, grain crops; P, pasture; Su, sunflower; W, wheat.

[c] CHT, chisel tillage; NT, no tillage; PT, plow tillage; HT, harrow tillage.

[d] Number of years since the beginning of the experiment in which measurements were performed.

exhibit a fine or loamy texture in many cases and had moderate organic-C content. Experimental designs compared tillage systems, crop rotations or combinations of both. Samples were taken from the surface soil horizon at different depths and the time since the installation of management treatments showed large variations. In all the experiments, organic-C and some active organic matter fractions were measured in management treatments, sometimes at multiple layer depths in the same experiment. Organic-C was determined in nearly all the experiments by the classical Walkley–Black method, and in only one case a dry combustion methodology was used (Nelson & Sommers 1996). In Pampean soils the oxidation coefficient of the Walkley–Black method for surface soil was determined under contrasting textural conditions with an average value of 81% and with a small range between different soils (Richter et al. 1973). Microbial-C was assessed by fumigation-incubation (Jenkinson & Powlson 1976). Using a bromoform–ethanol mixture with a density of 2 g ml^{-1}, the soil was shaken and centrifuged and the light-C fraction was isolated (Richter et al. 1975). The particulate-C fraction (>53 µm) was determined by the Cambardella and Elliott (1994) technique or some of its variations (Quiroga et al. 1996). Mineralized-C was measured during *in vitro* soil aerobic incubation from 7 to 10 days at 20–30°C in a manner similar to that described by Alvarez and Alvarez (2000). The compiled information allowed for the generation of 83 paired data of organic-C with biomass-C, 37 with light-C, 137 with particulate-C and 95 with mineralized-C, when making management comparisons within each experiment with samples taken at the same date and depth layer.

Calculation procedure

The impact of management treatments on organic-C was assessed using Equation (1):

$$\Delta\mathrm{organic}-\mathrm{C}=(\mathrm{organic}{-}\mathrm{C}_{\mathrm{x}}/\mathrm{organic}{-}\mathrm{C}_{\mathrm{min}}\times 100)-100 \tag{1}$$

where Δ organic-C is the relative organic-C change between one experimental treatment determined at a fixed depth (organic-C_{x}) related to the minimum organic-C value in that experiment at the same depth and sampling date (organic-$\mathrm{C}_{\mathrm{min}}$).

Using this equation the minimum organic-C value from each experiment and depth was used as a baseline and all other values from the same experiment and soil layer were calculated relative to this baseline. This analysis was similar to that performed by Poeplau and Don (2013) to compare the sensitivity of particulate-C and organic-C to management. Active fraction changes were measured using a similar equation, taking as baseline the same combination of treatment × depth × sampling time in which organic-$\mathrm{C}_{\mathrm{min}}$ was measured, independently of whether this combination had the minimum value or not of the active fraction values (Equation (2)). By doing this, the sign and magnitude of the organic-C changes and the active fractions changes could be compared.

$$\Delta\mathrm{active\ fraction}-\mathrm{C}=(\mathrm{active\ fraction}{-}\mathrm{C}_{\mathrm{x}}/\mathrm{active\ fraction\ in\ organic}{-}\mathrm{C}_{\mathrm{min}}\times 100)-100 \tag{2}$$

where Δ active fraction-C is the relative active fraction-C change between one experimental treatment determined at a fixed depth (active fraction-C_{x}) related to the active fraction-C measured in the treatment and depth where organic-$\mathrm{C}_{\mathrm{min}}$ was measured the same date.

The ratio between relative organic-C change and the relative active fraction-C change was calculated as

$$\mathrm{Ratio}=\Delta\mathrm{organic}-\mathrm{C}/\Delta\mathrm{active\ fraction}-\mathrm{C} \tag{3}$$

Statistical analysis

Relative changes in organic-C and labile fractions were statistically compared by the Wilcoxon matched pairs test because the data were not normally distributed. Because data from some

Table 2. Number of compared paired data, mean, minimum, and maximum values of organic-C and the different active fractions and R^2 of the regressions between organic-C and active fractions-C.

Variables compared	Paired data	Mean	Minimum	Maximum	R^2	$P <$
Organic-C (g kg^{-1}) vs. microbial-C (mg kg^{-1})	83	18.5 vs. 251	12.2 vs. 25	35 vs. 1570	0.22	0.05
Organic-C (g kg^{-1}) vs. light-C (g kg^{-1})	37	26.7 vs. 2.10	13 vs. 0.790	43.9 vs. 12.0	0.01	ns
Organic-C (g kg^{-1}) vs. particulate-C (g kg^{-1})	137	27.9 vs. 5.94	13.1 vs. 1.25	43.9 vs. 20.1	0.23	0.05
Organic-C (g kg^{-1}) vs. mineralized-C (mg kg^{-1})	95	16.8 vs. 160	8.30 vs. 35.0	35.0 vs. 1050	0.21	0.05

treatments were used as baseline and relative changes in these cases were zero, they were obviously omitted from the statistical analysis. We focused on comparing the magnitude of relative changes in relation to baselines. Consequently, the amount of paired data for comparison decreased (Table 2). Visual inspection of plotted organic-C changes and active fraction changes were performed. The significance of regression and correlation analysis was checked using the *F*-test. For this later analysis all samples were pooled across sites, depths, and sampling times. Organic-C and active fractions-C changes were also regressed against the time since managements were applied.

Results and discussion

Variations in organic-C from minimum to maximum values ranged from 3- to 4-fold in the different datasets, whereas active fraction variation was much greater ranging from 15- to 62-fold, depending on the accounted fraction (Table 2). Active fraction measurements tended to be greater in higher organic-C samples. Significant but low R^2 was observed between organic-C and microbial-C, particulate-C and mineralized-C; meanwhile the relationship between organic-C and light-C was not significant (Table 2).

As reported in previous studies, a larger variation due to management effects was detected in the active fractions compared to organic-C in the Pampean dataset (Xu et al. 2011). However, in those studies, it was uncommon that active fractions and organic-C were as poorly correlated as in the Pampas. Environmental analysis and some site-specific studies showed a good correlation between active fractions and organic-C. When many sites were taken into account and surface soil was sampled at a fixed depth, microbial-C (Adams & Laughlin 1981), light-C (Haynes 2000), particulate-C (Sleutel et al. 2006) and mineralized-C (Kubát et al. 2008) were correlated with organic-C ($R^2 = 0.45$–0.65; $P < 0.05$). At the site scale, particulate-C and organic-C may also correlate well when samples are taken at the same time but from different treatments and depths (Sequeira & Alley 2011). In our Pampean dataset, samples from different sites, taken at different depths and seasons were pooled for the regression analysis and this might be the cause of the lack of fit. The ratio between active fractions and organic-C usually decreased in depth (Nelson et al. 1994; Yang et al. 2009). Additionally, in the Pampas, microbial-C presents seasonal fluctuations, generally decreasing under water-limiting conditions during summer periods (Alvarez & Alvarez 2001). These effects may influence active fractions and organic-C relationships.

The effect of management on active fraction changes relative to the control treatment was frequently much more pronounced than changes in organic-C, but they were sometimes of similar magnitude or even showed an opposite trend (Figure 1). On average, changes in active fractions were 1.2- to 3.0-fold greater than changes in organic-C (Table 3) but only changes in particulate-C were significantly greater than changes in organic-C. In 14–52% of the cases active fraction changes showed a different sign than organic-C variations (Table 3). Active fractions decreased and organic-C increased. Opposite trends in active fractions and organic-C variations were observed mainly in experiments in which changes of organic-C were lower than approximately 15–25% (Figure 1); however, in some cases, active fraction variations were still opposed to organic-C changes above this threshold. When organic-C and active fraction changes showed the same

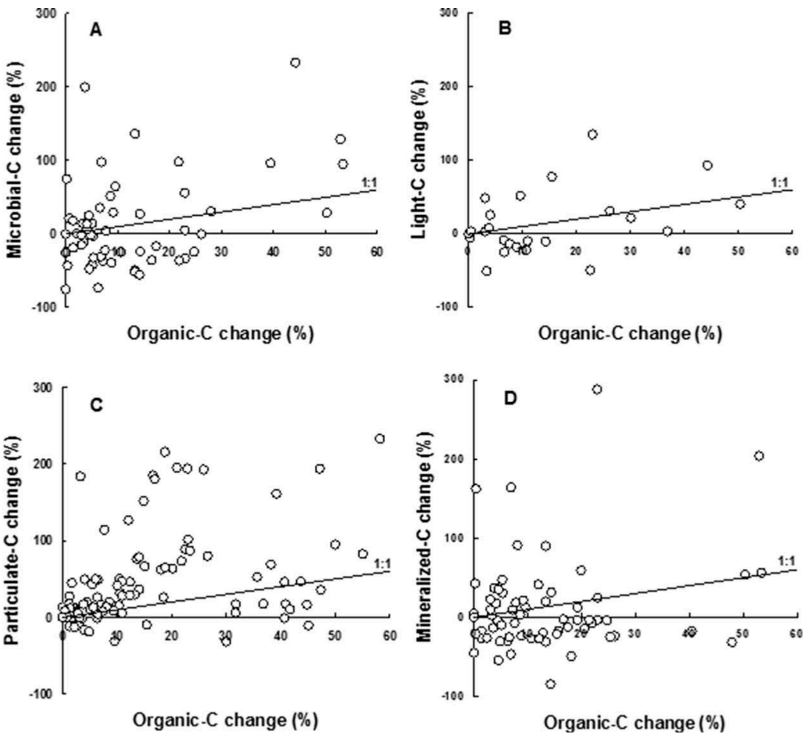

Figure 1. Organic-C change vs. carbon change in different active soil fractions: (A) vs. microbial-C, (B) vs. light-C, (C) vs. particulate-C, and (D) vs. mineralized-C. Three points were not plotted due to scale problems (only samples taken at the same date and depth were compared).

trend, in many cases, active fractions were much more deeply impacted by management than organic-C, but in 9–15% of the cases active fractions varied less than organic-C between managements (Table 3). Summing the cases in which active fraction changes were opposed to or lower than organic-C changes resulted in percentages rounding 50–60% for microbial-C, light-C and mineralized-C, indicating that these fractions were poor indices of organic-C changes. Particulate-C had better performance, although in 29% of the cases, its variation did not follow the organic-C trend or was lower than the change in organic-C. When analyzing the relationship between time since the initiation of rotation or tillage treatments and organic-C or active fraction-C changes, no significant regression could be fitted when pooling all the experiments, whose duration ranged from 1 to 15 years. The magnitude of the changes of organic C and active fractions-C was more

Table 3. Performance of soil active fractions that were used as organic-C changes indices.

	Fraction			
Variable	Microbial-C	Light-C	Particulate-C	Mineralized-C
Number of comparisons with organic-C change	56	24	101	67
Cases with opposite trend than organic-C change (%) = 1	50	42	14	52
Cases with similar trend but lower change than organic-C change (%) = 2	9	8	15	3
Sum of 1 + 2	59	50	29	55
Average active fraction change (%)	21	25	45	32
Average organic-C change (%)	15	21	15	16
Wilcoxon test (*P* < 0.05)	ns	ns	sig	ns
Average ratio between active fraction change and organic-C change	1.4	1.2	3.0	2.0

Baseline treatments were not included. Only samples taken at the same date and depth were compared.

impacted by the differences between management treatments than by time. The evolution of changes in organic pools over time in the same soil and under a continuous management system could not be assessed because of the scarcity of data from sites in which the same experiment was sampled over different years. Our analysis showed that in the Pampas active fractions were not good indices of organic-C changes. Some previous studies questioned the possibility of using active fractions as indices of organic-C changes. In a management experiment in Chile, microbial-C was less impacted by management treatments than organic-C (Zagal et al. 2009). As microbial-C was much more affected by recent plant residue input than organic-C, it has been proposed that this active fraction was useful as a predictor only when comparing treatments under similar carbon inputs (Ocio et al. 1991). Another limitation of the use of microbial-C as an index of organic-C changes was that its variability between samples taken from the same management treatment was greater than the organic-C variability (Hargreaves et al. 2003). Consequently, many samples or long time periods were required to detect significant changes. Similar results have been observed for particulate-C (Simonsson et al. 2014). In a Spanish experiment at deep soil layers (5–20 and 20–40 cm) but not in surface (0–5 cm) soil, particulate-C was identified as a more sensitive index of management's impact on soil than organic-C (Plaza-Bonilla et al. 2014). Additionally, some management experiments from Germany also indicated that light-C and particulate-C did not change following the same trend as organic-C (Leifeld & Kögel-Knabner 2005). Despite this limitation, active fractions evaluation has been a very useful tool for understanding organic matter dynamics in agroecosystems (Von Lüzow et al. 2007). They should be assessed when the impact of management on microbial activity and the stability of the different soil carbon pools want to be known.

Conclusions

The meta-analysis of data generated in the Pampas showed that active fractions are not useful indices of changes in total soil organic-C induced by tillage or rotation. When changes are small, active fractions may have an opposite variation sign than organic-C and when changes are big, active fractions usually present similar trends and greater variation than organic-C. Only in these later cases are active fractions adequate tools for estimating organic-C changes. As it is easier to determine organic-C than active fractions, the measurement of the former variable seems the best option for monitoring organic matter trends in Pampean soils.

Disclosure statement

No potential conflict of interest was reported by the authors.

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