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Contribution of Integrated Crop Livestock Systems to Climate Smart Agriculture in Argentina

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Abstract: Integrated crop-livestock system (ICLS) is a useful practice to enhance soil organic carbon (SOC) compared to continuous cropping systems (CC). However, robust data from different regions around the world remain to be collected. So, our objectives were to (i) compare SOC and its physical fractions in ICLS and CC, and (ii) evaluate the use of $\delta^{13}C$ to identify the source of C of SOC in these systems in the Pampas region of Argentina. For that, we compared two farms, an ICLS and a CC having the same soil type and landscape position. The ICLS farm produces alfalfa grazed alternatively with soybean and corn, and the CC farm produces the latter two crops in a continuous sequence. Soil samples (0–5, 5–20, 20–40, and 40–60 cm) were collected and analyzed for SOC, its physical fractions, and their isotopic signature ($\delta^{13}C$). Soils under ICLS showed an increment of 50% of SOC stock compared to CC in the first 60 cm. This increase was related to 100–2000 µm fractions of SOC. The shift in $\delta^{13}C$ signature is more in ICLS than in CC, suggesting that rotation with C3 legumes contributed to C sequestration and, therefore, climate-smart agriculture. The combination of on-farm research and isotopic technique can help to study deeply the effect of real farm practices on soil carbon derived from pasture.

Keywords: soil organic carbon; pastures; on-farm research; isotopic techniques; alfalfa; continuous cropping systems; humid pampas

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1. Introduction

Declining soil fertility and quality because of poor farming practices under the changing climate is a big threat to the sustainability of crop production. Climate-smart agriculture (CSA) is an approach that guides actions needed to transform and reorient agricultural systems to effectively support the development and ensure food security in a changing climate [1]. To meet the growing demand of the increasing human population and enhance soil fertility and health, an integrated crop–livestock system (ICLS) has been proposed as one of the best farm management practices [2]. Diverse multiple crop/pasture systems are required rather than crop rotation alone. Crop livestock integration diversifies landscape mosaics, enhancing biodiversity [3]. Among the benefits of ICLS, we find the better synchronization of biogeochemical cycles due to the alternation of pastures and crops, the increase in farm resilience to adverse climatic and economic events, and the promotion of the many ecosystem services they can provide [4].

Of these ecosystem services, the increment of soil organic carbon (SOC) contributes to improving soil quality and mitigating climate change. Forages have extensive, fibrous root systems that explore large volumes of soil deeper than most grain crops. Perennial forages also extend the growing season compared with annual cash crops, thereby photosynthesizing, depositing rhizosphere C inputs, and consuming soil water during longer periods than annual crops. This extended growth period is likely to contribute to soil C sequestration. Another key factor is that perennial forages remain in the field without soil disturbance for several years. Lack of soil disturbance may be vital for integrated crop-livestock systems to enhance SOC accumulation rather than simply to maintain it [5].

Robust data from a variety of regions around the world remain to be collected to generalize responses from this contrast in farming systems, especially at the farm level, which provides a more realistic estimation of the impact of the integration of livestock and crops than the plot level. On-farm research facilitates many of the troubleshoots of ICLS research, such as the experimental design and statistical analysis, the facility requirements, and the multidisciplinary approach [6]. On-farm research also leads to improved productivity, better economics, higher adoption of conservation practices, and greater farmer satisfaction [7,8].

In the humid pampas, the most important farming region of Argentina, the replacement of natural vegetation into farming systems and their oversimplification due to the high soybean proportion in the crop sequence has been the main cause of environmental degradation [9]. This process produced mainly a decline in the soil organic content and an increase in the soil erosion risk over the last century [10,11]. Fortunately, nowadays, most of the continuous cropping systems (CC) in Argentina are under no tillage [12], which contributes to the soil erosion reduction [13], but limits the SOC sequestration due to the oversimplification of the crop sequence [14], in this sense ICLS soils have a high potential to store additional amounts of SOC since degradation by agricultural uses have caused C losses in the past [15,16]. Design of well-planned cropping systems that include legumes, with crops established by no-till seeding procedures, should be a key practice to attend to sustainability in these systems.

The SOC is mainly stored in two major pools: as particulate organic carbon (POC), mostly of plant origin, and as mineral organic carbon (MOC), which is adhered to the mineral surface [17]. The study of these different fractions allows researchers a better understanding of the dynamic of SOC accumulation and its response to agricultural management [18,19]. In addition, the use of a stable isotope is a powerful tool for assessing plant carbon–soil interaction. The stable carbon isotope signature of soil is widely used to indicate the sources of SOC in agricultural ecosystems where there is a shift between C3 and C4 crops. The $\delta^{13}C$ compositions in soils inherit that of vegetation, and there were marked $\delta^{13}C$ discrepancies between C3 (from −20‰ to −33‰) and C4 (from −17‰ to −9‰) vegetation [20]. The combination of these approaches would allow us to better understand the long-term effects of legume pastures in ICLS and, therefore, its contribution to CSA. There is little information about the role of pasture on soil carbon sequestration under real farm conditions with the combined use of soil organic carbon fractions and isotopic techniques. Thus, our objectives were to compare SOC and its physical fractions in ICLS and CC, and evaluate the use of $\delta^{13}C$ to identify the source of C of SOC in these systems in the humid pampas region of Argentina under real farm conditions.

2. Materials and Methods

2.1. Site Description

The study was conducted near the city of Venado Tuerto, in Santa Fe province, Argentina (33°39′ S; 62°10′ W), which is located in the humid pampas ecoregion. The mean annual temperature is 16 °C and the mean annual precipitation is 950 mm [21]. Soils developed on Holocene loessical sediments predominating Mollisols [22]. Continuous cropping under no tillage is the predominant farming system, in which soybean (*Glicine max* L.) and maize (*Zea mays* L.) are the main crops [23]. The ICLS remains on a temperate pasture, mainly alfalfa (*Medicago sativa* Merril), extensively grazed by steers, which allows a beef production higher than 800 kg ha^{-1} y^{-1} [24].

2.2. Experimental Design

Two farms inside the same soil cartographic unit and landscape position in the region were compared (Figure 1). The ICLS farm produces alfalfa (C3 vegetation type) grazed extensively by cattle for four years alternatively with a grain summer crops sequence of soybean (C3 vegetation type) and maize (C4 vegetation type), and the farm under continuous cropping system (CC) produces soybean and corn in a continuous sequence. The corn and the soybean are made using the same technological management in both farms: under no-tillage, with low fertilization rates: from 25 to 50 kg N ha^{-1} in maize and from 0 to 10 kg P ha^{-1} in soybean. The grain yield ranges from 10 to 12 Mg ha^{-1} in maize and between 3.5 and 5 Mg ha^{-1} in soybean. These management practices have been carried out for more than 15 years on each farm, according to farmers' registers. In addition, we selected a third site under natural vegetation to have a reference soil (REF). This site was never cropped and is composed of grasslands and a xeric woodland.

Figure 1. Location of the study. ICLS, limits of the integrated crop-livestock farm; CC, limits of the continuous cropping farm. Soil cartographic units at 1:50,000 [25]. Mg-01. 1-05: Maggiolo soil series (Typic Hapludoll).

The soil is classified as a Typic Hapludoll series Maggiolo according to the USDA Soil Taxonomy [26]. The first 21 cm of the profile corresponds to a black A horizon, well supplied with organic matter, with a loamy texture, and structured in blocks. The subsoil (horizon B) is loamy to sandy clay loam in texture and barely meets the requirements of being an argillic horizon. It extends up to 46 cm, from which a transitional horizon (BC) begins until reaching the original material (horizon C) at 74 cm. The soils of the Maggiolo series are fertile and do not present physical–chemical limitations [27]. The soil texture and the soil bulk density of the upper horizon are shown in Table 1.

Table 1. Texture and bulk density (BD) in composite samples in CC, continuous cropping farm; ICLS, integrated crop-livestock farm; and REF, reference soil under natural vegetation.

	BD	Clay	Silt	Sand
	Mg m^{-3}		g kg^{-1}	
CC	1.3	360	330	310
ICLS	1.3	340	260	400
REF	0.8	310	400	280

2.3. Soil Sampling and Analytical Determination

Soil samples were taken before the planting of the summer crops in the spring of 2014 in all treatments. The sampling sites in the ICLS were chosen in paddocks that had alfalfa no more than four years ago and at least two pasture periods in the last ten years, according to the farmers' information. We took triplicate random samples using a soil probe at the following soil depths: 0–5 cm, 5–20 cm, 20–40 cm, and 40–60 cm. At a deeper depth (>60 cm), we found the presence of a water table.

Samples were air-dried and passed through a 2 mm sieve. The physical fractionation of SOC was carried out, from which the following fractions were obtained: coarse particulate organic carbon (POCc, 100–2000 μm), intermediate particulate organic carbon (POCi, 50–100 μm), and mineral organic carbon (MOC, <50 μm) according to [28]. The technique consisted of suspending 30 g of soil in 120 mL of distilled water to make a homogeneous stirring; three small spheres of glass were used in a mechanical agitator for 4 h. The wet sieving was carried out with a vibration sieve (FRITSCH Analysette 3 PRO). The different fractions were dried in an oven at 60 °C until they reached a stable weight. The SOC was determined using the Walkley and Black procedure [29]. We also determined the bulk density (BD) using the core sampler method at each depth using cylinders of 245 cm^3 volume [30]. The SOC stock was calculated with the following expression in which T is the sampling depth (Equation (1)):

$$SOC\ Stock\ \left[Mg\ ha^{-1}\right] = \sum_{0}^{0.6} SOC\ \left[g\ kg^{-1}\right] \times BD\left[Mg\ m^{-3}\right] \times T\ [m] \times 10 \quad (1)$$

The $\delta^{13}C$ is an expression of the natural abundance of the isotope in relation to a laboratory reference material calibrated against an international standard Pee Dee Belemnite (PDB). The measurement of $\delta^{13}C$ was carried out using the mass isotopic mass spectrometry (EA-IRMS) technique, and normalization of $\delta^{13}C$ results was performed on the L-SVEC-NBS-19 scale, according to [31]. The $\delta^{13}C$ is expressed in units per thousand (‰) and calculated using Equation (2).

$$\delta^{13}C\ (‰) = \left[\frac{R_{sample} - R_{PDB}}{R_{PDB}}\right] \times 1000 \quad (2)$$

where $R_{sample} = {}^{13}C/{}^{12}C$ is the isotopes ratio in the sample, and $R_{PDB} = {}^{13}C/{}^{12}C$ is the isotopes ratio in the international standard Pee Dee Belemnite (PDB).

2.4. Data Analysis

The three land uses: CC, ICLS, and REF were compared assuming the same soil type and landscape position [32]. The SOC, MOC, POCi, POCc, and $\delta^{13}C$ data at each depth were subjected to an analysis of variance (ANOVA). Differences among treatment means were examined using the least significant difference (LSD). All the tests were performed at the 5% level of probability using Infostat v.2017 [33].

3. Results and Discussion

3.1. Total Soil Organic Carbon Content

The vertical distribution of SOC in the soil profile is shown in Figure 2. The higher SOC concentration in the upper layer was observed in REF (30.6 g kg^{-1}), followed by ICLS (21.9 g kg^{-1}) and CC (17.2 g kg^{-1}). There was a similar trend in the 5–20 cm layer, with values of 22.2, 15.9, and 11.7 g kg^{-1} ($p < 0.05$). At 20–40 cm, REF was equal to ICLS ($p > 0.05$), and both were statistically higher than the CC ($p < 0.05$). At the deepest layer, there were no differences among treatments ($p > 0.05$). These results agree with those of [34], which found that the differences in SOC content among land uses are limited to the first 50 cm in the study region. The main differences in SOC observed in the first 20 cm were probably due to the effect of different soil disturbances and above-ground plant residue input. The deeper roots in ICLS and REF can explain the effect at 20–40 cm. These results agreed with those reviewed to pasture-crop rotations in Europe and America [35,36]. It has been shown that the type of vegetation root system affects the vertical distribution of SOC [37,38].

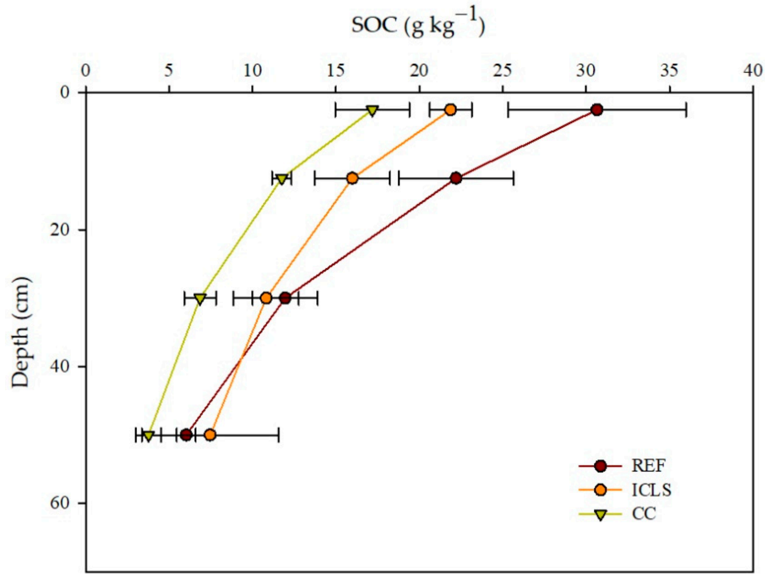


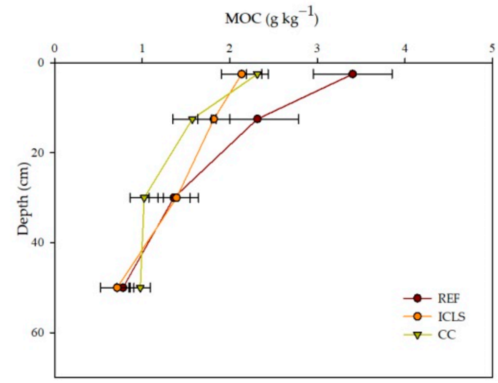
Figure 2. Vertical distribution in the soil profile of soil organic carbon (SOC) among different land uses: integrated crop-livestock system (ICLS), continuous cropping system (CC), and a reference soil (REF). Horizontal bars represent the standard deviation (n = 3).

The SOC stock to 60 cm soil depth was 102 Mg ha^{-1} in REF, 93 Mg ha^{-1} in ICLS, and 62 Mg ha^{-1} in CC ($p < 0.05$). The soil bulk density was similar between CC and ICLS ($p > 0.05$) and higher than in REF ($p < 0.05$). These values were consistent with those of previous regional studies [34]. This means an increment of 50% in SOC stock from the conversion of CC into ICLS. These agreed with previous findings after the long-term growth of alfalfa in China [39,40]. In the same region, a previous study has reported similar differences due to cultivation, in which soils with similar SOC content to REF tended to lose SOC when they were converted to agriculture or pastures [34]. The large gain in SOC with the establishment and maintenance of perennial pastures seems a key mitigation strategy to climate change offered by ICLS in soil with low carbon saturation as agricultural ones [41,42]. In this sense, this could be a good strategy to overcome the limitation of agriculture under no-tillage to sequester SOC and, therefore, to achieve international policy [43,44].

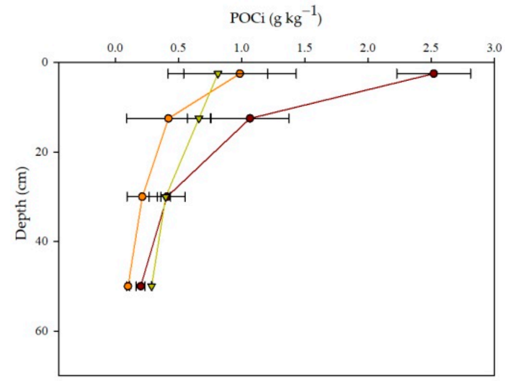
3.2. Mineral and Particulate Organic Carbon

The vertical distribution of MOC, POCi, and POCc in the soil profile among land uses is presented in Figure 3. The MOC, POCi, and POCc contents decreased with soil depth. There was a greater accumulation of POCi in REF (2.5 g kg^{-1}) compared to ICLS (0.98 g kg^{-1}) and CC (0.81 g kg^{-1}, $p < 0.05$) in the superficial layer (0–5 cm). According to [19], levels of POC are directly related to the input of plant residues in soil. No differences were detected between ICLS and CC in POCi, unlike [19], although these authors analyzed POCc and POCi together. Therefore, the carbon coming from the surface residues was similar between ICLS and CC. These results can be explained by the fact that in our study, we sampled during the same period (before the planting of the summer crops) in both CC and ICLS.

The POCc fraction was similar among treatments in the first 20 cm, whereas at 20–60 cm was greater in ICLS than in CC ($p < 0.05$). This means that the most active fraction of organic carbon was only sensitive at subsoil, probably for a greater root system. Previous research concluded that the relationship between root biomass and SOC is driven mainly by the POC fraction [45]. It has been shown that the majority of below-ground-derived-POC is contributed by roots, especially in low shoot:root ratio species, such as alfalfa, when compared to higher root:ratio species, such as annual grain crops [46].



(**a**)



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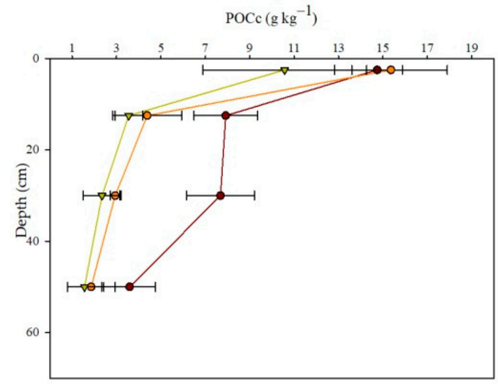

(**c**)

Figure 3. Vertical distribution in the soil profile of (**a**) mineral organic carbon (<50 μm, MOC), (**b**) intermedium particulate organic carbon (50–100 μm, POCi), and (**c**) coarse particulate organic carbon (100–2000 μm, POCc) among different land uses: integrated crop-livestock system (ICLS), continuous cropping system (CC), and a reference soil (REF). Horizontal bars represent the standard deviation (n = 3).

The MOC was higher in REF (3.4 g kg^{-1}) compared to ICLS (2.1 g kg^{-1}) and CC (2.3 g kg^{-1}, $p < 0.05$) in the upper layer (0–5 cm), reflecting the low influence of management on the formation or rupture of aggregates under 53 μm. There was no difference among treatments at deeper depths (5–60 cm; $p > 0.05$). This agrees with [47], who affirm that the accumulation of soil organic C occurred primarily in the particulate rather than the non-particulate organic C pool.

3.3. Isotopic Determination

3.3.1. Total Soil Organic Carbon

The $\delta^{13}C$ values increased with increases in soil depths, with the exception of ICLS and CC at 40–60 cm (Figure 4). This is related to several processes: (a) The Suess effect (^{13}C-depleted CO_2 in the modern atmosphere since the industrial revolution); (b) the change of environmental factors, such as water and light, affect the efficiency of CO_2 conservation in photosynthesis; (c) preferential utilization of ^{13}C-depleted plant compounds and accumulation of ^{13}C-enriched microbial biomass; (d) downward translocation of ^{13}C-enriched dissolved organic carbon (DOC) through profiles [48]. The $\delta^{13}C$ signatures varied among the three land uses and were higher for REF and ICLS compared to CC (Figure 4). The $\delta^{13}C$ signatures in 0–5 cm for REF, ICLS, and CC were −20.10, −20.04, and −19.76‰, respectively. In cold regions, the mineralization and processes associated with humus formation in the topsoil, the abundance in ^{13}C is lower (−26.2‰) [49]; while such values in 5–20 cm soil depth for these treatments were −17.88, −17.60, and −17.29‰, respectively. At 20–40 cm, we found the maximum shift, with −17.03‰ in REF, −15.96‰, in ICLS and −14.91‰ in CC ($p < 0.05$). There were no differences between treatments at 40–60 cm ($p > 0.05$).

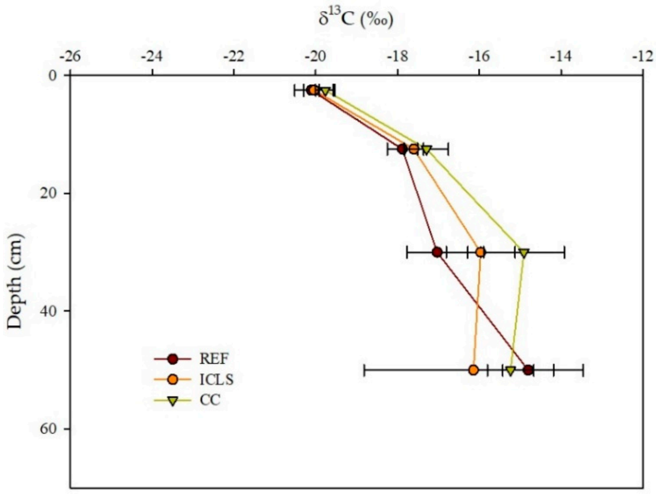

Figure 4. Vertical distribution in the soil profile of $\delta^{13}C$ natural abundance in soil organic carbon (SOC) among different land uses: integrated crop-livestock system (ICLS), continuous cropping system (CC), and a reference soil (REF). Horizontal bars represent the standard deviation (n = 3).

The fractionation, which occurs during CO_2 uptake and photosynthesis, depends on the type of plant and the climatic and ecological conditions. The Hatch–Slack photosynthetic pathway (C4) results in $\delta^{13}C$ figures of −10 to −15‰ and is primarily represented by certain grains and desert grasses (sugar reed, corn). In temperate climates, most plants employ the Calvin mechanism (C3), producing $\delta^{13}C$ values in the range of −26‰ [49,50]. These results agree with previous research in the same sites and reflect a higher proportion of C3 species in the crop sequence due to the incorporation of alfalfa [51]. Previous research found that the increasing trend of $\delta^{13}C$ with soil depths is owing to carbon input. During SOC decomposition, ^{12}C atoms are preferred to ^{13}C in the microbially metabolized CO_2 product; thereby, ^{13}C atoms accumulate in the decomposed substrate. An increase in the decomposition process results in ^{13}C enriched SOC relative to newer SOC at the soil surface that migrates down the soil profile and, in turn, is reflected in the relatively increased $\delta^{13}C$ gradient with depth [52,53].

3.3.2. Mineral and Particulate Organic Carbon

The vertical distribution in the soil profile of $\delta^{13}C$ among the MOC, POCi, and POCc is shown in Figure 5. The fractions differed in the range of $\delta^{13}C$ values on the soil surface

(0–5 cm), taking into account the three land uses; they were: −23.3, −21.3, and −19.1‰ for POCc, POCi, and MOC, respectively This indicates that δ^{13}C accumulates in MOC in greater quantity than in the other fractions, this is due to physical protection and the slower turnover rate of soil organic C in clay fraction [54].

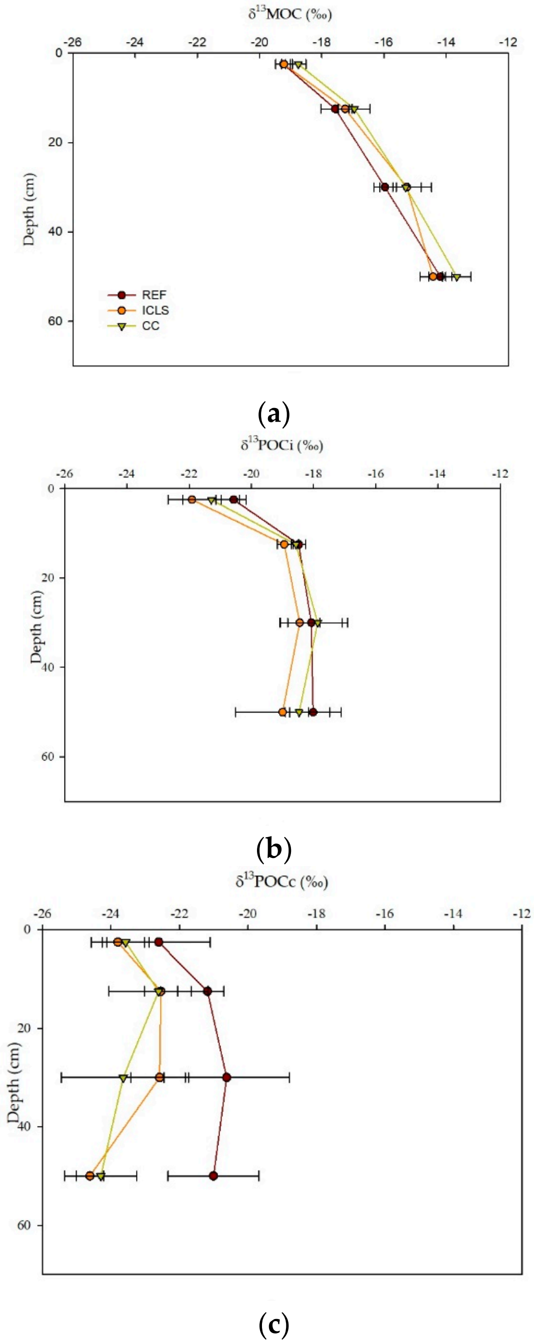

Figure 5. Vertical distribution in the soil profile of δ^{13}C natural abundance in (**a**) mineral organic carbon (<50 µm, MOC), (**b**) intermedium particulate organic carbon (50–100 µm, POCi), and (**c**) coarse particulate organic carbon (100–2000 µm, POCc) among different land use: integrated crop-livestock system (ICLS), continuous cropping system (CC), and a reference soil (REF). Horizontal bars represent the standard deviation (n = 3).

The natural abundance δ^{13}C in MOC was higher in CC (−18.7‰) than in ICLS and REF (−19.22‰) at 0–5 cm soil depth. This suggests a high proportion of C derived from C3 in ICLS and REF. In this fraction, there were no differences among land uses in the other depths, with a tendency for higher values at deeper depths (Figure 5a). The POCi followed the same trend in depth as SOC (Figure 5b). There were differences among treatments only at 40–60 cm, at which REF > ICLS > CCS ($p < 0.05$). In relation to POCc, the differences among treatments were detected at 20–40 cm, at which REF > ICLS = CC. It is also observed that the lower values of $\delta^{13}C$ are found in MOC than POCi and POCc this may be related to the lower rate of decomposition of MOC and the protection of $\delta^{13}C$. In turn, in the MOC fraction, an enrichment of $\delta^{13}C$ in depth is observed due to the lower disturbance in the soil, decreasing the decomposition rate of carbon [55,56].

3.4. General Discussion

The land use change from natural vegetation to agricultural systems produces a decline of total SOC and its physical fractions. Between the latter, the change from ICLS to CC has reduced 50% the SOC stock, especially in the first 40 cm. This difference can be related to the reduction of POC, especially from 100–2000 µm in the sub-soil (20–40 cm). This change can be traced in the SOC and in the POC by the shift of $\delta^{13}C$, which indicates that their source is related to a higher proportion of C3 pasture roots. Using the combination of isotopic techniques and physical fractionation of SOC, it can be shown under real farming conditions that alfalfa increased C sequestration in ICLS by below-ground-derived-POC which is contributed by roots.

The effect of the roots is also expressed in the abundance $\delta^{13}C$ in depth. During SOC decomposition, ^{12}C atoms are preferred to ^{13}C in the microbially metabolized CO_2 product, thereby, ^{13}C atoms accumulate in the decomposed substrate. An increase in the decomposition process results in ^{13}C enriched SOC relative to newer SOC at the soil surface that migrates down the soil profile and, in turn, is reflected in the relatively increased $\delta^{13}C$ gradient with depth. This trend appears in $\delta^{13}C$ of MOC; in this fraction, an enrichment of $\delta^{13}C$ in depth is observed, due to the lower disturbance in the soil, decreasing the decomposition rate of carbon.

4. Conclusions

The integration of crop and livestock under no tillage improved SOC levels compared to continuous cropping systems under real farm conditions in the humid pampas. This confirms the importance of this farming style as a climate-smart agriculture practice.

The change of SOC was associated with an increase in POC, especially the fraction between 100–2000 µm in the sub-soil. The use of $\delta^{13}C$ was useful to identify the source of this increase, as shown values are associated with the shift of C4 to C3 vegetation, associated with alfalfa roots.

The combination of on-farm research and isotopic technique can help to study deeply the effect of real farm practices on soil carbon derived from pastures and to improve farmers' perception of the importance of perennial pastures to soil health and climate-smart agriculture. More research is needed to assess if the emission of CH_4 by cattle and N_2O by crops and pastures under these conditions can neutralize the benefits of soil organic carbon storage under these conditions.

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References

1. FAO. *Climate Smart Agriculture Sourcebook*; Food and Agriculture Organization: Rome, Italy, 2013.
2. Lemaire, G.; Franzluebbers, A.J.; De Fassio Carvalho, P.C.; Debieu, B. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agric. Ecosyst. Environ.* **2014**, *190*, 4–8. [CrossRef]
3. Sanderson, M.; Archer, D.; Hendrickson, J.; Kronberg, S.; Liebig, M.; Nichols, K.; Schmer, M.; Tanaka, D.; Aguilar, J. Diversification and ecosystem services for conservation agriculture: Outcomes from pastures and integrated crop–livestock systems. *Renew. Agric. Food Syst.* **2013**, *28*, 129–144. [CrossRef]
4. Martin, G.; Moraine, M.; Ryschawy, J.; Magne, M.A.; Asai, M.; Sarthou, J.P.; Duru, M.; Therond, O. Crop-livestock integration beyond the farm level: A review. *Agron. Sustain. Dev.* **2016**, *36*, 53. [CrossRef]
5. Franzluebbers, A.J.; Lemaire, G.; De Fassio Carvalho, P.C.; Sulc, R.M.; Debieu, B. Toward agricultural sustainability through integrated crop-livestock systems: Environmental outcomes. *Agric. Ecosyst. Environ.* **2014**, *29*, 192–194. [CrossRef]
6. Tanaka, D.; Karn, J.F.; Schilljegerdes, E.J. Integrated crop/livestock systems research: Practical research considerations. *Renew. Agric. Food Syst.* **2007**, *23*, 80–86. [CrossRef]
7. Kyeryga, P. On-Farm Research: Experimental Approaches, Analytical Frameworks, Case Studies, and Impact. *Agron. J.* **2019**, *111*, 2633–2635. [CrossRef]
8. Buck, H.J.; Palumbo-Compton, A. Soil carbon sequestration as a climate strategy: What do farmers think? *Biogeochemistry* **2022**, *161*, 59–70. [CrossRef]
9. Viglizzo, F.E.; Carreño, L.V.; Pereyra, H.; Ricard, F.; Clatt, J.; Pincén, D. Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. *Glob. Chang. Biol.* **2011**, *17*, 959–973. [CrossRef]
10. Villarino, S.H.; Studdert, G.A.; Laterra, P.; Cendoya, M.G. Agricultural impact on soil organic carbon content: Testing the IPCC carbon accounting method for evaluations at county scale. *Agric. Ecosyst. Environ.* **2014**, *185*, 118–132. [CrossRef]
11. Colazo, J.C.; Carfagno, P.F.; Gvozdenovich, J.; Buschiazzo, D.E. Soil erosion. In *The Soils of Argentina*; Rubio, G., Lavado, R., Pereyra, F., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 118–132.
12. Peiretti, R.; Dumanski, J. The transformation of agriculture in Argentina through soil conservation. *Int. Soil Water Conserv. Res.* **2014**, *2*, 14–20. [CrossRef]
13. Borelli, P.; Robinson, D.A.; Fleischer, L.R.; Lugato, E.; Ballabio, C.; Alewell, C.; Meusburger, K.; Modugno, S.; Schutt, B.; Ferro, V.; et al. An assessment of the global impact of 21st century land use change on soil erosion. *Nat. Commum.* **2017**, *8*, 2013. [CrossRef] [PubMed]
14. Luo, Z.; Wang, E.; Sun, O.J. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agric. Ecosyst. Environ.* **2010**, *139*, 224–231. [CrossRef]
15. Lorenz, K.; Lal, R. *Carbon Sequestration in Agricultural Ecosystems*; Springer Nature: Cham, Switzerland, 2018; pp. 137–173.
16. Hendrickson, J.; Colazo, J.C. Using crop diversity and conservation cropping to develop more sustainable arable cropping systems. In *Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality*; Lemaire, G., de Faccio Carvalho, P., Kronberg, S., Recous, S., Eds.; Elsevier: London, UK, 2019; pp. 93–108.
17. Witzgall, K.; Vidal, A.; Schubert, D.I.; Höschen, C.; Schweizer, S.; Buegger, F.; Pouteau, V.; Chenu, C.; Mueller, C. Particulate organic matter as a functional soil component for persistent soil organic carbon. *Nat. Commun.* **2021**, *12*, 4115. [CrossRef] [PubMed]
18. Franzluebbers, A.J.; Stuedemann, J. Early Response of Soil Organic Fractions to Tillage and Integrated Crop-Livestock Production. *Soil Sci. Soc. Am. J.* **2008**, *72*, 613–625. [CrossRef]
19. Loss, A.; Pereira, M.G.; Perin, A.; Silva Coutinho, F.; Cunha Dos Anjos, L.H. Particulate organic matter in soil under different management systems in the Brazilian Cerrado. *Soil Res.* **2012**, *50*, 685–693. [CrossRef]
20. Zhu, X.; Di, D.; Ma, M.; Shi, W. Stable Isotopes in Greenhouse Gases from Soil: A Review of Theory and Application. *Atmosphere* **2019**, *10*, 377. [CrossRef]
21. De Ruyver, R.; Di Bella, C. Climate. In *The Soils of Argentina*; Rubio, G., Lavado, R., Pereyra, F., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 27–48.
22. Rubio, G.; Pereyra, F.X.; Taboada, M. Soils of the Pampean region. In *The Soils of Argentina*; Rubio, G., Lavado, R., Pereyra, F., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 82–100.
23. Dominguez, J.; Rubio, G. Agriculture. In *The Soils of Argentina*; Rubio, G., Lavado, R., Pereyra, F., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 209–238.
24. Garbulsky, M.; Deregibus, A. Argentina. In *Country Pasture/Forage Resources Profiles*; Suttie, J.M., Reynolds, S.G., Eds.; FAO: Rome, Italy, 2004; p. 28.
25. GEOINTA. Available online: http://visor.geointa.inta.gob.ar/ (accessed on 2 September 2022).

26. Soil survey staff. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd ed.; USDA–NRCS: Washinton, DC, USA, 1999; pp. 235–287.
27. INTA. Soil Series. Available online: http://rafaela.inta.gov.ar/maps/suelos/__series/mg/ (accessed on 2 September 2022).
28. Cambardella, C.A.; Elliot, E.T. Particulate soil organic matter changes across a grassland cultivation sequence. *Soil Sci. Soc. Am. J.* **1992**, *56*, 777–783. [CrossRef]
29. Nelson, D.W.; Sommers, L.E. Total carbon, organic carbon and organic matter. In *Chemical Methods. Methods of Soil Analysis. Part 3*; Bigham, J.M., Ed.; SSSA: Madison, WI, USA, 1996; pp. 961–1010.
30. Grossman, R.B.; Reinsch, T.G. Bulk density and linear extensibility: Core method. In *Methods of Soil Analysis Part 4, Physical Methods*; Dane, J.H., Topp, G.C., Eds.; SSSA: Madison, WI, USA, 2002; pp. 201–228.
31. Coplen, T.B.; Brand, W.A.; Gehre, M.; Gröning, M.; Meijer, H.; Toman, B.; Verkouteren, R.M. New Guidelines for $\delta^{13}C$ Measurements. *Anal. Chem.* **2006**, *78*, 2439–2441. [CrossRef]
32. Pennock, D.J. Designing field studies in soil science. *Can. J. Soil Sci.* **2004**, *84*, 1–10. [CrossRef]
33. Di Rienzo, J.A.; Casanoves, F.; Balzarini, M.G.; Gonzalez, L.; Tablada, M.; Robledo, C.W. *InfoStat*, v. 2017; Universidad Nacional de Córdoba: Córdoba, Argentina, 2017. Available online: http://www.infostat.com.ar/(accessed on 2 September 2022).
34. Berhongaray, G.; Álvarez, R.; De Paepe, J.; Caride, C.; Cantet, R. Land use effects on soil carbon in the Argentine Pampas. *Geoderma* **2013**, *192*, 97–110. [CrossRef]
35. Franzluebbers, A.J.; Sawchik, J.; Taboada, M. Agronomic and Environmental impacts of pasture-crop rotations in temperate North and South America. *Agric. Ecosyst. Environ.* **2014**, *190*, 18–26. [CrossRef]
36. Peyraud, J.L.; Taboada, M.; Delaby, L. Integrated crop and livestock systems in Western Europe and South America: A review. *Eur. J. Agron.* **2014**, *57*, 31–42. [CrossRef]
37. Jobbágy, E.G.; Jackson, R.B. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* **2000**, *10*, 423–436. [CrossRef]
38. Lal, R. Sequestering carbon and increasing productivity by conservation agriculture. *J. Soil Water Conserv.* **2015**, *70*, 55–62. [CrossRef]
39. Song, X.; Fang, C.; Yuan, Z.; Li, F. Long Term Growth of Alfalfa Increased Soil Organic Matter Accumulation and Nutrient Mineralization in a Semi-Arid Environment. *Front. Environ. Sci.* **2021**, *9*, 649346. [CrossRef]
40. Chang, S.; Liu, N.; Wang, X.; Zhang, Y.; Xie, Y. Alfalfa Carbon and Nitrogen Sequestration Patterns and Effects of Temperature and Precipitation in Three Agro—Pastoral Ecotones of Northern China. *PLoS ONE* **2012**, *7*, e50544. [CrossRef]
41. Álvarez, R.; Berhongaray, G. Soil organic carbon sequestration potential of Pampean soils: Comparing methods and estimation for surface and deep layers. *Soil Res.* **2020**, *12*, 346–358. [CrossRef]
42. Georgiou, K.; Jackson, R.; Vindusková, O.; Abramoff, R.; Ahlström, A.; Feng, W.; Harden, J.; Pellegrini, A.; Polley, H.; Soong, J.; et al. Global stock and capacity of mineral-associated soil organic carbon. *Nat. Commum.* **2022**, *13*, 3797. [CrossRef]
43. Powlson, D.S.; Stirling, C.M.; Jat, M.L.; Gerard, B.G.; Palm, C.A.; Sanchez, P.; Cassman, K. Limited potential of no-till agriculture for climate change mitigation. *Nat. Clim. Chang.* **2014**, *4*, 678–683. [CrossRef]
44. Minasny, B.; Malone, B.; Mc Bratney, A.; Angers, D.; Arrouays, D.; Chambers, A.; Chaplot, V.; Chen, Z.-S.; Cheng, K.; Das, B.S.; et al. Soil Carbon 4 per mile. *Geoderma* **2017**, *292*, 59–86. [CrossRef]
45. Ojeda, J.; Caviglia, O.; Agnusdei, M. Vertical distribution of root biomass and carbon stocks in forage cropping systems. *Plant Soil* **2018**, *423*, 175–191. [CrossRef]
46. Villarino, S.; Pinto, P.; Jackon, R.; Piñeiro, G. Plant rhizodeposition: A key factor for soil organic matter formation in stable fractions. *Sci. Adv.* **2021**, *7*, eabd3176. [CrossRef] [PubMed]
47. Franzluebber, A.; Studemann, J.A. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. *Environ. Pollut.* **2002**, *116*, 53–62. [CrossRef]
48. Liu, M.; Han, G.; Zhang, Q.; Song, Z. Variations and Indications of $\delta^{13}C_{SOC}$ and $\delta^{15}N_{SON}$ in Soil Profiles in Karst Critical Zone Observatory (CZO), Southwest China. *Sustainability* **2019**, *11*, 2144. [CrossRef]
49. Balesdent, J.; Mariotti, A. Natural ^{13}C abundance as a tracer for studies of soil organic matter dynamics. *Soil Biol. Biochem.* **1987**, *19*, 25–30. [CrossRef]
50. IAEA. *Use of Isotope and Radiation Methods in Soil and Water Management and Crop Nutrition*; IAEA: Vienna, Austria, 2001; pp. 21–96.
51. De Dios Herrero, J.M.; Colazo, J.C.; Guzmán, M.L.; Saenz, C.A.; Sager, R.; Sakadevan, K. Soil organic carbon assessments in cropping systems using isotopic techniques. In Proceedings of the EGU General Assembly Conference, Vienna, Austria, 23 April 2016.
52. Qu, Q.; Zhang, J.; Hay, X.; Wu, J.; Fan, J.; Wang, D.; Li, J.; Shangguan, Z.; Deng, L. Long-term fencing alters the vertical distribution of soil $\delta^{13}C$ and SOC turnover rate: Revealed by MBC-$\delta^{13}C$. *Agric. Ecosyst. Environ.* **2022**, *339*, 108119. [CrossRef]
53. Smith, C.J.; Chalk, P.M. Carbon ($\delta^{13}C$) dynamics in agroecosystems under traditional and minimum tillage systems: A review. *Soil Res.* **2021**, *59*, 661–672. [CrossRef]
54. Acton, P.; Fox, J.; Campbell, E.; Rowe, H.; Wilkinson, M. Carbon isotopes for estimating soil decomposition and physical mixing in well-drained forest soils. *J. Geophys. Res. Biogeosci.* **2013**, *118*, 1532–1545. [CrossRef]
55. Accoe, F.; Boeckx, P.; Van Cleemput, O.; Hofman, G.; Zhang, Y.; Li, R.; Chen, G. Evolution of ^{13}C signature related to total carbon in a soil profile under grassland. *Rapid Commun. Mass Spectrom.* **2002**, *16*, 2184–2189. [CrossRef]
56. Loss, A.; Pereira, M.; Perin, A.; Beutler, S.; Cunha Dos Anjos, L. Carbon, Nitrogen and natural abundance of $\delta^{13}C$ and $\delta^{15}N$ of light-fraction organic matter under no-tillage and crop-livestock integration systems. *Acta Sci. Agron.* **2012**, *34*, 465–472. [CrossRef]