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A comparative analysis of soil organic carbon stock and soil aggregation in two crop sequences in the Rolling Pampa (Argentina)

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ABSTRACT

Understanding how farming practices affect soil organic carbon (SOC) accumulation is essential for sustainable agriculture. Agronomic decisions, such as crop sequence, significantly influence various soil properties. However, the overall benefits of crop rotation on soil structure and SOC storage remain uncertain. We compared the effects of soybean (*Glycine max* L.) monocropping with a three-year crop rotation comprising wheat (*Triticum aestivum* L.)/soybean double crop, maize (*Zea mays* L.), and soybean on the vertical distribution of SOC up to one metre depth. Additionally, we examined carbon accumulation as particulate organic matter-carbon (POM-C), soil aggregation, and structural stability in the topsoil. Compared to monocropping, crop rotation increased SOC concentrations (19 *vs.* 16 gC kg soil^{-1}), stock (12 *vs.* 10.7 MgC ha^{-1}), and POM-C content (6 *vs.* 3.2 gC kg soil^{-1}) in the first 5 cm of soil. At 20–65 cm depth, rotation showed a marginal increment of SOC stock with respect to soybean monocropping. The increased surface SOC content in the rotation positively affected the POM-C content and macro-aggregation. However, soil structural stability showed a tendency to be higher in the monocropping, especially at a depth of 5–20 cm. Overall, crop rotation demonstrated potential for enhanced carbon sequestration in temperate agroecosystems within three years, despite not significantly improving soil structural stability.

1. Introduction

Soil organic carbon (SOC) in agricultural lands is recognised for its importance in providing multiple benefits, including both carbon sequestration and the improvement of soil quality (Six et al., 2004; Plaza-Bonilla et al., 2014; Chang et al., 2018). Agricultural practices that increase SOC stock while reducing losses are critical for climate change mitigation. Crop rotation is an important one, particularly under continuous agriculture, because it increases the amount and variety of plant biomass entering into the soil as stubble while roots enhance soil aggregate formation, where carbon is more protected from mineralization (Zheng et al., 2023; Giustiniani et al., 2024).

The physical protection of soil aggregates is a well-documented mechanism for SOC stabilisation and sequestration, among other benefits for plants and soil biota (e.g. bulk density, nutrient cycles and aeration) (Liu et al., 2021). Approximately 90 % of SOC sequestration occurs at the soil aggregate level (Liu et al., 2021). Soil aggregation is a complex and hierarchical process of soil particle organisation, in which persistent, transient and temporary binding agents lead to the formation of micro- and macroaggregates. Aggregates can be formed around fresh residues, which then become coarse intra-aggregate particulate organic matter (Six et al., 2000). In no-till systems, the continuous input of organic matter increases soil microbial activity and stimulates the production of aggregating agents such as microbial by-products and root exudates (Six et al., 2004). Therefore, a comprehensive evaluation of crop rotation effects on soil aggregation and carbon concentration is imperative to understand and predict the potential benefits of this practice for enhancing soil productivity and carbon sequestration.

The positive effects of crop rotation on soil carbon storage and aggregate formation are well documented; however, the effectiveness of different crop rotations can vary significantly (Zheng et al., 2023). While existing literature largely supports the overall beneficial effects of crop rotation on macroaggregate (> 250 μm) proportion and macroaggregate-associated organic carbon, often at the expense of microaggregates (< 250 μm), some studies report no significant effects on aggregate composition and stability (Iheshiulo et al., 2023). This variability in findings underscores the complexity of soil dynamics and the need for further research to optimise crop rotation strategies for SOC

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sequestration.

In South American agroecosystems, soybean monocropping dominates, while more diverse crop rotations, such as wheat/soybean-maize-soybean sequences, are less common (Wingeyer et al., 2015). A high frequency of soybean in the sequence can negatively affect soil organic matter, particularly labile fractions and carbon stocks (Caviglia and Andrade, 2010). In the rolling Pampean soils, long term diversified crop rotations increase crop residue inputs, soil macroaggregate formation and SOC storage in macroaggregates compared to soybean monocropping (Novelli et al., 2017; Semmartin et al., 2023); however, the effects of crop rotation on soil aggregation and the distribution of SOC within aggregates remain understudied.

While extensive research on soil carbon sequestration has focused on surface layers, deeper soil horizons have been comparatively neglected (Gál et al., 2007; Syswerda et al., 2011). Although it is generally accepted that most soil carbon concentration is stored in the first 30 cm of the soil profile, total carbon storage is higher in deeper soil layers than at the surface, mainly due to increased soil density and mass (Jobbágy and Jackson, 2000; Paustian et al., 2016). Global evidence suggests that approximately 50 % of SOC stocks are located below the top 30 cm of the soil profile (Minasny et al., 2017). While sampling deeper soil layers can introduce greater variability in carbon stock quantification, potentially obscuring significant differences, it is nonetheless recommended to sample beyond 30 cm depth. This is because root distribution and agronomic practices can significantly influence carbon inputs at lower depths (VandenBygaart and Angers, 2006; Kravchenko and Robertson, 2011).

This study evaluates the effects of two cropping sequences—soybean monocropping and a three-year rotation (wheat/soybean-corn-soybean)—on SOC accumulation, its vertical distribution to a depth of one meter, and its impact on soil structure (aggregation and stabilization). We hypothesize that in the rolling Pampean Mollisols, compared to soybean monocropping, the three-year rotation will: (i) increase the SOC stock throughout the one-meter soil profile, and (ii) enhance particulate organic matter-carbon, aggregate stability, and macroaggregate formation in the surface layers.

2. Materials and methods

The research was based on a long-term experiment established at the Estancia Don Eduardo (33° 51' 55.7" S; 60° 40' 28.39" W), rolling Pampa, Buenos Aires province, Argentina. The climate is humid subtropical, with hot summers and no marked dry season (Cfa according to the Köppen climate classification). The average annual rainfall is 980 mm (1932–2015). July is the driest month (33 mm), while the highest rainfall occurs in March (130 mm). The average annual temperature is 18ºC with January being the warmest month (22ºC), while July is the coldest month (10ºC). The soils are developed on deep loess sediment. Soil is a Mollisol (Pergamino series, finely silty, mesic, Typic Argiudoll), well-drained with an upper horizon rich in organic matter. Soils usually have a silt-loam A horizon (19–26 % clay, 55–74 % silt and 4–24 % fine and very fine sand) followed by a silty-clay Bt horizon. The thickness of the Bt horizon is ~60 cm (Table 1) (Urrutia Larrachea et al., 2022).

Table 1
Textural characteristics of typic Argiudoll in the different soil horizons and depth in the Bayer Crop Sciences Field experiment. Soil texture class and %-percentages of clay, silt and sand were represented.

Soil horizons	Depth (cm)	Soil texture class	Clay (%)	Silt (%)	Sand (%)
Ap	0–20	Silty loam	22	68	9
Bt1	20–65	Silty clay	42	52	5
Bt2	65–95	Silty clay loam	26	64	9
BC	95–120	Silty loam	16	74	9

2.1. *Crop sequences and characteristics*

A soybean monocropping and the wheat/soybean-corn-soybean rotation (three-year rotation) were analysed (Fig. 1). This experiment was installed in 2015/2016 in a commercial field, which had been cropped with soybean in 2014. Before the experiment, the field received the regular farming management used in the study region for at least 40 years. The experiment comprised three blocks (replicates). Plot size was 7.3 m and 100 m long. No-till sowing system was implemented because no-tillage management is the most frequently used practice in the region. Soybean seeds were treated with appropriate *Bradyrhizobium* inoculant before sowing. Land occupancy was 111 days year^{-1} for soybean monocropping and 167 days year^{-1} in the rotation (Hisse et al., 2022). Weeds, insects and diseases were throughout the growing season by applying chemical controls using a self-propelled sprayer when necessary.

Sowing dates, density and crop genotype as fertilisation schemes varied between monocropping and crop rotation. While soybean monocropping was managed with "conventional technology", based on the current agricultural management used by the average farmer, the crop rotation was managed with "intensified technology". This management included high-yielding genotypes, higher sowing density for maize and wheat, improved fertilisation technology and doses, and a more advanced crop protection technology (Hisse et al., 2022).

For the 2018–2019 season, soybean monocropping was seeded on November 7 with the DM4612 genotype at a density of 33 plants m^{-2}. For the rotation, wheat was seeded on June 18 with the Don Basilio genotype at a density of 420 plants m^{-2}. In the soybean monocropping, P was supplied as triple superphosphate (16 kg P ha^{-1}) at sowing. In the rotation, wheat was fertilised with N (21 kg N ha^{-1} at sowing and 67.5 kg N ha^{-1} at early tillering), P as complex compound fertiliser (19.6 kg P ha^{-1}) and S (12 kg Sha^{-1}) (see details of the previous seasons in Supplementary Material, TableS1).

From the start of the experiment to the sampling date, plant carbon inputs from the rotation system were double those from soybean monocropping (19±1.9 t C ha^{-1} *vs.* 8.7±2 t C ha^{-1}) (see methodological details in Semmartin et al., 2023). Crop yields were consistently higher in the rotation system compared to soybean monocropping across all three seasons studied (2015/2016, 2016/2017, and 2017/2018).In the 2015/2016 season, wheat yields in the rotation system (4302 kg ha^{-1}) were double those of soybean in monoculture (2470 kg ha^{-1}). For 2016/2017, maize yields in the rotation (15262 kg ha^{-1}) were four times higher than soybean yields in monoculture (3436 kg ha^{-1}). In 2017/2018, soybean yields in the rotation system showed a slight increase (2328 kg ha^{-1}) compared to soybean monocropping (2131 kg ha^{-1}). Overall, soybean yields within the rotation system (2703 kg ha^{-1}) consistently surpassed those of soybeans grown in monoculture (Hisse et al., 2022).

2.2. *Soil sampling and laboratory determinations*

In the spring of the 2018–2019 season (November 2018), soil sampling was conducted in six subplots divided into three blocks. At the time, the soybean monocropping was already sown and the rotation was cropped with wheat. For the upper depths (0–5 cm and 5–20 cm), samples were taken with a cylinder of 5 cm in height and 6 cm in diameter (Buker et al., 1986). These samples were dried at 105 ºC and the bulk density was determined.

Sampling at a depth of 1 m followed the horizons indicated in Table 1, using a 1.9 cm diameter and 60 cm long tubular auger. After the extraction of the sampler, the different soil horizons were first identified and, within each horizon and in the central part, a 10 cm high sample was taken. The sampler was introduced from a depth of 20 cm. The bulk density was determined by subtracting the moisture content calculated in the aliquots of all the subsamples. The remaining samples were taken at air temperature and sieved at 2 mm.

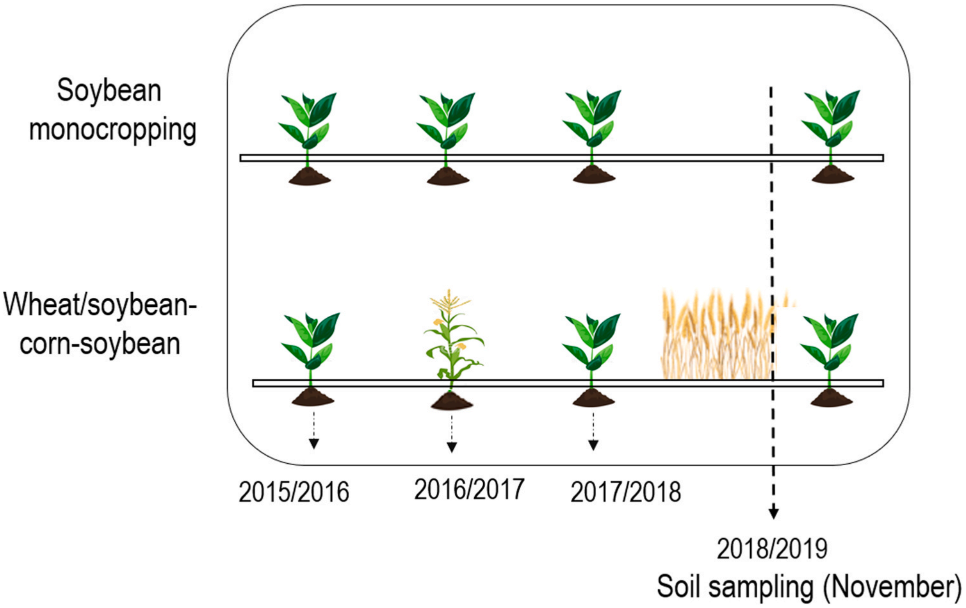

Fig. 1. Diagram of the crop sequence: soybean monocropping (control) and rotation (wheat/soybean-corn-soybean) from the 2015/2016–2018/2019 seasons. The dashed black line indicates the soil sampling time, and the crops present at that time.

Undisturbed samples at 0–5 cm and 5–20 cm were taken with a shovel in each subplot. Part of the sample was used for the determination of structural stability (reserving aggregates of 3–5 mm), another part was sieved at 8 mm and dried at air temperature for soil aggregate sizes determination, and another part was dried and sieved at 2 mm for the determination of SOC and POC.

Total organic carbon concentration was determined by the Walkley and Black method (Nelson and Sommers, 1982), where the easily oxidisable carbon was affected by 1.3 to obtain total organic carbon. Particulate organic matter carbon was obtained after physical fractionation (Cambardella and Elliott, 1992). Briefly, 10 g of dry and sieved soil was dispersed with a sodium hexametaphosphate solution followed by the wet sieving at 53 microns. Subsequently, the Walkley and Black method was applied to determine the POM-C concentration as explained for total organic carbon.

For comparisons of the total soil organic carbon stocks up to one-metre depth, a correction was made to bring soil profiles to equivalent soil mass by applying the cubic spline interpolation model proposed by Wendt and Hauser (2013). Briefly, this model allows better fits of linear interpolations by providing non-linear flexibility between data points, while ensuring that the model passes through the original data points. The data were fitted to the R script proposed by von Haden et al. (2020) to calculate carbon in depth.

Structural stability was assessed by an adaptation from Le Bissonnais (1996). Initially, 10 g of dry soil aggregates with sizes between 3 and 5 mm were weighed and subjected to rapid wetting through immersion in 50 mL of distilled water for 10 minutes. Subsequently, the wet samples underwent sieving using the Féodoroff device (a helical sieve) to separate aggregates into <50 µm and >50 µm fractions. Aggregates larger than 50 µm, obtained from sieving, were dried at 40 °C in an oven. These dried aggregates were further sieved using a series of mesh sizes—2000 µm, 1000 µm, 500 µm, 200 µm, 100 µm, and 50 µm—by manual pendulum movements on a sieve column.

Results were expressed as the weighted mean diameter (WMD) in millimetres. This was determined by calculating the sum of the masses of the fractions remaining on each sieve, multiplied by the average aperture of adjacent sieves. The mass on the 2000 µm sieve was multiplied by 4000 µm, representing the average initial aggregate size (3–5 mm). The obtained DMP (Diameter Mean Particle) result was categorised into one of five stability classes (Le Bissonnais, 1996): (i) > 2.0 mm, very stable material; (ii) 2.0–1.3 mm, stable material; (iii) 1.3–0.8 mm, medium stability; (iv) 0.8–0.4 mm, unstable material; (v) < 0.4 mm, very unstable stability.

Soil aggregates of different sizes were fractionated using a method adapted from Six et al. (2004). This method separates, by rapid wetting by water, aggregates into four size classes (>2000 µm, 2000–250 µm, 250–50 µm, and <50 µm). Before fractionation, soil samples were sieved to 8 mm and dried at room temperature. The results were expressed as a percentage of the total sample weighed.

2.3. *Statistical analysis*

Soil organic carbon concentration and stock at depth, soil bulk density, particulate organic carbon concentration, structural stability and distribution of aggregates of different sizes were compared between soybean monocropping and rotation using Student's t-tests for $p< 0.05$ significance.

3. Results

3.1. *Vertical distribution of SOC and bulk density*

In the uppermost soil layer (0–5 cm), total organic carbon concentration was significantly higher under crop rotation (19 g C kg^{-1}) compared to soybean monocropping (16 g C kg^{-1}) (Fig. 2A). However, at other depths, no significant differences were observed between the two systems. Similarly, organic carbon stock was greater in crop rotation at 0–5 cm (12.02 Mg C ha^{-1}) versus monocropping (10.69 Mg C ha^{-1}) and showed marginal differences at 20–65 cm ($p= 0.06$) (Fig. 2B).

Soil bulk density showed no differences up to 20 cm, but significant differences were found at 65–95 cm ($p= 0.002$) and 95–100 cm ($p= 0.01$) in favor of crop rotation. A residual effect was noted at 20–65 cm ($p= 0.1$) (Fig. 2C).

3.2. *Particulate organic matter-carbon, aggregate size, and soil structural stability of topsoil*

The POM-C was nearly double in crop rotation (6 g C per kg soil^{-1}) compared to soybean monocropping (3.2 g C kg soil^{-1}) (Fig. 3). At the 5–20 cm depth, C-POM levels were similar between both systems (p=

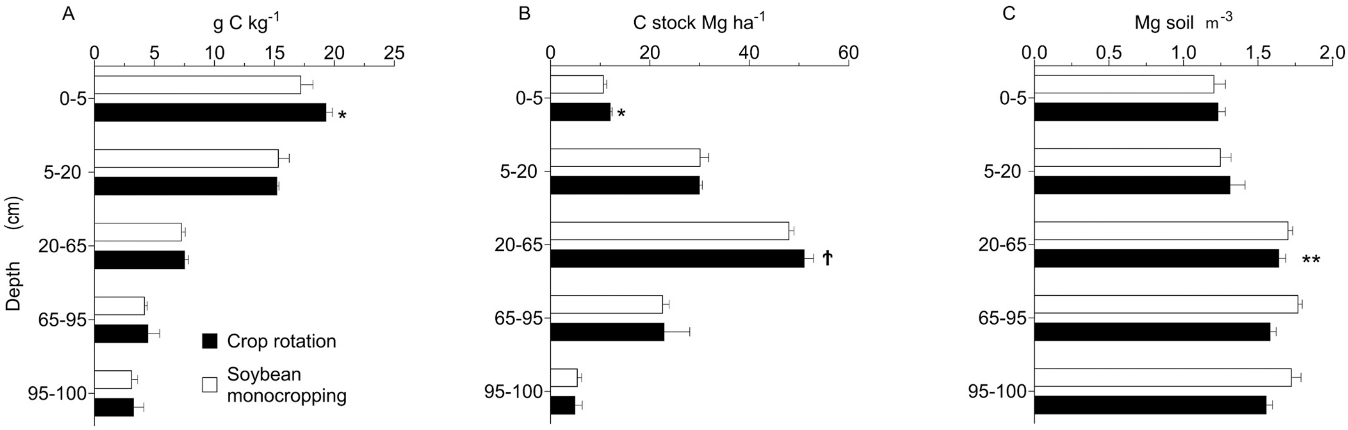

Fig. 2. Concentration of total organic carbon (A), total organic carbon stock as equivalent mass (B) and soil bulk density (C) to 1 m depth in the soybean monocropping and crop rotation. * indicates significant differences between the two agronomic systems at $p<0.05$ and ↑ at $p<0.1$. Bars indicate standard errors.

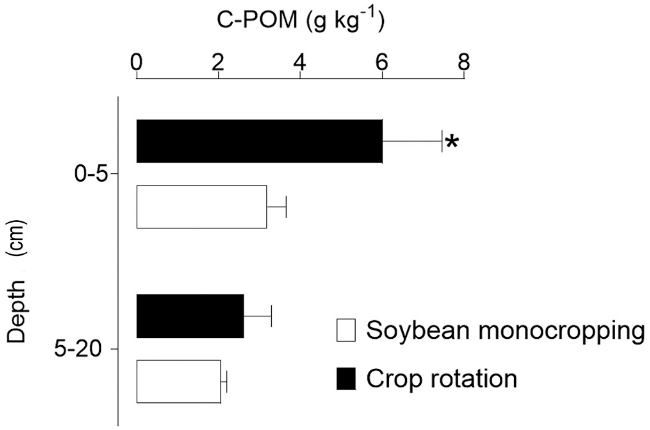

Fig. 3. Distribution of soil particulate organic carbon at 0–5 cm and 5–20 cm in soybean monocropping and crop rotation.*indicates significant differences at each depth ($p<0.05$). Vertical bars in the column indicate standard error.

0.23; Fig. 3).

The proportion of larger aggregates (>2000 µm) was consistent with C-POM concentration (Fig. 4 A). It was 60 % higher in rotation than in monocropping at both depths, but only significant at 0–5 cm (Fig. 4 A). Conversely, the smaller aggregates did not differ significantly between treatments (Fig. 4 A).

Structural stability was low for both crop sequences, classified as 'unstable material' according to Six et al. (2004). Although structural stability at 0–5 cm was similar for both treatments, it was unexpectedly higher for soybean monocropping compared to rotation at the 5–20 cm depth (Fig. 4B).

4. Discussion

In this study, we present field evidence of early increases in soil carbon and macroaggregate proportions in a three-year crop rotation compared to soybean monocropping. Positive effects on soil carbon were most pronounced in the topsoil (0–5 cm), with both total and particulate organic matter carbon higher in rotation than in monocropping. Additionally, the proportion of macroaggregates was significantly greater in rotation. The low structural stability documented was similar in the topsoil but it was significantly higher in monocropping at 5–20 cm. Lastly, marginally significant increases in SOC stocks were observed in the 20–65 cm layer of rotation, coinciding with lower soil bulk density.

The increased soil organic carbon concentration and stock in the topsoil (0–5 cm) under rotation is one of the few cases of positive early responses to this practice (Fig. 2). Recent meta-analyses have quantified the generalised positive effects of rotation on topsoil carbon content (Zheng et al., 2023; Giustiniani et al., 2024). Specifically, Giustiniani and colleagues (2024) found that the most substantial positive effects (12 %) occurred in rotations lasting more than nine years, whereas short sequences showed no detectable effects. We attribute these early positive effects to two main factors: first, the intensification of the rotation with gramineae (wheat and maize), and second, the initially low soil carbon content. The stubble contribution from wheat and corn is consistently greater in this region compared to soybean (Novelli et al., 2011; Milesi Delaye et al., 2013; Giustiniani et al., 2024). In our study, plant carbon inputs from the rotation were double those from soybean monocropping since the experiment began (19 t C ha^{-1} *vs.* 8.7 t C ha^{-1}) (Semmartin et al., 2023). These carbon inputs, in the context of reduced tillage and continuous soil biological activity, account for the observed increases in soil carbon. Similar systems in the region have shown that soybean contributes about 3.1 t C ha^{-1} yr^{-1} as residue, while corn contributes around 5.8 t C ha^{-1} yr^{-1} (Milesi Delaye et al., 2013). These authors found that annual crop intensification increases soil organic carbon storage in the first 30 cm depth, with observed biomass values of 15.9 t ha^{-1} in soybean monocropping and 41.5 t ha^{-1} in wheat/soybean-corn-soybean rotations. The second explanation is the low initial soil carbon content. These soils are likely undergoing a regenerative phase after being ploughed for more than 50 years, showing signs of degradation (platy structure) at the start of the experiment (Semmartin et al., 2023). Moreover, these soils are considered carbon unsaturated, as pristine surrounding areas present about 19 t C ha^{-1} in the first 5 cm of the soil profile, significantly higher than the 10–12 t C ha^{-1} documented in this study (Fig. 2B) (Alvarez and Berhongaray, 2021).

Total organic carbon differed between crop sequences up to a depth of 65 cm, with rotation showing 5 % more total organic carbon content than soybean monocropping (Fig. 2B). This was accompanied by reductions of bulk density, which is also beneficial for plant growth (Fig. 2C). This divergence in bulk density in the deeper horizons could be attributed to the contribution of roots, particularly from wheat. In agroecosystems, 30–90 % of the total organic carbon inputs come from roots (rhizodeposition and dead roots) (Kätterer et al., 2014). Winter wheat roots can grow up to 150 cm in depth, with an effective root zone estimated at 80–100 cm, resulting in more heterogeneous soil pore systems (Fan et al., 2016). Moreover, Alvarez et al. (2014) observed that maize contributes 7 t ha^{-1} yr^{-1} of dry matter, while soybean contributes only half that amount. Typically, legumes exhibit about half the root mass and one-fifth the length of cereals due to the higher mass per unit length of legumes (Gregory et al., 1996). Hirte et al. (2018) observed

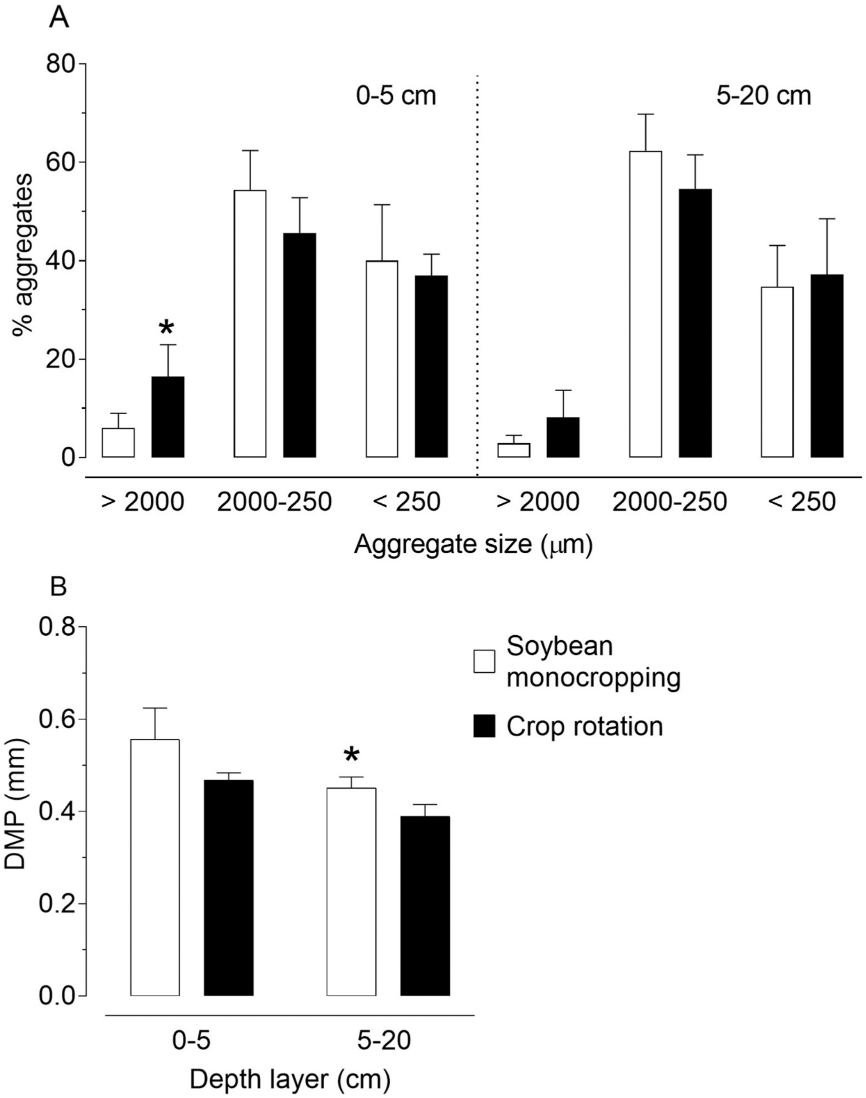

Fig. 4. . (A) Soil aggregates distribution and (B) soil aggregates structural stability (DMP) (B) soil structural at 0–5 cm and 5–20 cm in soybean monocropping and crop rotation-*indicates significant differences at each depth ($p<0.05$). Vertical bars in the column indicate standard error.

that vertical root distribution differed considerably between maize and wheat, with the proportion of total biomass allocated to roots in the top layer being 4 % higher in maize than in wheat. Root biomass below 50 cm depth was three times higher in maize than in wheat.

Remarkably, approximately 65 % of the total organic carbon in the soil is stored below the 20 cm depth in both crop sequences (Fig. 2 B). This concurs with the results documented by Alvarez and Berhongaray (2021), who found that two-thirds of total organic carbon is stored below 25 cm depth in soils within the Pampean region. The efficacy in stabilising total organic carbon in deeper soil layers compared to surface layers stems from various factors: notably, the lower saturation deficit (Alvarez and Berhongaray, 2021), the efficiency of carbon inputs in generating soil organic matter (Shahbaz et al., 2017), and the enhanced stability of synthesised organic matter (Balesdent et al., 2018; Berhongaray and Alvarez, 2019). Another factor that could have a positive effect is the clay content in the deep layers. Zhang et al. (2020) found a positive correlation between clay content and SOC content in the deep layers of the soil profile in a Mollisol in China. These results would agree with those observed in this work, where a higher proportion of clays was found in 20–65 cm (Table 1). Furthermore, the methodology applied in this study for computing soil organic carbon stock—employing the equivalent mass approach and linear interpolation (spline) as proposed by von Haden et al. (2020)—stands out as a novel technique offering heightened accuracy in results compared to other methodologies since it incorporates eventual differences in bulk density.

The inherent greater variability of organic carbon estimation in depth might have hindered the detection of differences between rotation and monocropping. As Kravchenko and Robertson (2011) highlighted, the considerable variability in soil organic carbon in deeper layers can pose challenges in detecting statistically significant differences. Nevertheless, this incorporation allowed us to quantify approximately 63 % of the organic carbon of this soil. This becomes particularly crucial in estimating the equilibrium between soil organic carbon sequestration and greenhouse gas emissions (Jantalia et al., 2007). The greater uncertainty observed in the deeper horizons may hinder the detection of changes in SOC. Syswerda et al. (2011) also detected greater variability in organic carbon concentration in the B-horizons than in the topsoil. This resulted in carbon gains in surface soils from no-till and other agricultural treatments not being offset or magnified by the carbon change at depth.

POM-C is an indicator of soil quality because it shows faster variations than SOC and closely relates with macroaggregate formation and structural stability (Six et al., 2000; Poeplau and Don, 2013). After 3 years, our study showed that POM-C was nearly 50 % higher in the rotation than in the monocropping (Fig. 3) consistently with a larger macroaggregate formation (Fig. 4). These results are consistent with global patterns (Iheshiulo et al., 2023) and with the greater carbon inputs as stubble of rotation discussed above. Salvagiotti et al. (2013), who found that including wheat as a cover crop in a soybean monocropping increased particulate organic carbon in the topsoil, but did not significantly impact on other soil properties after three years of experimentation. This could be because crop rotation, particularly the inclusion of a winter crop, such as wheat, maintains the continuous activity of roots and soil biota and increases the amount and frequency of residue inputs (Franzluebbers, (2002); (Acosta-Martinez et al., 2007; Caviglia et al., 2011).

Crop rotation positively affected soil aggregation. Wheat/soybean-maize-soybean improved macroaggregates mass 60 % compared to soybean monocropping (Fig. 4 A). This could be attributed to more residue and root mass obtained in the rotation (Semmartin et al., 2023). In the same region, in concordance to Novelli et al. (2017), crop rotation (wheat-maize) and the use of cover crops promoted the formation of macroaggregates (>250 μm) and the accumulation of SOC within them. In other agroecosystems, Wang et al. (2015), reported that a high annual stubble input rate (13.5 t ha^{-1}) significantly increased the stability of large aggregates. On the other hand, although we did not study the effect of different stubble quality in the aggregation, different effects of wheat and maize straw can be expected in the rotation. For example, Zhao et al. (2018) found that the macroaggregate mass was greater under stubble incorporation of maize than wheat. This difference may be due to the bioavailability of these stubbles as maize decomposes faster (Hadas et al., 2004; Abiven et al., 2007) than wheat straw. On the contrary, Geng et al. (2022) found that compared to the maize-wheat rotation, the mass ratios of large macroaggregates and small macroaggregates in 0–20 cm increased by 52 % under the soybean-wheat rotation, and increased by 51 % in the 20–40 cm. Similarly, recent studies have also found adverse effects of maize as a predecessor crop on soil aggregation compared to soybean (Zheng et al., 2023).

Soil aggregation at the soil surface is crucial to reduce erosion, as the soil is heavily impacted by rainfall in this layer. Despite the observed increase in POM-C, SOC and macroaggregate mass in the topsoil of the rotation compared to soybean monoculture, soil aggregate stability did not show the expected improvement (Fig. 4 B). Note that the methodology followed for the measurement of structural stability only included the fast wetting, and the stability by capillary and ethanol was not tested. Hence, the low values obtained here may be due to the methodology, whereas if all three measurements had been completed, the stability values may have been higher. In any case, the values obtained here were consistent with others observed by Kraemer et al. (2021), even though they found more MWD values closer to 1 mm than in our study. On the other hand, even though rolling Pampean soils have a high natural chemical fertility, their high silt content, which usually reaches 60–70 % in the A horizon, is the cause of a low structural stability that favours a rapid deterioration (Kraemer et al., 2021). Alvarez et al. (2017) observed a weak relationship between soil organic carbon and soil structural stability in the Pampean region, particularly in experiments of less than 2 years duration and assuming that other mechanisms may be involved in this process. In our study this might be attributed to several factors. First, the time required for changes in soil aggregate stability is typically longer than that for alterations in organic carbon content and macroaggregate formation. Soil stability is influenced by gradual and longer processes of soil carbon transformation by microbes and its eventual stabilisation in the finer clay components (Cotrufo et al., 2013; Álvarez et al., 2017). Therefore, the inclusion of wheat and maize in the rotation, with their distinct root architectures and residue contributions, may initially contribute positively to soil porosity and macroaggregate formation, while the immediate impact on soil stability might not be as pronounced, given the longer-term nature of these benefits (Bodner et al., 2021). Second, the necessary agricultural practices for managing wheat and maize, including planting and harvesting, could introduce soil disturbances that temporarily offset the advantages provided by diverse root systems and increased residue inputs. In a no-till system, even minor disturbances can impact soil structure. Therefore, while the rotational system enhances soil organic carbon and macroaggregate formation, the translation of these improvements into enhanced soil stability likely requires a longer duration than the timeframe of this study.

5. Conclusions

Soil quality maintenance and improvement is essential for developing competitive and sustainable farming systems. Our results have shown that the soybean-wheat-corn-soybean rotation allowed higher amounts of SOC, POM-C and macroaggregates to accumulate in the 0–5 cm depth. The quantification of deep organic carbon allowed a better understanding of the effect of agricultural management on the capacity to sequester carbon and the importance of deep horizons on the total stock. When deeper layers were included in the sampling, it was observed that 65 % of the SOC was stored below 20 cm depth. In our experiment, we found early marginal positive effects of rotation at 20–65 cm depth. Finally, contrary to expectations, stability was higher in monocropping than in the rotation, especially at a depth of 5–20 cm. Additionally, the low values observed in both cropping sequences indicate a weak structure.

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CRediT authorship contribution statement

Diego Cosentino: Writing – review & editing, Supervision, Investigation, Conceptualization. **Santiago Poggio:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Maria Semmartin:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Idoia Urrutia Larrachea:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109183.

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