Pruning residues incorporation and reduced tillage improve soil organic matter stabilization and structure of salt-affected soils in a semi-arid Citrus tree orchard

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Abstract

Soil salinization is an emerging problem worldwide as a result of unsustainable land management practices and climate change. However, salt-affected soils under agricultural use could act as a C sink if these negative effects can be offset by combination of sustainable land management practices (SLM). In this study, we assessed the effect of (i) intensive tillage along with flood irrigation (IT); (ii) combination of no-tillage with pruning residues (branches and leaves) as mulch, and drip-irrigation (NT+PM); and (iii) combination of reduced tillage with the incorporation of pruning residues and drip-irrigation (RT+PI), on physico-chemical soil parameters, aggregate stability, amount and quality of organic matter fractions and soil organic carbon (SOC) sequestration in a lemon tree orchards (*Citrus limon* var. *Verna*) under semi-arid climate conditions. The RT+PI management system showed a decrease in salinity and bulk density, and increased soil porosity, soil OC and N stocks, and percentage of OC-rich macroaggregates as compared to the IT system. The aggregate-occluded particulate organic matter fraction (oPOM) played a key role in macroaggregate stability. The NT+PM treatment also showed positive effects on the investigated soil properties, but this was limited to the upmost topsoil (0-5 cm). The IT management system revealed highest values of salinity and bulk density, and considerably lower SOC stocks. Moreover, a degradation of soil structure with a low percentage of macroaggregates depleted in SOC was observed. We conclude that the incorporation of pruning residues in combination with reduced tillage and drip-irrigation is an effective management system to improve soil structure and facilitate SOC sequestration. Therefore, conventional management systems based on intensive tillage and flood irrigation should be abandoned in salt-affected soils under semi-arid climate conditions in favour of systems with higher organic matter inputs incorporated into the soil combined with measures to reduce the salt content.

1. Introduction

Around 40% of the world’s food is produced on irrigated arid and semi-arid soils. However, nearly 11% of these irrigated soils are saturated with salts (primary and/or secondary formation), which is a widespread problem that threatens food security (FAO 2001; FAO 2009; Qadir et al. 2001; Wicke et al. 2011, 2013). Environmental problems related to soil salinization have existed for millennia and historical records displayed that many civilizations failed due to increases in the salinity of agricultural fields, e.g. in Mesopotamia (Shahid et al. 2018). The intensive land use of salt-affected soils (poor drainage, inappropriate irrigation, high evaporation rate, excessive use of chemical fertilizer) causes severe degradation of these soils (Amini et al. 2016; Wicke et al. 2011). These degraded soils are characterized by low soil organic matter (SOM) contents and poor soil structure leading to reduced farmers' profits and finally to land abandonment (Bernstein 1975; Brinck and Frost 2009; Cuevas et al. 2019; Lakhdar et al. 2009; Smedema and Shiati 2002). On the other hand, salt-affected soils can be very productive if a properly management is done according to the environmental conditions, adapted crops and soil properties (Amini et al., 2016; Gonçalo Filho et al., 2019; Rengasamy and Olsson, 1991).

Currently, the extent of salinization and sodification is projected to increase in the next decades by up to 40% in arid and semi-arid ecosystems as a result of climate change (Bischoff et al. 2018; Wong et al. 2010). Since global warming is leading to temperature increases and more frequent droughts, evapotranspiration and thus salt accumulation increases in the root zone leading to a decline of soil quality (Cuevas et al., 2019; Leogrande and Vitti, 2019; Shahid et al., 2018). The decrease of organic matter (OM) inputs and the salinity-induced dispersion of clay particles with the subsequent disruption of soil aggregates, resulting in decomposition of stabilized SOM, lead to an overall decrease of soil organic carbon (SOC) stocks (Adu and Oades, 1978; Amini et al., 2016; Manukyan, 2018; Wong et al., 2010). The SOC level is mainly dependent on C inputs from vegetation/crops, which can be adversely impacted by salinity and sodicity, leading to less SOC in these soils (Wong et al., 2010). However, salt-affected soils could act as a C sink if these negative effects can be reversed (Bischoff et al., 2018; Omar et al., 2017). Thus, adequate implementation of sustainable land management (SLM) practices in the long-term may change the role of salt-affected soils from a source to a sink for greenhouse gases. The global technical potential of C sequestration through the reclamation of salt-affected soils was estimated by 0.4-1.0 Pg C yr^{-1} (Lal, 2010). Therefore, the improvement of salt-affected soils is an urgent priority to break the vicious circle of soil degradation.

Flood irrigation, which is the main irrigation system used for salt-affected soils, can lead to water and nutrient losses by runoff and leaching losses, favoring the destruction of the soil structure (Fentabil et al., 2016; Uckoo, 2005). As a result of an inappropriate irrigation management, salinization and sodification of land continue to occur at an estimated rate of 0.25-0.5 M ha each year (Wicke et al., 2013). There is ample evidence that agricultural SLM practices have positive effects on soil aggregation and aggregate-related stabilization of SOC in many semi-arid agroecosystems (Almagro et al., 2017; Garcia-Franco et al., 2015, 2018; Gu et al., 2016; Nieto et al., 2011). The incorporation of OM in salt-affected soils (such as green manure, compost, biochar, and food processing wastes) has been identified as a technique to reduce the negative effects of salts on soil structure (Leogrande and Vitti, 2019; Tejada et al., 2006; Wang et al., 2014) while improving physical conditions. However, studies on the fate of OM amended to salt-affected soils and its effect on SOC stabilization and soil aggregate stability are scarce (Amini et al., 2016; Chorom and Rengasamy, 1997; Wicke et al., 2013; Wong et al., 2010). Thus, there is a knowledge gap regarding the amount and composition of different functional SOM pools and the formation of aggregates in salt-affected soils as affected by SLM practices (Cong et al., 2017).

Eastern Spain (mainly the regions of Murcia and Valencia) is one of the semi-arid irrigated areas where a high amount of Citrus (mainly oranges and lemons) is produced in Europe (Díez Calpena et al., 2009; Hondebrink et al., 2017). Some of these citrus tree orchards were established on Calcisols and Solonchaks. In the early 1980s, conservation tillage was implemented to improve the retention of water in the soil and reduce erosion (Giráldez et al., 1995). Input of OM to the soils is limited, as it is common practice to burn the tree pruning residues (branches and leaves) (Acar et al., 2018; Hondebrink et al., 2017). However, some recent studies showed that OM amendments such as green manure, compost, biochar, and food processing wastes (Amini et al., 2016; Cong et al., 2017; Cuevas et al., 2019; Wicke et al., 2011) improved physical conditions in salt-affected soils.

Here, we investigated different combinations of SLM management options including pruning residues incorporation and drip-irrigation to off-set negative physical and chemical conditions in salt-affected soils under citrus orchards. We took advantage of a long-term experiment (17 years) under citrus trees in SE Spain to identify how such combinations of management practices affect the amount and quality of SOM, as well as soil structure delineated from aggregate stability and stabilization of OC in aggregates.

2. Material and methods

2.1. Site description and experimental design

The study was conducted in an irrigated agricultural orchard of citrus trees (*Citrus limon* var. *Verna*) located in "Paraje la Alberquilla" between "Sierra de Carrascoy" mountains and Librilla´s town (Murcia), Southeast Spain (37° 52' 18.8''N, 1° 20' 58.6''W; 119 m a.s.l.). This citrus variety is widely cultivated in the Segura Valley (Murcia) (Blanco et al., 1989). Citrus trees were established in rows with a 6 m x 6 m spacing in 1987 under a flood irrigation system called "furrow irrigation". This type of irrigation is frequently used in orchards and row crops in this region. Approximately 576 m^3 of water were used each year for irrigation of the orchard (4400 ha^{-1}) in January, April, June, August and September. The climate is semi-arid, with an average annual precipitation of 350 mm, concentrated in the spring and autumn. The mean annual temperature is 18°C and mean annual potential evapotranspiration ranges between 900 and 1000 mm yr^{-1} (calculated by the Thornthwaite method), so the mean annual water deficit is around 600 mm. The soil is classified as Calcaric Solonchak (IUSS Working Group WRB, 2015).

Since 1987, the traditional soil management system carried out by the farmers in the study area was intensive tillage (until 40 cm soil depth and 3 times per year) with flood irrigation only in the topsoil (IT). The irrigation water comes from the river Tajo. The quality of the water is regularly evaluated (Directive 2000/60/ EC) to avoid pollution.

In 2000, at two adjacent fields SLM practices were implemented (Table 1): (i) no-tillage plus lemon pruning residues applied on the topsoil as mulch and drip-irrigation (NT+PM), and (ii) reduced tillage plus incorporation of the lemon pruning residues to a soil depth of 15 cm (RT + PI) and drip-irrigation (Table 1). The drip-irrigation system consists of an automatic flow of water (approximately an average of 760 L per tree and per month adjusted to the varying climatic site conditions). Since 2015, 0.044 kg total nitrogen and 0.028 kg potassium chloride (KCl) (per tree and per month) were applied with the water of the drip-irrigation system. In addition, the farmers added 0.22 kg m^{-2} of a commercial solution of 15% of CaO and 0.5% of MgO per tree and per month in NT+PM and RT+PI management systems, because gypsum, calcite, calcium chloride, and other chemical agents that provide Ca tend to replace exchangeable Na, effectively ameliorating salt-affected soils (Hanay et al., 2004; Wang et al., 2014).

The experimental design consisted of three replicated plots per treatment of approximately 432 m^2 per plot and with 12 lemon trees per plot. The reduced tillage (RT+PI) system consisted of chisel plowing to 15 cm depth using a rotovator once per year. The pruning residues of the lemon trees orchards were ground (< 5 cm) every year in September and added as mulch on the soil surface in the NT+PM treatment or incorporated into the soil to 15 cm soil depth in the RT+PI treatment. The weeds were controlled in all management systems using a commercial herbicide (usually glyphosate i.e. N-(phosphonomethyl)glycine).

2.2. Soil sampling and analysis

Soil samples were collected from two soil layers (0-5 and 5-15 cm) in May 2017. The soil samples were collected in the inter-rows between the lemon trees with a distance from the tree trunks of 2.6 m. Two disturbed composite soil samples of 4 sub-samples per plot and treatment were collected. In total 36 samples of the whole experiment were taken (3 management systems x 3 plots x 2 depths x 2 replicates). Undisturbed samples were also collected at the same locations and soil layers (0-5 and 5-15 cm) using steel cylinders with a volume of 98.175 cm^3.

2.2.1. Determination of chemical and physical soil properties

The disturbed soil samples were air-dried, sieved to <2 mm, and analyzed in the laboratory, in triplicate. The pH (1:5 soil: water) was determined with a pH meter (CRISON 20). As soil salinity parameters, electric conductivity (EC) and the sodium adsorption ratio (SAR) were determined according to Bischoff et al. (2018). Because of the equilibrium between the soil and soil solution, it is possible to measure the sodicity from SAR derived from the concentrations of Na^+, Ca^{2+} and Mg^{2+} in the soil solution (Choudhary and Kharche, 2015). The concentration of Na^+, Ca^{2+}, and Mg^{2+} that were used to calculate the SAR according to Eq. (1) were determined by using inductively coupled plasma optical emission spectrometry (ICP-OES, Vista Pro CCD Simultaneous, Varian, Darmstadt, Germany).

$$SAR = \frac{Na^{+}}{(Ca^{2+}+Mg^{2+})^{0.5}} \tag{1}$$

The base saturation of the soil was determined using the ICP-OES (Vista Pro CCD Simultaneous, Varian, Darmstadt, Germany) after previous extraction with a solution of 0.5 M NH_4Cl according to the method of Trüby and Aldinger (1989). Soil texture was determined using a Coulter LS200 'Laser particle sizer' (Coulter corporation, Miami, Florida), which analyzes particle sizes from 0.4 to 2000 µm diameter. Previously, samples were sieve at 2 mm and treated with hydrogen peroxide to remove OM before being dispersed using sodium hexametaphosphate for 12 h. Soil bulk density (BD) was calculated from the oven-dried mass (105 °C, 24 h) corrected for the content of coarse fragments (Robertson and Paul, 2000). The soil water holding capacity (WHC) at matrix potentials of -33 kPa and -1500 kPa was determined using pressure ceramic plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA). The available water content (AWC) was calculated as the difference in soil moisture content at field capacity (-33 kPa) and wilting point (-1500 kPa). The wilting point was considered as indirect measurement of the distribution of fine pores in the soil (Heitman, 2017). In fact, the AWC may be considered as an indirect measure of the soil medium porosity size distribution (pores between 0.0002-0.05 mm of diameter) of the soil (Hamblin, 1986). The total porosity (%) was estimated for each agricultural management system and for each soil depth according to (Heitman, 2017):

$$\textit{Total porosity (\%)} = \left(\frac{Real\ density - Bulk\ density}{Real\ density}\right) * 100 \qquad (2)$$

$$\textit{Real density}\ (\mathrm{g\ cm^{-3}}) = \textit{Density of the mineral fraction - Density of the OM}\ \text{fraction} \qquad (3)$$

The amount of the large pores of the soil (> 0.05 mm) was also estimated according to Heitman (2017) as the difference between total porosity and field capacity (-33 kPa).

2.2.2. Separation of water-stable soil aggregates

The aggregate-size class separation was carried out for each sample using a modified wet sieving method adapted from Elliott, (1986). Briefly, a 100-g sample of air-dried soil, which was gently disaggregated by hand, was placed on top of a 2 mm sieve and submerged for 5 min in deionized water at room temperature. The sieving was done manually by moving the sieve up and down 3 cm, 50 times in 2 min, to achieve aggregate separation. A series of three sieves (2000, 250, and 63 µm) was used to obtain four aggregate size classes: (i) >2000 µm (large macroaggregates; LM), (ii) 250–2000 µm (small macroaggregates; SM), (iii) 63–250 µm (microaggregates; m), and (v) <63 µm (silt plus clay-sized particles; s + c). The aggregate-size classes were oven-dried (50 °C), weighed, and stored in glass jars at room temperature (21 °C). The mean weight diameter (MWD), calculated by summing the product of aggregate fractions ($\bar{X}$i) and mean diameter for each class (Wi), was used as a measure for macroaggregate stability (Kemper and Rosenau, 1986).

$$MWD = \sum_{i=1}^{n} \bar{X}i * Wi \qquad (4)$$

2.2.3. SOM fractionation

Bulk soil samples were fractionated using a physical fractionation method (Figure 1). Briefly, 20 g of air-dried soil sieved to 2 mm were added to 200 mL of a sodium polytungstate (SPT) solution with a density of 1.6 g cm^{-3} (Cerli et al., 2012) and left for 16 hours. Then, the floating material (< 1.6 g cm^{-3}), representing free particulate organic matter (fPOM), was dried with a freeze-drying machine (BETA 1-16, CHRIST, Germany) and weighed. The fraction > 1.6 g cm^{-3} was dispersed using a calibrated ultrasonic probe-type with an output energy of 450 J ml^{-1} in order to destroy soil aggregates (Figure 1). Then, the mixture was centrifuged at 1000 g for 30 min and the dispersed suspension, representing occluded particulate matter (oPOM), was decanted, dried and weighed. The residue (> 1.6 g cm^{-3}) which contained the mineral-associated organic matter (MAOM) fraction was decanted, dried and weighed (Figure 1). Before drying, this fraction was washed with deionized water to remove SPT.

2.2.4. SOC and N determination

Total C and N contents were determined for bulk soils, aggregate size classes and SOC fractions using an Elemental Analyzer (CNS Vario Max Cube, Elementar, Germany). Inorganic C (IC) was determined in the same way after SOM removal by heating samples at 550°C for 4 hours. The SOC concentration was obtained as the difference between total C and IC. All samples were analyzed in triplicate. The SOC and N stocks (kg m^{-2}) of bulk soils were calculated on an “equivalent mass”, except for those whose BD was comparable (Wendt and Hauser, 2013).

2.2.5. Determination of molecular composition of SOM fractions

The molecular composition of SOM fractions was determined by solid-state ^{13}C cross-polarization magic angle spinning (CPMAS) nuclear magnetic resonance (NMR) spectroscopic analysis, using a DSX 200 spectrometer (Bruker Biospin, Rheinstetten, Germany). The frequency was 50.32 MHz and the spinning speed 5 kHz. The contact time was 1 ms and the recycle delay was 1 s for all fractions. Depending on the SOC content of the samples, between 2,000 and 250,000 scans were accumulated and a line broadening between 0 and 50 Hz was applied. For the calibration of the ^{13}C chemical shifts, tetramethylsilane was used and set to 0 ppm. Spectral analysis was performed using the spectrometer software Bruker TopSpin 3.2 (Bruker, Billerica, USA). Integrated chemical shift regions were: i) aliphatic or Alkyl-C (0–45 ppm) of lipids, fatty acids, and plant aliphatic polymers; ii) N-Alkyl/Methoxyl-C (45-60 ppm), O-Alkyl-C (65-95 ppm) and Di-O-Alkyl-C (95-110), the sum of them considered as total O-N—Alkyl-C deriving primarily from polysaccharides (cellulose and hemicelluloses), but also proteins and side chains of lignin; iii) aromatic-C (110-145 ppm) and phenolic-C (145-165 ppm), considered as the sum of both as total Aryl-C deriving from lignin and/or protein; and finally (iv) Amide/Carboxyl-C (165–215 ppm) from aliphatic esters, carboxyl groups, and amide carbonyls (Wilson 1987). All NMR spectra were baseline corrected and phased. The integration of the peaks within each of the chemical shift regions allowed an estimation of the relative C contents expressed as percentages of the total area. From this data, the ratio between Alkyl-C and total O-N-Alkyl-C (A: OA ratio) was calculated as an indicator of the decomposition state of SOM (Baldock and Skjemstad, 2000).

2.3. Statistical analyses

All data were analyzed with General Linear Models (GLM) using the IBM SPSS statistics 23.0 software (SPSS Inc., Chicago, Illinois). The normal distribution of the data was analyzed by the Kolgomorov-Smirnov test, and the homogeneity of the variances according to the Levene test. Data that was not normally distributed, such as the permanent wilting point, soil available water content, weight distribution of MAOM and the C:N ratio of LM were ln-transformed. To compare the different management systems and soil depths using GLM analyses, first, we considered treatment and depth as a fixed factor. When significant, differences among management systems were identified at the 0.05 probability level of significance using Tukey's test. Pearson correlations were used to explore the relationships between SOM fractions and percentage of LM and SM and between the MWD and SOC of the bulk soil. Principal component analysis (PCA) was used to select those variables that affect SOM stabilization and aggregate stability. Variables which showed significant differences between management systems were considered for the PCA analysis (carbonate content, clay content, MWD, macro-porosity, pH, BD, SAR and OC and

A: OA ratios of fPOM, oPOM and MAOM) using the package FactorMineR (Lê et al., 2008) in the statistical software R (R Core Team, 2018). The number of components was chosen according to the eigen value criteria (PC with eigen value >1; Supplementary table 1A). Within the PCA, the variables that explained a high proportion of the variance on their respective dimension (> 10%, or loading > 0.9) were then used (Supplementary table 2A) to construct a structural equation model (SEM), using the Lavaan package (Rosseel, 2012). If pairs of variables that are highly correlated in salt-affected soils (namely pH – carbonate content, and SAR and EC) were selected by the PCA, we tested the SEM model using each variable individually and assessed our model using fit statistics and the cut-offs that indicate a good fit: a) TLI: Tucker Lewis index, b) Comparative fit index (CFI), c) root mean square error of approximation (RMSEA), and d) Standardized Root Mean Square Residual (SRMR), and e) Akaike information criterion (AIC) (Hooper et al., 2008; Medrano and Muñoz-Navarro, 2017; Sallan et al., 2012; Tabri and Elliott, 2012).

3. Results

3.1. Basic soil properties

Electric conductivity was significantly higher in the topsoil under the intensive management system (IT) compared to both SLM management systems (RT+PI and NT+PM). Below 5 cm soil depth, no significant differences were found between management systems (Table 2). The pH values were 8.5 and BS was 100% in all soils. The SAR was significantly higher under intensive tillage than in both SLM practices. Soil texture was comparable among the study sites with silt contents ranging between 65 and 71% and clay contents between 23 and 28 %. Sand contents were around 6% with somewhat higher values in the upmost soil layer (0-5 cm) of the NT+PM system. BD was significantly higher in IT compared to NT+PM and RT+PI management systems in both soil depths (Table 2). Total porosity as well as contents of medium- and large pores were significantly higher under RT+PI compared to NT+PM and IT management systems. Bulk soil OC and N contents were significantly higher in RT+PI than in NT+PM and IT at 0-5 and 5-15 cm soil depth. No differences in the C:N ratio between management systems were found (Table 2).

3.2. SOC and N stocks

The SOC stocks increased by 38.6% in the NT+PM system and by 82.3% in the RT+PI system compared to the IT system at 0-5 cm soil depth (Figure 2A). Below 5 cm soil depth, the SOC stocks in NT+PM were not significantly different from IT. For the RT+PI system, the SOC stocks in the 5-15 cm depth increased by 95.2% compared to the IT system (Figure 2A). The N stocks showed the same trend as the SOC stocks with increases of 55.6% and 133.3% in NT+PM and RT+PI, respectively, compared to the IT system in the topsoil, while in the subsoil increases of 38.5% in NT+PM and 215.4% in RT+PI systems were determined (Figure 2B).

3.3. Distribution of aggregate size classes

The silt+clay-sized fraction (<63 µm) was the predominant size class in NT+PM and IT systems, representing between 64 and 79% of the bulk soil, respectively (Figure 3). The microaggregate distribution was similar for all systems and depths. With respect to large macroaggregates (> 2,000 µm) and small macroaggregates (250-2,000 µm), we found a significantly higher proportion in the RT+PI system (27-32%) than in NT+PM (6-18%) and IT (1-7%) systems in both soil depths (Figure 3). In the topsoil, the MWD was significantly higher in RT+PI (1.5 ± 0.2) compared to NT+PM and IT systems (0.7 ± 0.2 and 0.3 ± 0.1, respectively). In the subsoil, we found the same trend for MWD: RT+PI > NT +PM > IT (1.5± 0.2 > 0.5 ± 0.1 > 0.2 ± 0.0, respectively) (Table 2).

3.4. OC and N associated within aggregate-size classes

The highest OC concentration was found for both macroaggregate sizes classes LM (> 2,000 µm) and SM (250-2,000 µm) in the RT+PI system, whereas lower OC concentrations were found for the s+c fraction in the IT management system (Table 3) at 0-5 cm soil depth. In the RT+PI system, the OC concentration decreased with the aggregate size-class (LM>SM>m>S+C). The IC concentration was higher in IT compared to NT+PM and RT+PI for all aggregate size classes and both soil depths. The N concentration in LM, SM, and m showed the same trend than OC with decreasing concentrations in the order RT+ PI > NT+PM > IT at 0-5 and 5-15 cm soil depth. However, we found no differences in the N concentration of the s+c fraction between tillage systems in the topsoil (Table 3).

In the topsoil, the OC associated with LM represented 43% of the total SOC in RT+PI, whereas for NT+PM and IT, its contribution to total SOC was lower (with 17 % and 7%, respectively; Figure 4). Below 5 cm soil depth, the OC associated with LM represented 44% of total SOC in RT+PI, whereas in NT+PM and IT, it represented 11% and 3% of total SOC (Figure 4). In RT+PI, the OC of the s+c fraction and the microaggregates showed the lowest contribution to total SOC (12-13%) in both soil layers (Figure 4). The contribution of N in aggregate size classes to total N of the bulk soil followed the same trend as SOC (Figure 4).

3.5. Mass distribution, OC and N in SOM fractions

The MAOM fraction had the highest mass contribution in all tillage systems and soil depths, followed by fPOM and oPOM (Table 4). In addition, the mass contribution of the MAOM fraction was significantly higher in IT than in NT+PM and RT+PI management systems in the topsoil. Below 5 cm soil depth, we observed no differences for MAOM among tillage systems. The fPOM was the fraction with the lowest mass contribution among tillage systems. Despite the lower mass contribution of fPOM, this fraction was significantly higher in RT+PI compared to NT +PM and IT at 0-5 cm soil depth. In the topsoil, the mass contribution of the oPOM fraction showed the following trend: NT+PM>RT+PI>IT. However, below 5 cm soil depth, we found a higher mass contribution of oPOM in the RT+PI than in NT+PM and IT systems (Table 4).

The MAOM was the fraction with the highest OC contribution to total SOC in all tillage systems and in both soil depths (Figure 5). The OC of the oPOM fraction followed the trend

RT+PI>NT+PM>IT in both soil depths. The OC in oPOM decreased with depth only in NT+PM, whereas for RT+PI and IT, the OC in oPOM did not change with depth. The fraction with the lowest OC content in all tillage systems and depths was the fPOM. Regarding the N content of the fractions, the MAOM was the fraction with the highest contribution to total N. The N content of oPOM was higher in RT+PI compared to NT+PM and IT. The N content in fPOM showed the lowest values compared to the other SOM fractions in all tillage systems and depths.

3.6. Molecular composition of OC in SOM fractions

The ^{13}C NMR spectra showed significant differences between tillage systems with regard to the quality of SOM fractions (Table 5 and Supplementary fig. 2A). In the topsoil, the content of total O-N-Alkyl (45-110 ppm) in fPOM was slightly higher in RT+PI and NT+PM than in IT. However, the Alkyl-C and Aryl C compounds were higher in the IT system. The ratio A:OA indicated that in the IT system, the OC in the fPOM was more decomposed compared to NT+PM and RT+PI systems. The total O-N-Alkyl content of the oPOM decreased in the order NT+PM>IT>RT+PI, whereas the content of Alkyl C and Carbonyl-C decreased in the order IT>RT+PI>NT+PM. The A:OA ratio in the oPOM was significantly higher in IT and RT+PI compared to NT+PM system. Furthermore, in the oPOM fraction, the relative content of Alkyl-C was significantly higher in all management systems compared to the fPOM fraction (Table 5 and Supplementary fig. 2A). However, the opposite trend was found for total O-N-Alkyl-C compounds in the oPOM fraction (44.9, 46.1 and 43.5% in IT, NT+PM and RT+PI, respectively). with significantly lower contents compared to the fPOM fraction in all the systems in the topsoil (50.9, 53.1 and 55.2% in IT, NT+PM and RT+PI, respectively). The same trend was found for Aryl-C compounds. The content of Alkyl-C was significantly higher in RT+PI than in NT+PM and IT. The content of total O-N-Alkyl-C was higher in NT+PM compared to IT and RT+PI systems. The Aryl-C content was higher in IT than in NT+PM and RT+PI systems. The A:OA ratio of the MAOM fraction decreased in the order RT+PI>IT>NT+PM in the topsoil.

In the 5-15 cm soil layer, the content of total O-N-Alkyl-C in the fPOM fraction was significantly higher in RT+PI and NT+PM compared to IT system. In addition, the total O-N-Alkyl-C increases with depth in RT+PI and NT+PM, whereas in IT, we observed no changes (Table 5). Regarding Aryl-C and Carbonyl-C groups, their contents were higher in IT compared to NT+PM and RT+PI systems. The A:OA ratio was higher for NT+PM and IT compared to RT+PI system. In general, the same trends that we described above for the fPOM fraction for Alkyl-C compounds and the A:OA ratio were found for the oPOM fraction. However, the content of total O-N-Alkyl C in the oPOM fraction increased in RT+PI system with depth. In the NT+PM system, we observed a lower value of total O-N-Alkyl C in the oPOM compared to the topsoil. The contents of Aryl-C and Carbonyl-C were higher in RT+PI and NT+PM than in IT. Finally, the MAOM fraction displayed a higher content of Alkyl-C in RT+PI and NT+PM compared to IT system, and higher total O-N-Alkyl-C content in NT+PM than in RT+PI and IT systems. In addition, the contents of Aryl-C and Carbonyl-C were higher in IT compared to the other management systems. The total O-N-Alkyl signal decreased with depth in all systems, whereas the A:OA ratio increased with depth in all systems.

3.7. Multivariate analysis (PCA) and structural equation modelling (SEM) of aggregate stability and soil OC stabilization

In the PCA, up to four factors fulfilled the eigen-value criterion. The factor 1, explaining 42.5% of the total variance was loaded by the factors OC of oPOM, OC of MAOM fraction, BD, MWD and SAR. Factor 2, explaining 21.1% of the total variance, was loaded by carbonate, clay contents and the A:OA ratio of the fPOM and MAOM fraction (Supplementary table 1A). Factor 3, explaining 12.8% of the total variance, was loaded by EC and OC of both fPOM and MAOM. Factor 4, explaining 8.4% of the total variance, was loaded by pH (Figure 6, Supplementary table 1A). These four factors together explained 84.8% of the total variance. The variables that explained a high proportion of the variance on their respective dimension (> 10% or loading > 0.9) were then used for the SEM (Supplementary table 2A). We found that the SAR and the OC-oPOM were, by far, the main factors significantly affecting the macro-stability (estimate = -0.74 and 1, respectively). The carbonate content did not have significant importance, while other variables like pH, and EC expressed similar physico-chemical phenomena.

4. Discussion

4.1. Drawbacks of intensive tillage and flood irrigation in salt affected soils

The use of the soil management practices in the IT system (tillage down to 40 cm soil depth and flood irrigation) favored the accumulation of Na^+ and the dispersion of clay particles, with a subsequent breakdown of soil aggregates. This is indicated by high SAR and EC values (Table 2). This is associated with high BD, low porosity (low content of total, medium and large pores) and low values of MWD in the IT system (Table 2). This is due to the fact that the irrigation water does not supply Ca^{2+} and Mg^{2+} ions to counteract the high Na^+ concentrations in the IT management system (Hanay et al., 2004; Wang et al., 2014). Under the high salinity conditions in association with the intensive tillage, dispersion of OM and clay particles occurs and plugs soil pores, resulting in increased soil permeability (Taboada et al., 2001). When soil is repeatedly wetted and dried, as it occurs under the climatic conditions in the investigated sites, clay dispersion occurs, soil particles are rearranged and solidify into an almost cement-like soil with little or no structure (Wong et al., 2010). As a result, we observed salinity crusts in the IT system. This kind of crusts, also called “hard setting”, is characteristic of poorly aerated, salt-affected soils, which were not adequately managed under semi-arid conditions (high temperature, low precipitation and high evapotranspiration) (Agassi et al., 1981; Qadir and Schubert, 2002). Choudhary and Kharche (2015) suggested that in salt-affected soils, poor drainage can be improved by breaking up a hardpan with deep tillage. However, in our case the combination of intensive tillage with flood irrigation was not effective to remove the salt crust. In addition, intensive tillage increased the soil compaction such as it was supported by the high BD and low contents of medium and large pores (Table 2). This deterioration of the soil structure was also evident by the relatively low SOC and N stocks in the IT system (Figure 2).

Our results further indicated that the occlusion of SOM in macroaggregates was reduced in the IT treatment (Table 3). In a review by Amini et al. (2016), it was demonstrated that in salt-affected soils, SOC storage decreased as a result of salinization and sodicity. In our study, the PCA and the SEM analyses indicated that the IT system was far from a medium or high macro-stability (Figure 6) and salt contents had also a strong negative correlation with macro-stability and SOC sequestration. In the IT management system, OM return to the soil only occurred via belowground OM inputs. A lack of other OM inputs is indicated by low amounts of labile organic matter, such as fPOM (Table 4). If OM inputs are limited, the supply for the buildup of the oPOM fraction within aggregates is also low, leading to a decline in the amount of aggregates (Figure 3). This is supported by the results of ^{13}C NMR spectroscopy showing that both the fPOM and oPOM fractions in the IT system had the lowest values of total O-N-Alkyl-C, which is indicative of a high degree of degradation (Table 5, Supplementary figure 2A). In turn, the deterioration of aggregation is consistent with the observed high contribution of the MAOM fraction. However, this fraction was also negatively affected as it was depleted in OC and N compared to the other management systems. The high signal intensity for the Carboxyl-C area (165-215 ppm) in the 5-15 cm depth (Table 5, Supplementary figure 2A) is probably related to the frequent burning of pruning residues in the past (17 years ago), which is part of the traditional residue management in Spain, where it is still a legal practice, despite fire control restrictions (Hondebrink et al., 2017).

4.2. Combination of no-tillage with pruning residues as mulch and drip-irrigation

In the NT+PM management system, where pruning residues were left on the topsoil as mulch and the cessation of tillage started 17 years ago, we found lower EC and SAR compared with the IT system (Table 2). This is probably due to the combination of OM addition and application of Ca^{2+} and Mg^{2+} supporting the flocculation of clay particles, which facilitated the leaching of soluble salts. For salt-affected soils, the use of gypsum, calcite, calcium chloride, and other chemical agents that provide Ca, has been shown effective to induce leaching of salts from these soils (Hanay et al., 2004; Seenivasan et al., 2015; Wang et al., 2014).

Several studies in salt-affected soils also attributed soil structural improvements to the use of mulch from crop residues, which moderates soil temperature variations, decreases BD, enhances the balance among fine, medium and large pores, and reduces runoff and erosion (Grigg et al., 2006; Iqbal et al., 2008; Kahlon et al., 2013; Kang et al., 2009; Leogrande and Vitti, 2019). Similarly, in a study carried out by Pang et al. (2010), the use of straw mulching in salt-affected soils decreased the salt content of the soil surface by regulating the vertical distribution, by salts avoiding the clay dispersion and by reducing the risk of soil salinization and erosion. In our case, the NT+PM system did not affect the soil pore system, as the distribution of medium and large pores showed not differences compared to the IT system (Table 2). In another study under similar semi-arid climate conditions a no-tillage treatment was not effective to increase the soil porosity and the soil water capacity in the long-term (López et al., 1996). Nieto et al. (2011) also found that no-tillage in combination with the application of pruning residues of olive trees as mulch, increased soil porosity only in the upmost 2-5 cm of the soil compared to intensive tillage.

In the NT+PM system, we observed a higher proportion of small and large macroaggregates compared to the IT system (Figure 2). However, these macroaggregates revealed only slightly higher OC and N contents compared to the IT management system (Table 3). This can be explained by the cessation of tillage, limiting the incorporation of the pruning residues into the soil profile. In fact, the higher total SOC and N concentrations (Table 2) and stocks (Figure 2) under NT+PM were only found in the topsoil (0-5 cm depth), where, also higher amounts of fPOM and oPOM were observed (Figure 5). However, at deeper layers, reduced contact among OM, soil particles and soil microbes probably led to decreased physical protection of SOC through the formation of aggregates (Christopher et al., 2009; Garcia-Franco et al., 2015; Wiesmeier et al., 2014; Zhao et al., 2012), which was supported by lower SOC and N concentrations and stocks at 5-15 cm soil depth compared to RT+PI system.

4.3. Combination of reduced tillage with incorporation of pruning residues and drip-irrigation

Our results showed a significant improvement of both physical and chemical soil properties 17 years after the implementation of the RT+PI management system. The incorporation of pruning residues with reduced-tillage and the application of Ca^{2+} and Mg^{2+} via drip irrigation enhanced soil physical and chemical properties. This is supported by the lower BD, EC and SAR values in the RT+PI management system compared to the other tillage systems; together with the higher amount of total, medium and large pores, low EC, and higher MWD values also in the RT+PI management system compared to IT and NT+PM systems (Tables 2). Some of these effects were also evident in the NT+PM system, but in the case of RT+PI system, these effects were found for both soil depths.

The higher values of MWD and higher SOC and N stocks in RT+PI compared to NT+PM and IT systems indicated the offset of a breakdown of macroaggregates and the subsequent dispersion of clay particles, and also the formation of new macroaggregates (Oster and Shainberg, 2001). Our results are consistent with those of Abdollahi and Munkholm (2014), who reported that reduced tillage systems increased MWD values, penetration resistance and water-stable aggregates in salt-affected soils under semi-arid conditions. We also found a positive correlation between the MWD and SOC of the bulk soil ($r = 0.97$, $p < 0.01$), which indicated that OM was the major binding factor in macroaggregate formation. Reduced tillage favored the contact of the mineral soil particles with OM in the deeper layer. Thus, SOM facilitated the formation of macroaggregates and the occlusion of OM (Courtier-Murias et al., 2013; Trigalet et al., 2014), indicated by higher amounts of oPOM and mineral-associated OM (Figure 5, Table 4). This was also supported by the strong positive correlation between the OC-oPOM and OC-MAOM with the percentage of LM ($r = 0.90$, $p < 0.01$; and $r = 0.95$, $p < 0.01$, respectively) and SM ($r = 0.88$, $p < 0.01$; and $r = 0.78$, $p < 0.01$, respectively) observed in our study. Consistent with this, the oPOM fraction was less degraded as shown by the low alkyl-to-O/N-alkyl ratio in the ^{13}C NMR spectra (Table 5 and Supplementary figure 2A). In addition, the SEM model showed that OC-oPOM is a valid measure to describe our latent variable called "macro-stability" (Figure 7), whereas the salinity represented by SAR, indicated reduced macro-stability. Therefore, pruning residues addition in combination with reduced tillage led to the formation of macroaggregates and fostered SOC sequestration. Moreover, the drip irrigation system avoids a disruption of macroaggregates and a loss of OM through processes such as runoff and erosion under semi-arid climatic conditions (Blanco et al., 1989; Cuevas et al., 2019; Fentabil et al., 2016; Hondebrink et al., 2017; Uckoo, 2005) and also avoids an excessive use of chemical fertilizer which in turn could increase salinity (Bernstein, 1975; Lakhdar et al., 2009). A meta-analysis of 30 studies with different soil-improving cropping systems for salt-affected soils demonstrated that besides specific optimization of irrigation systems and combinations of soil amendments, conditioners and residue management could contribute to significant reductions of salinity and improve the soil structure (Cuevas et al., 2019).

5. Conclusions

Our results showed that sustainable land management practices in a Citrus tree orchard in salt-affected soils offset the negative effects of salts on soil structure by i) decreasing SAR, EC, and BD values; ii) increasing the amount of large and medium pores and macroaggregate formation and iii); maximizing the accumulation of SOC. The incorporation of OM by tree pruning residues combined with drip-irrigation makes soils less susceptible to the unfavorable influence of exchangeable Na under semi-arid climate conditions. These improvements were higher when the pruning residues were incorporated into the soil by reduced tillage. In our study, the assess of macroaggregates and their relationship with the oPOM were s good indicators for soil macro-stability and SOC sequestration. We conclude that pruning residues incorporation with reduced tillage and drip-irrigation was the most effective combination of SLM practices in order to sequester C in salt-affected soils under Citrus tree orchards. Intensive tillage systems, widely used in salt-affected soils in semi-arid regions, need to be disregarded as usual practice in favour of other management systems incorporating higher OM in the soil combined with measures to reduce the salt content.

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Table 1. Description of different management practices in the management systems: i) intensive tillage with flood irrigation (IT); ii) no-tillage plus lemon pruning residues on the topsoil as mulch (NT+PM); and iii) reduced tillage plus incorporation of lemon pruning residues (RT + PI).

Management practices	**IT**	**NT+PM**	**RT+PI**
Tillage	until 40 cm soil depth, 3 times per year	-	until 15 cm soil depth, 1 time per year
Addition of pruning	-	Mulching	Incorporation into the soil
Addition of Ca^{2+} and Mg^{2+}	-	+	+
Irrigation	Flood (since 1987)	Drip-irrigation (since 2000)	Drip-irrigation (since 2000)
Fertilization	-	+	+
Pesticides	+	+	+

Table 2. Bulk soil properties at two depths (0-5 and 5-15 cm) for IT (intensive tillage plus flood irrigation), NT+PM (no tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation). Numerical values are means ± standard errors for n = 6. Different letters in rows indicate significant differences between management systems (Tukey's test, $P < 0.05$). EC: electrical conductivity, BS: base saturation, SAR: sodium adsorption ratio, BD: bulk density, WHC: water holding capacity, MWD: mean weight diameter; OC: soil organic carbon, N: total nitrogen

Soil properties	Soil depth (cm)	Management systems IT	NT+PM	RT + PI
pH (1:5)	0- 5	8.5 ± 0.1a	8.4 ± 0.0a	8.5 ± 0.0a
	5-15	8.6 ± 0.0a	8.5 ± 0.0a	8.5 ± 0.0a
EC (µS cm^{-1})	0- 5	694.3 ± 69.3a	356.6 ± 14.0b	459.6 ± 36.3b
	5-15	391.7 ± 5.9a	317.5 ± 18.6a	356.1 ± 13.8a
BS (%)	0- 5	99.8 ± 0.2a	100.0 ± 0.0a	99.9 ± 0.0a
	5-15	99.8 ± 0.2a	99.8 ± 0.1a	99.9 ± 0.0a
SAR	0- 5	1.1 ± 0.0a	0.3 ± 0.2b	0.1 ± 0.0b
	5-15	1.1 ± 0.0a	0.3 ± 0.2b	0.1 ± 0.0b
$CaCO_3$	0- 5	51.8 ± 0.9a	49.7 ± 1.6a	48.6 ± 2.3a
	5-15	53.4 ± 0.3a	49.3 ± 1.5a	48.3 ± 2.4a
Texture (%):				
Clay	0- 5	24.0 ± 0.1a	22.6 ± 2.0a	22.5 ± 0.0a
	5-15	25.1 ± 0.1a	28.2 ± 0.3a	26.5 ± 0.2a
Silt	0- 5	70.4 ± 0.7a	64.4 ± 3.1a	70.9 ± 0.0a
	5-15	69.8 ± 0.3a	69.3 ± 0.4a	67.8 ± 0.5b
Sand	0- 5	5.6 ± 0.3b	13.0 ± 5.1a	6.6 ± 0.0b
	5-15	5.2 ± 0.4a	2.5 ± 0.5b	5.7 ± 0.3a
BD (g cm^{-3})	0- 5	1.6 ± 0.0a	1.3 ± 0.0b	1.1 ± 0.1b
	5-15	1.6 ± 0.0a	1.3 ± 0.0b	1.2 ± 0.0b
Pore size distribution (%):				
Fine pores	0- 5	16.4 ± 3.3a	18.7 ± 0.8a	16.6 ± 1.6a
	5-15	15.1 ± 0.5c	18.2 ± 0.8a	16.9 ± 0.7b
Medium pores	0- 5	9.9 ± 1.5b	11.2 ± 0.3b	15.2 ± 0.6a

	5-15	10.1 ± 0.6b	10.4 ± 0.1b	15.5 ± 0.5a
Large pores	0- 5	15.0 ± 4.1b	22.0 ± 4.0ab	27.2 ± 2.2a
	5-15	12.6 ± 2.1b	21.1 ±1.7a	20.1.5 ±3.4a
WHC (%)	0- 5	26.2 ± 0.8c	29.9 ± 0.6b	31.8 ± 1.3a
	5-15	25.2 ± 1.0c	28.6 ± 0.7b	32.4 ± 1.6a
Total porosity (%)	0- 5	41.2 ± 4.7b	51.9 ± 8.2ab	59.0 ± 5.6a
	5-15	37.8 ± 3.1b	49.7 ± 2.3a	50.5 ± 4.1a
MWD (mm)	0- 5	0.3 ± 0.0c	0.7 ± 0.2b	1.5 ± 0.1a
	5-15	0.2 ± 0.0c	0.5 ± 0.1b	1.5 ± 0.3a
OC (mg g^{-1})	0- 5	11.8 ± 1.0b	19.1 ± 1.0ab	31.6 ± 2.2a
	5-15	11.2 ± 0.5b	14.0 ± 1.9b	29.8 ± 4.3a
N (mg g^{-1})	0- 5	1.4 ± 0.2b	2.2 ± 0.4b	3.3 ± 0.6a
	5-15	1.2 ± 0.1b	1.7 ± 0.3b	3.2 ± 0.6a
C:N ratio	0- 5	8.3 ± 0.8a	8.5 ± 0.9a	9.5 ± 0.9a
	5-15	9.6 ± 1.2a	8.3 ± 0.6a	9.4 ± 0.4a

Table 3. OC, IC and N concentration (mg g^{-1} aggregate) of aggregate size classes LM (>2,000 µm), SM (250–2,000 µm), m (63–250 µm), and s+c (<63 µm) in the 0–5 and 5–15 cm soil layers for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth. Numerical values are means ± standard errors. Different lower-case letters in columns indicate significant differences between management systems for each aggregate size classes (Tukey's test, P < 0.05).

OC (mg g^{-1} aggregate)				
	LM	**SM**	**m**	**s+c**

0-5 cm				
IT	18.7 ± 2.9b	24.4 ± 4.0b	18.6 ± 0.9b	9.0 ± 1.1c
NT+PM	26.0 ± 8.0b	28.8 ± 1.6ab	31.2 ± 3.4a	12.5 ± 1.0b
RT+PI	42.5 ± 3.0a	32.2 ± 1.2a	33.1 ± 3.3a	15.7 ± 1.0a
5-15 cm				
IT	22.0 ± 5.3b	20.8 ± 1.8b	16.2 ± 1.1c	9.2 ± 1.4a
NT+PM	27.1 ± 0.9b	21.4 ± 1.3b	23.0 ± 2.3b	9.1 ± 2.0a
RT+PI	40.2 ± 3.6a	33.4 ± 1.9a	33.0 ± 2.3a	14.2 ± 2.9a
IC (mg g^{-1} aggregate)				
0-5 cm				
IT	61.3 ± 0.7a	61.6 ± 1.4a	61.1 ± 0.4a	63.7 ± 1.2a
NT+PM	58.2 ± 1.1b	56.6 ± 1.3b	55.3 ± 1.2b	60.5 ± 0.6b
RT+PI	56.6 ± 1.1b	57.0 ± 0.6b	56.5 ± 0.3b	60.9 ± 0.5b
5-15 cm				
IT	61.7 ± 2.3a	62.1 ± 0.6a	62.3 ± 1.0a	63.7 ± 2.2a
NT+PM	56.7 ± 2.6b	58.5 ± 0.5b	58.0 ± 0.2b	61.7 ± 0.9a
RT+PI	56.8 ± 1.3b	57.0 ± 0.5c	56.1 ± 0.9b	61.3 ± 0.2a
N (mg g^{-1} aggregate)				
0-5 cm				
IT	2.2 ± 0.3b	2.5 ± 0.3b	2.0 ± 0.1b	1.2 ± 0.2a
NT+PM	3.1 ± 0.7ab	3.0 ± 0.1ab	3.5 ± 0.6a	1.6 ± 0.4a
RT+PI	4.1 ± 1.0a	3.5 ± 0.4a	3.7 ± 0.6a	1.9 ± 0.3a
5-15 cm				
IT	2.7 ± 1.0a	2.2 ± 1.0b	1.8 ± 0.1c	0.9 ± 0.1b
NT+PM	2.7 ± 0.1a	2.6 ± 0.7ab	2.5 ± 0.2b	1.2 ± 0.3ab

RT+PI	4.1 ± 0.5a	3.5 ± 0.4a	3.6 ± 0.3a	1.7 ± 0.4a

Table 4. Weight distribution of SOM fractions (g fraction 100 g^{-1} soil): fPOM (particulate organic matter), oPOM (occluded particulate organic matter) MAOM (mineral-associated organic matter) for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth. Numerical values are means ± standard errors. Different lower-case letters in columns indicate significant differences between management systems for each fraction (Tukey's test, P < 0.05).

	(g fraction 100 g^{-1} soil)		
0-5 cm	**fPOM**	**oPOM**	**MAOM**
IT	0.2 ± 0.0c	0.7 ± 0.0c	99.2 ± 0.0a
NT+PM	0.4 ± 0.1b	4.2 ± 0.0a	95.4 ± 0.1c
RT+PI	0.7 ± 0.0a	3.0 ± 0.1b	96.4 ± 0.1b
5-15 cm			
IT	0.2 ± 0.0c	0.8 ± 0.1c	96.1 ± 0.2a
NT+PM	1.2 ± 0.1a	1.4 ± 0.0b	97.5 ± 0.1a
RT+PI	0.8 ± 0.1b	2.6 ± 0.1a	96.6 ± 0.2a

Table 5. Relative contents (%) of Alkyl-C, total O-N-Alkyl-C, Aryl-C, and Carbonyl-C and the A:OA ratio (Alkyl-C : total O-N-Alkyl-C) in the fractions fPOM (particulate organic matter), oPOM (occluded particulate organic matter), and MAOM (mineral-associated organic matter), for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth. Numerical values are means ± standard errors. Different

lower-case letters in columns indicate significant differences between management systems for each fraction (Tukey's test, $P < 0.05$).

0-5 cm	**Alkyl-C** **0-45 ppm**	**O-N-Alkyl-C** **45-110 ppm**	**Aryl-C** **110-165 ppm**	**Carboxyl-C** **165-215 ppm**	**Ratio** **A:OA**
fPOM					
IT	18.0 ± 1.4a	50.9 ± 1.4b	25.2 ± 0.6a	5.8 ± 0.8a	0.4 ± 0.0a
NT+PM	16.7 ± 1.0b	53.1 ± 0.2ab	24.6 ± 1.5a	5.6 ± 0.6a	0.3 ± 0.0b
RT+PI	18.6 ± 0.2a	55.2 ± 1.2a	21.7 ± 0.8b	4.5 ± 0.7a	0.3 ± 0.0b
oPOM					
IT	26.6 ± 1.2a	44.9 ± 1.1ab	19.1 ± 1.0a	9.4 ± 0.5a	0.6 ± 0.0a
NT+PM	24.6 ± 0.8b	46.1 ± 0.6a	22.1 ± 0.4a	7.2 ± 0.8ab	0.5 ± 0.0b
RT+PI	25.8 ± 0.3ab	43.5 ± 0.4b	21.2 ± 0.2a	9.5 ± 0.3a	0.6 ± 0.0a
MAOM					
IT	21.6 ± 1.4b	39.9 ± 2.0b	27.3 ± 1.7a	11.2 ± 1.2a	0.5 ± 0.0c
NT+PM	20.9 ± 0.8b	47.1 ± 2.1a	21.9 ± 1.8b	10.1 ± 1.6a	0.4 ± 0.0b
RT+PI	24.5 ± 0.1a	40.6 ± 1.5b	23.5 ± 0.7b	11.4 ± 1.6a	0.6 ± 0.0a
5-15 cm	**Alkyl-C** **0-45 ppm**	**O-N-Alkyl-C** **45-110 ppm**	**Aryl-C** **110-165 ppm**	**Carboxyl-C** **165-215 ppm**	**Ratio** **A:OA**
fPOM					
IT	15.1 ± 1.4b	50.9 ± 2.0b	25.8 ± 1.7 a	8.2 ± 0.5a	0.3 ± 0.0a
NT+PM	17.3 ± 0.7a	55.6 ± 0.1a	21.5 ± 0.9b	5.6 ± 0.2b	0.3 ± 0.0a
RT+PI	14.2 ± 0.5b	56.9 ± 0.3a	22.5 ± 0.8b	6.4 ± 0.2b	0.2 ± 0.0b
oPOM					
IT	30.1 ± 1.5a	48.4 ± 0.9b	18.8 ± 2.4a	2.7 ± 1.4b	0.6 ± 0.0a
NT+PM	25.3 ± 0.7b	44.5 ± 0.1c	22.1 ± 0.6a	8.1 ± 0.4a	0.6 ± 0.0a

RT+PI	14.5 ± 0.2c	54.9 ± 0.2a	23.0 ± 0.1a	7.6 ± 0.6a	0.3 ± 0.0b
MAOM					
IT	17.8 ± 1.1b	39.3 ± 2.6a	29.8 ± 0.7a	13.1 ± 1.6a	0.5 ± 0.0b
NT+PM	22.6 ± 1.7ab	42.9 ± 2.0a	23.6 ± 2.6b	10.9 ± 1.2a	0.5 ± 0.0b
RT+PI	24.5 ± 1.1a	39.9 ± 1.3a	23.7 ± 0.5b	11.9 ± 2.1a	0.6 ± 0.0a

Graphical abstract

Figure 1. Scheme of the SOM fractionation method: SPT (Sodium polytungstate), fPOM (free particulate organic matter, density < 1.6 g cm^{-3}), oPOM (occluded particulate organic matter, ultrasonication and density < 1.6 g cm^{-3}) and MAOM (mineral-associated organic matter, density > 1.6 g cm^{-3}).

Figure 2. **A)** Soil OC stocks and **B)** N stocks (kg m^{-2}) (mean values ± standard errors) among the different treatments: IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth. Different lowercase letters in bars indicate significant differences between management systems (Tukey's test, P < 0.05).

Figure 3. Aggregate size class distribution (g aggregate 100 g^{-1} soil): LM (>2000 µm), SM (250–2000 µm), m (63–250 µm), and s + c (<63 µm) in the 0–5 and 5–15 cm soil layers for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation). Numerical values are means ± standard errors. Different lowercase letters in bars indicate significant differences between management systems for each aggregate size (Tukey's test, P < 0.05).

Figure 4. Contribution of OC (left) and N (right) contents (mg g^{-1} soil) of aggregate size classes to total SOC and N of bulk soils (LM >2,000 µm, SM 250–2,000 µm, m 63–250 µm, and s+c <63 µm) for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth. Different lowercase letters in bars indicate significant differences between management systems (Tukey's test, P < 0.05).

Figure 5. OC (left) and N (right) content (mg g^{-1} soil) in SOM fractions fPOM (particulate organic matter), oPOM (occluded particulate organic matter), MAOM (mineral-associated organic

matter), in the 0–5 and 5–15 cm soil layers, for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation). Different lowercase letters in bars indicate significant differences between management systems (Tukey's test, $P < 0.05$).

Figure 6. PCA (Principal Component Analysis) results of the factors facilitating macro-aggregation and SOC stabilization in IT (intensive tillage plus flood irrigation; red color), NT+PM (no tillage plus pruning residues mulching plus drip-irrigation; orange color) and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation; green color).

Supplementary table 1A. Loading of long-term macroaggregate forming and soil OC stabilization in a Principal Component Analysis (PCA) for the management practices.

Supplementary figure 1A. Radar charts showing the difference between the main soil variables for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth. BD (Bulk density), SAR (sodium adsorption ratio), fPOM (free particulate organic matter), oPOM, (particulate organic matter) MAOM (Mineral-associated organic matter), MWD (Mean Weight Diameter), EC (electric conductivity), A: OA (Alkyl: O-N-Alkyl ratio).

Supplementary figure 2A: ^{13}C NMR spectra with chemical shift regions of Alkyl-C , total O-N-Alkyl-C , Aryl-C , and Carbonyl-C and the ratio A:OA (Alkyl-C : total O-N-Alkyl-C ratio) for the fractions fPOM (particulate organic matter), oPOM (occluded particulate organic matter) and MAOM (mineral-associated organic matter) for IT (intensive tillage plus flood irrigation), NT+PM (no-tillage plus pruning residues mulching plus drip-irrigation), and RT+PI (reduced tillage plus pruning residues incorporation plus drip-irrigation) at 0-5 and 5-15 cm soil depth.

Supplementary figure 3A. Structural equation modelling (SEM) for the aggregate stability. TLI: Tucker Lewis index, CFI: Comparative fit index, RMSEA: root mean square error of approximation, and SRMR: Standardized Root Mean Square Residual.

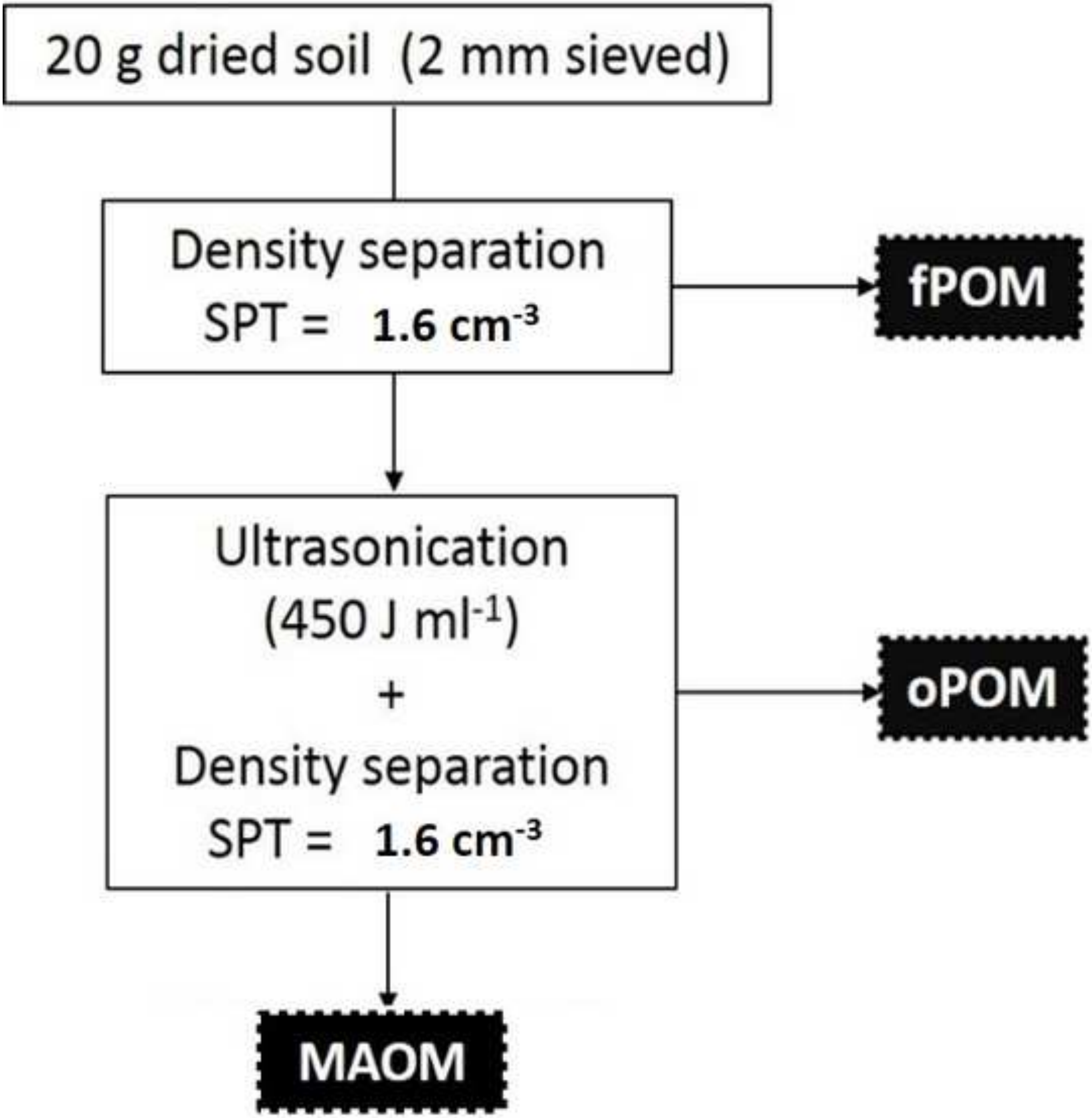
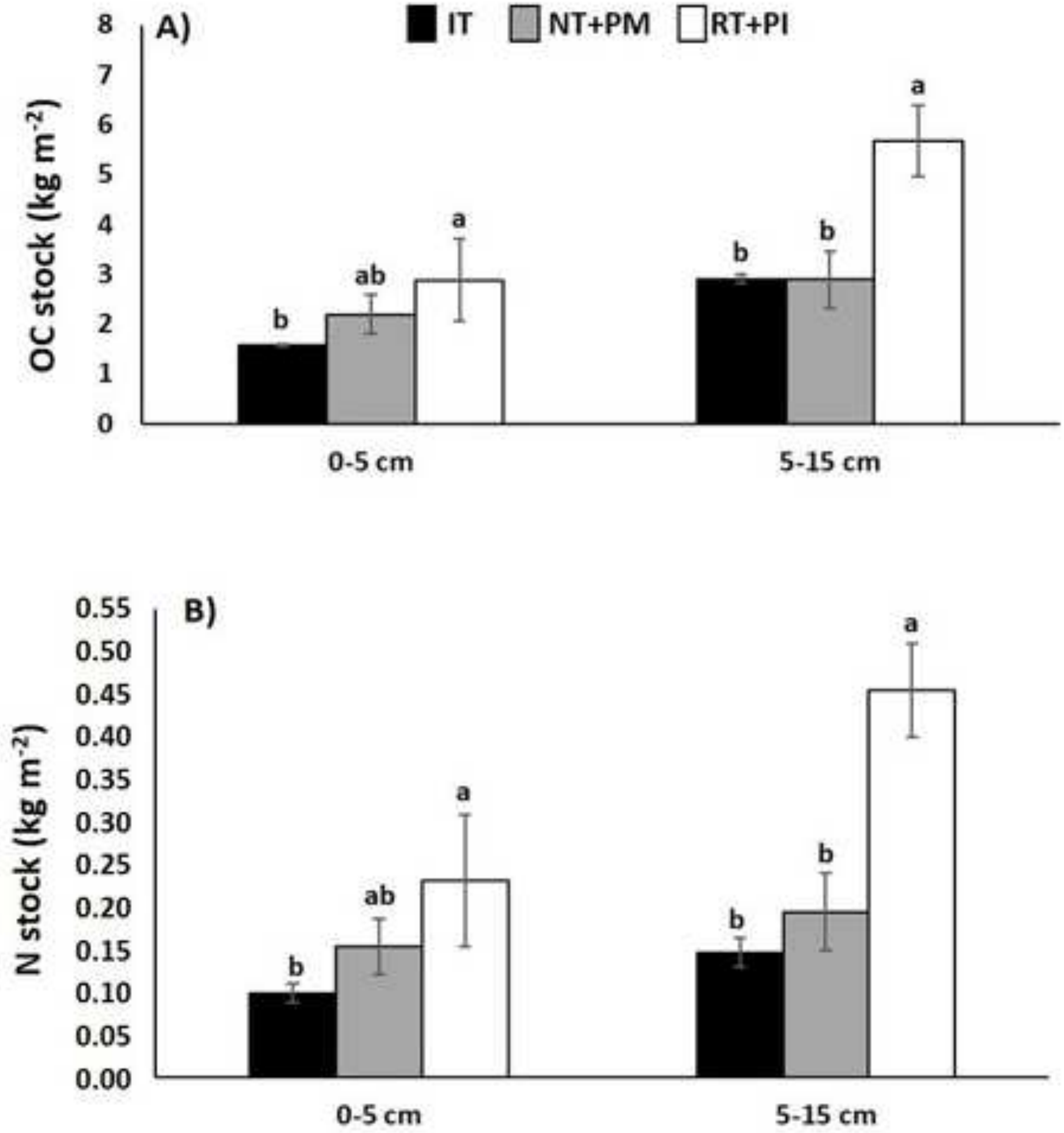

20 g dried soil (2 mm sieved)
Density separation
SPT = 1.6 cm-3
fPOM
Ultrasonication
(450 J ml-1)
+
Density separation
SPT = 1.6 cm-3
oPOM
MAOM

Figure 2


A)
IT
NT+PM
RT+PI
OC stock (kg m^{-2})
8
7
6
5
4
3
2
1
0
b
ab
a
b
b
a
0-5 cm
5-15 cm
B)
N stock (kg m^{-2})
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
b
ab
a
b
b
a
0-5 cm
5-15 cm

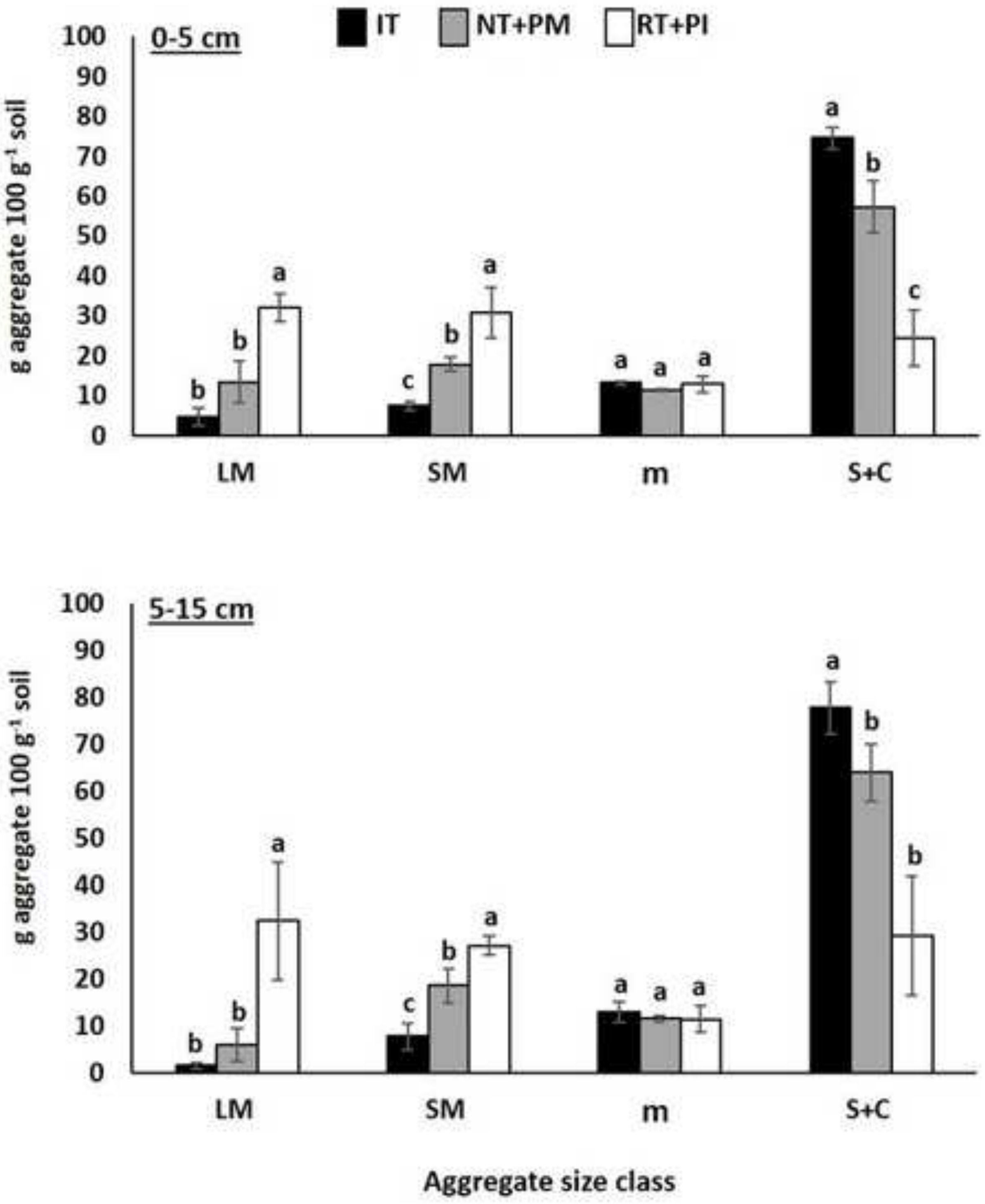

IT
NT+PM
RT+PI
0-5 cm
g aggregate 100 g⁻¹ soil
100
90
80
70
60
50
40
30
20
10
0
b
b
a
c
b
a
a
a
a
a
b
c
LM
SM
m
S+C
5-15 cm
g aggregate 100 g⁻¹ soil
100
90
80
70
60
50
40
30
20
10
0
b
b
a
c
b
a
a
a
a
a
b
b
LM
SM
m
S+C
Aggregate size class

Figure 4

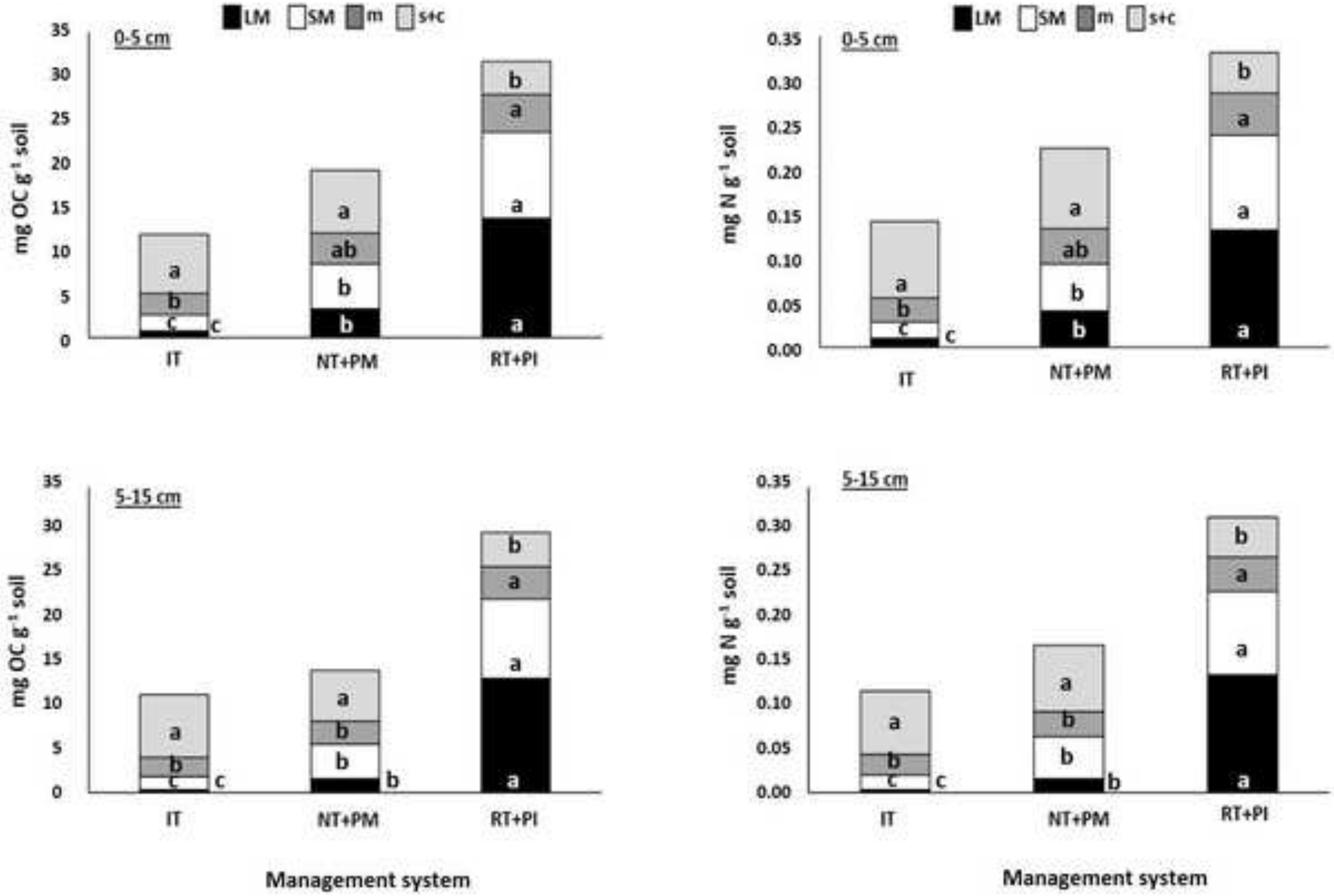
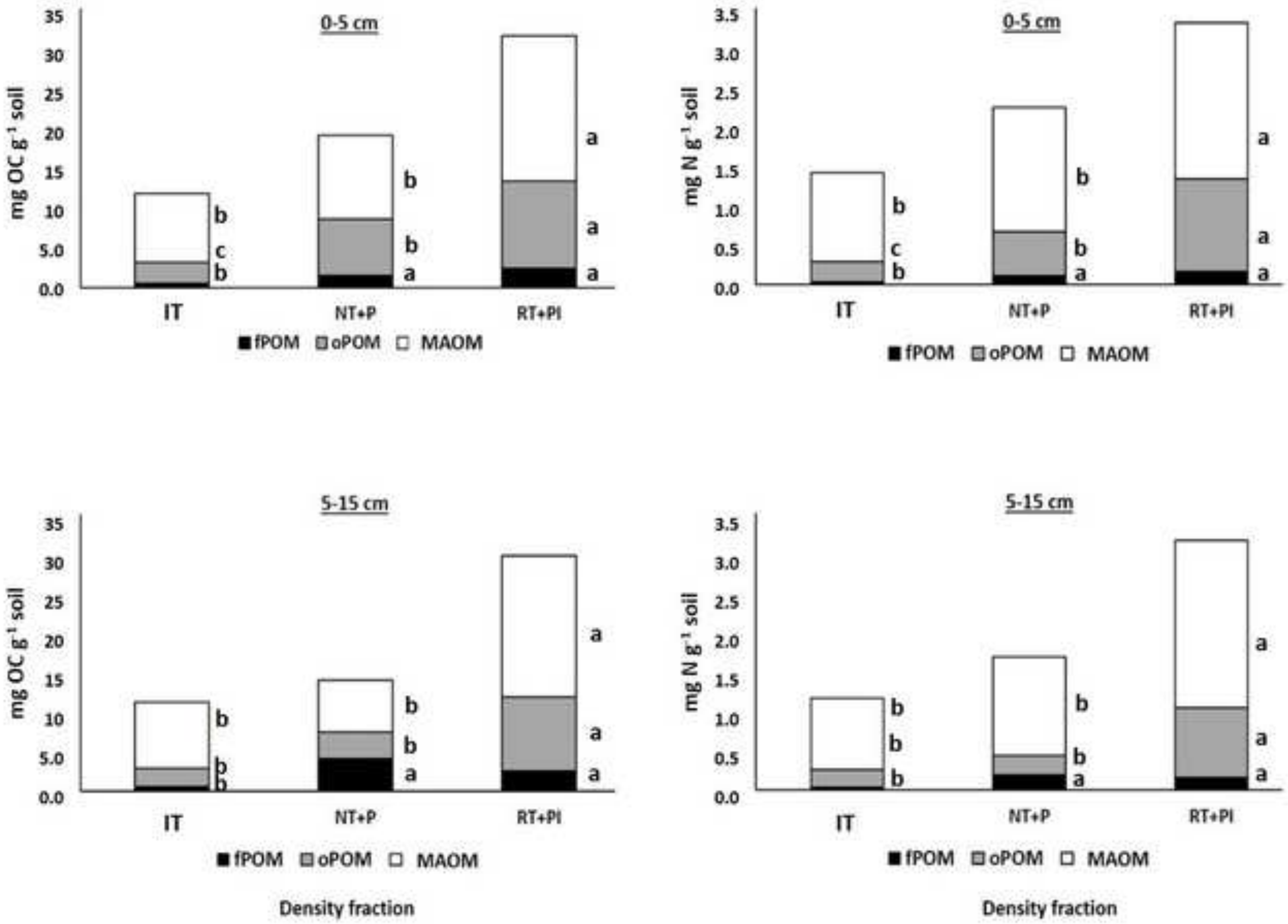

■ LM
□ SM
▨ m
░ s+c
0-5 cm
mg OC g⁻¹ soil
35
30
25
20
15
10
5
0
a
b
c
c
a
ab
b
b
b
a
a
a
IT
NT+PM
RT+PI
mg N g⁻¹ soil
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
5-15 cm
Management system

Figure 5


0-5 cm
mg OC g^{-1} soil
35
30
25
20
15
10
5.0
0.0
IT
NT+P
RT+PI
b
c
b
b
b
a
a
a
a
■ fPOM ▨ oPOM ☐ MAOM
0-5 cm
mg N g^{-1} soil
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
IT
NT+P
RT+PI
b
c
b
b
b
a
a
a
a
■ fPOM ▨ oPOM ☐ MAOM
5-15 cm
mg OC g^{-1} soil
35
30
25
20
15
10
5.0
0.0
IT
NT+P
RT+PI
b
b
b
b
b
a
a
a
a
■ fPOM ▨ oPOM ☐ MAOM
Density fraction
5-15 cm
mg N g^{-1} soil
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
IT
NT+P
RT+PI
b
b
b
b
b
a
a
a
a
■ fPOM ▨ oPOM ☐ MAOM
Density fraction

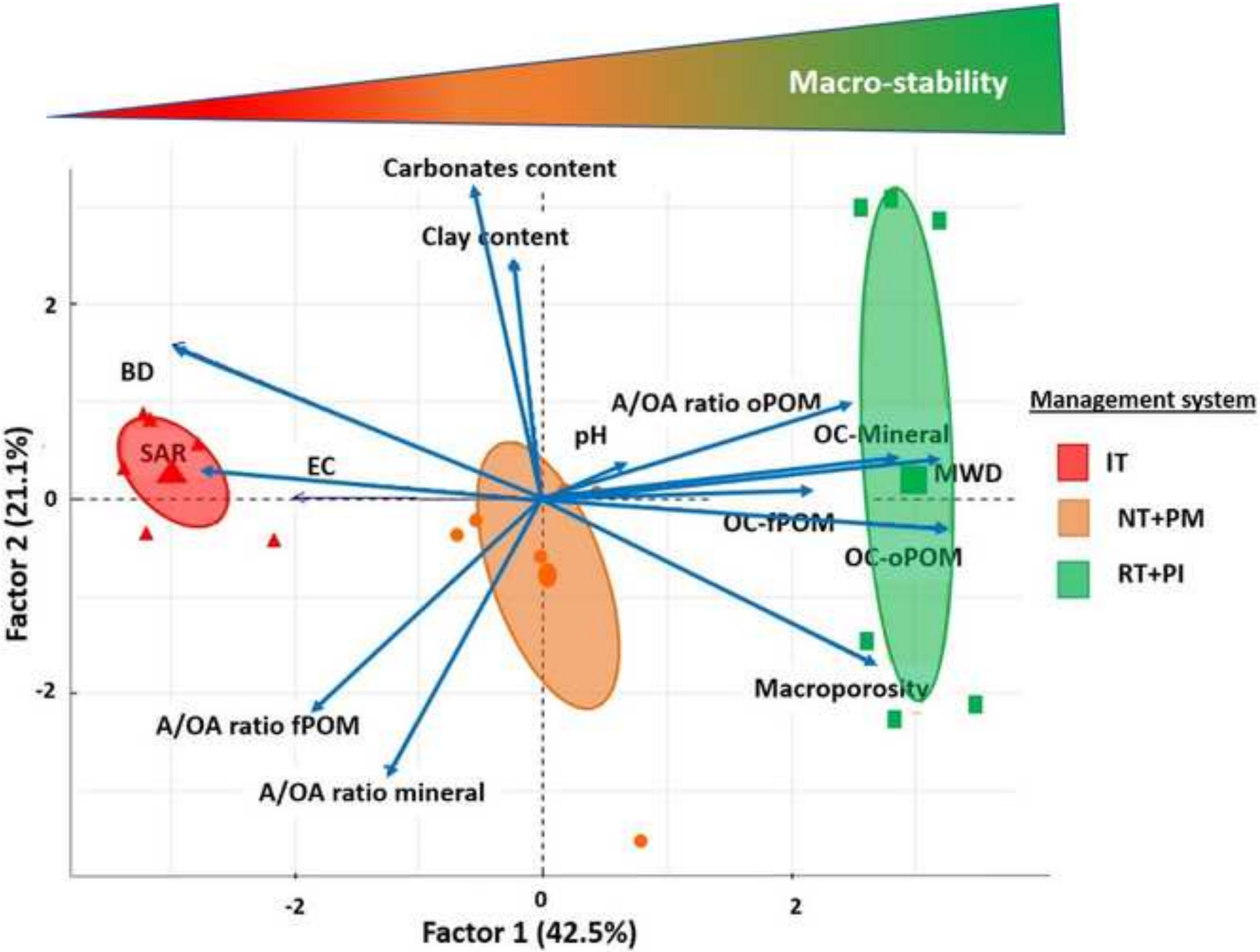

Macro-stability
Carbonates content
Clay content
BD
A/OA ratio oPOM
pH
OC-Mineral
MWD
SAR
EC
OC-fPOM
OC-oPOM
Macroporosity
A/OA ratio fPOM
A/OA ratio mineral
Management system
IT
NT+PM
RT+PI
Factor 2 (21.1%)
Factor 1 (42.5%)
2
0
-2
-2
0
2

Figure Supplementary 1A

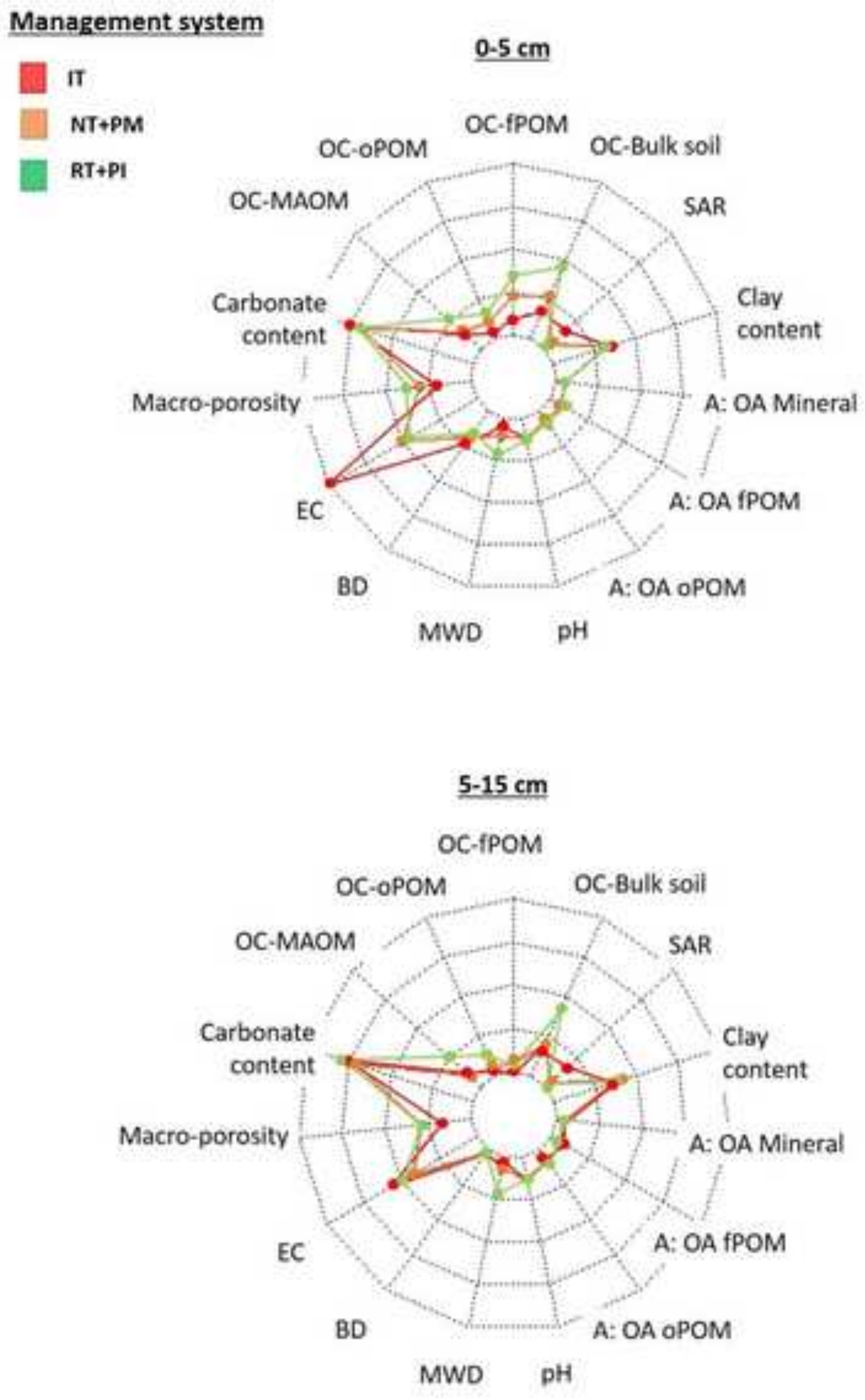
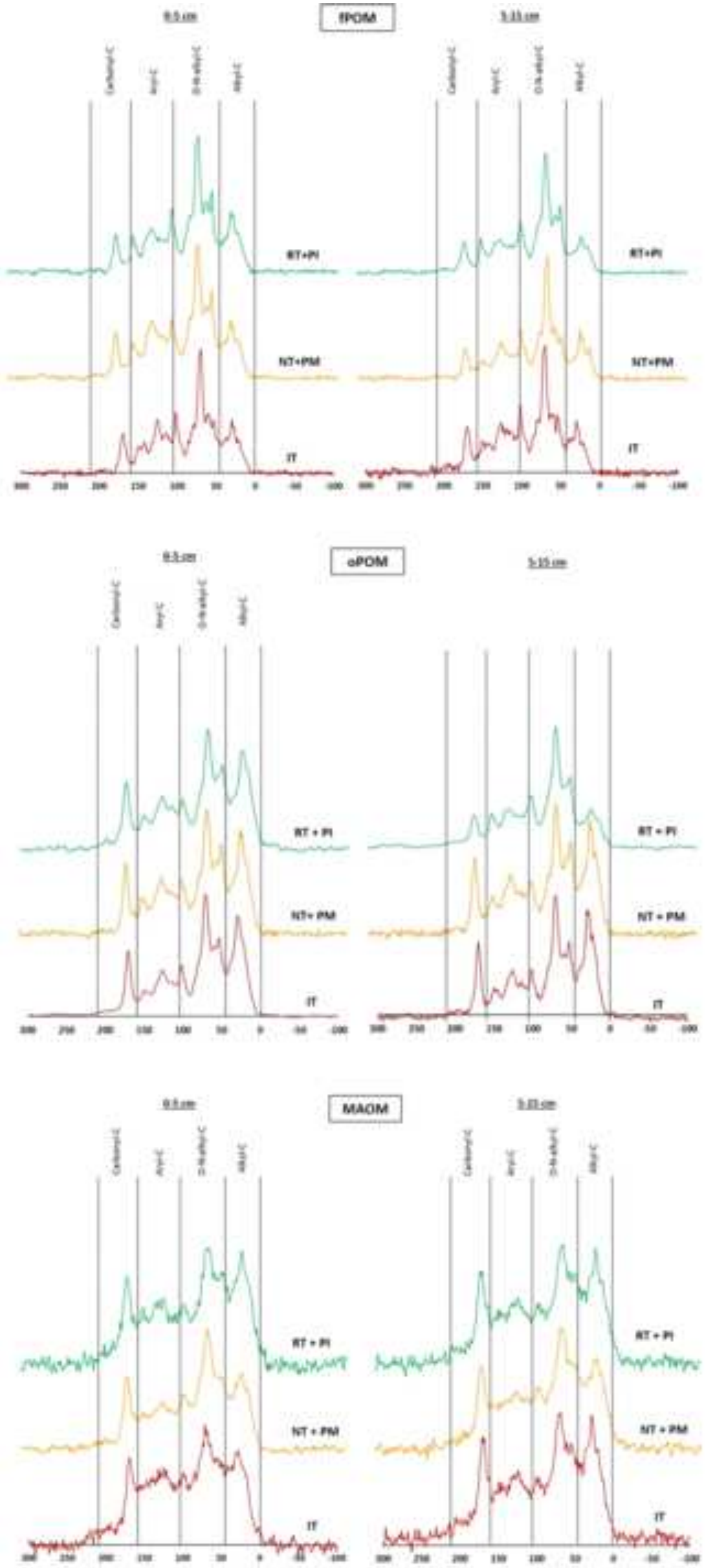
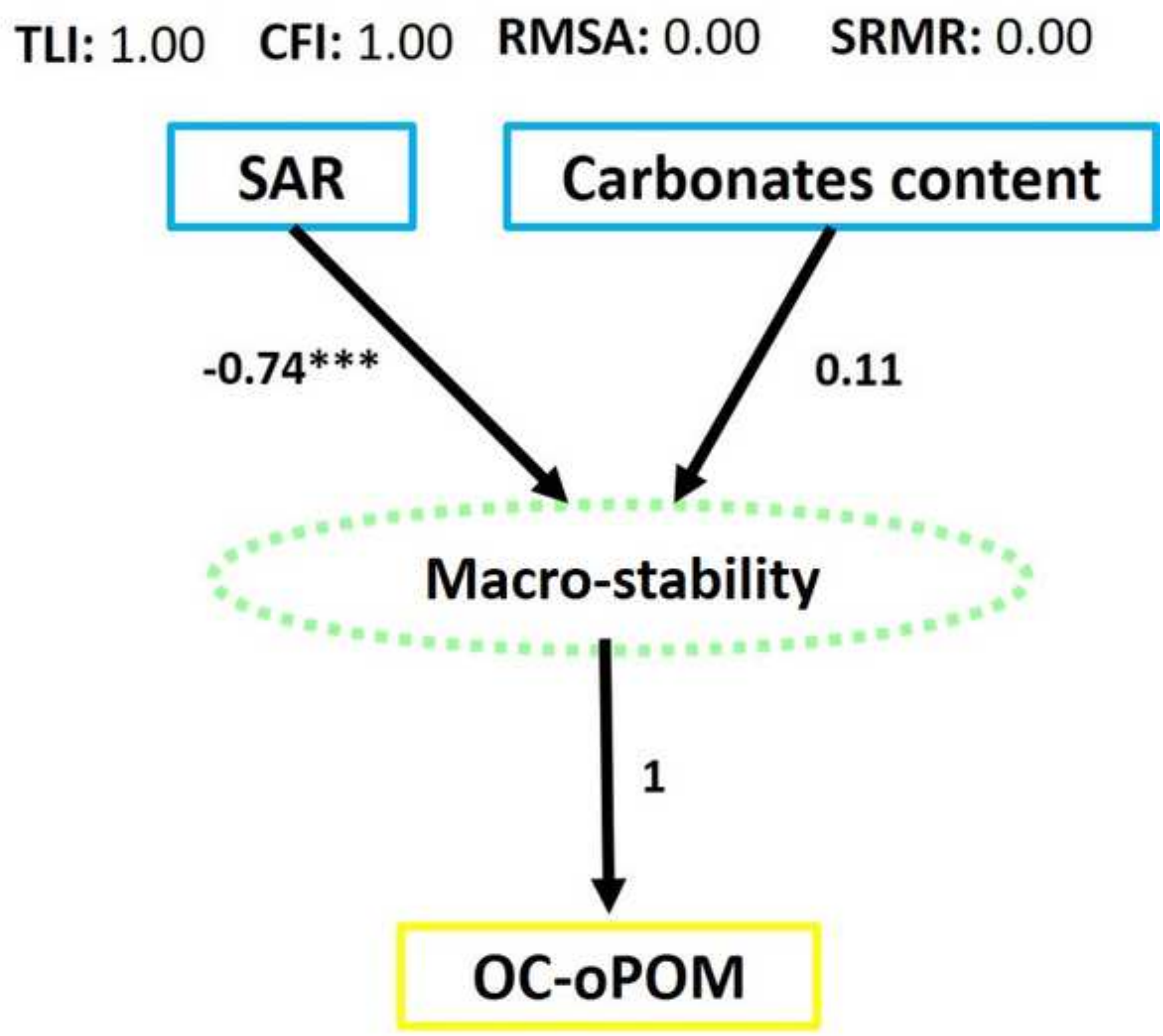


Figure Supplementary 2A




TLI: 1.00
CFI: 1.00
RMSA: 0.00
SRMR: 0.00
SAR
Carbonates content
-0.74***
0.11
Macro-stability
1
OC-oPOM

Supplementary Table 1A Eigenvalues of each PCA dimension

	Eigenvalue	Variance percent	Cumulative variance percent
Dim.1	6.0	42.5	42.5
Dim.2	3.0	21.1	63.6
Dim.3	1.8	12.8	76.4
Dim.4	1.2	8.4	84.8
Dim.5	0.9	6.6	91.4

Supplementary Table 2A Loadings of different soil variables on the two most important factors as identified in Principal Component Analysis

	Factor 1	***Factor 2***	***Factor 3***	***Factor 4***
Explained variance	***0.43***	***0.21***	***0.13***	***0.08***
Fraction related with SOM pools (concentration in mg g^{-1})				
OC-fPOM	0.60	0.02	**-0.61**	-0.45
OC-oPOM	**0.91**	-0.25	0.28	0.10
OC-MAOM	**0.80**	-0.12	**0.46**	0.20
Degradation status of SOM pools				
A: OA ratio fPOM	-0.58	**-0.68**	-0.20	0.10
A: OA ratio oPOM	0.67	0.27	0.24	-0.08
A: OA ratio MAOM	-0.36	**-0.75**	0.15	-0.08
Physical and chemical soil properties with influence in soil aggregation				
Carbonate content (%)	-0.16	**0.92**	0.18	0.18
Clay content (%)	-0.07	**0.68**	-0.50	-0.29
Macro-porosity (%)	0.75	-0.48	-0.11	0.04
E.C. (µS cm^{-1})	-0.56	0.01	**0.59**	-0.32
SAR (mmol L^{-1})	**-0.91**	0.10	0.21	0.24
pH	0.17	0.10	-0.47	**0.79**
Bulk density	**-0.83**	0.44	0.11	-0.03
MWD	**0.89**	-0.11	0.31	-0.03

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: