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Carbon and nitrogen contents and aggregation index of soil cultivated with onion for seven years using crop successions and rotations

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ABSTRACT

Onion is usually cultivated using conventional tillage system (CTS), with excessive soil turning, leaving it with low or no vegetation cover. This favors erosive processes and impacts negatively diverse edaphic attributes. Adopting soil management systems with conservationist bases that use permanent soil coverage and crop rotation can maintain or improve these attributes (for example, soil aggregation and soil organic matter). The objective of this work was to evaluate the total organic carbon (TOC) and total nitrogen (TN) contents, aggregation index, and aggregate mass distribution of a Humic Cambisol cultivated with onions in succession or rotation with other species in no-tillage system (NTS) and CTS. The treatments were: maize/onion (NTS-T1); cover plants (winter)/onion (NTS-T2); maize/winter grasses/onion (NTS-T3); velvet bean/onion (NTS-T4); millet/cover plants (winter)/onion (NTS-T5); velvet bean/rye/onion (NTS-T6); maize/onion (CTS-T7); intercrops cover plants (summer)/onion (NTS-T8). Seven years after the implementation of the experiment, the weighted mean diameter (WMD) of the aggregates, distribution of macroaggregates, mesoaggregates, and microaggregates, and TOC, and TN contents of the soil (0–0.05, 0.05–0.10 and 0.10–0.20 m layers) were evaluated. Periodic soil turning (CTS) in the succession of maize, and onion (T7) reduces TOC and TN contents in the soil surface layer, compared to succession and rotation systems with onion crops in NTS. This negative effect on soil quality is connected to the reduction of aggregate stability, especially the decrease in the amount of macroaggregates. The use of grasses, especially winter grasses in rotation with maize (T3), preceding onion crops in NTS increases TOC content in the soil surface layer. Higher TN accumulation in the surface layer is found in areas with more soil cover plant species in rotation or succession with onion in NTS (T2, T3, T5, T6 and T8). The use of NTS for onion crops generates high soil aggregate stability, with predominance of macroaggregates, regardless of the crop succession or rotation system used. Treatments with no winter soil cover plants (T1, T4 and T7) reduce soil TOC contents and the mass of water-stable macroaggregates and increase the amount of microaggregates in the soil surface layer when compared to the other treatments.

1. Introduction

Onion (*Allium cepa*) is grown worldwide in 3.72 million hectares; China, India and the United States are the main producing countries; and Brazil has the ninth greatest onion production (The Daily Records, 2018). Onion crops have economic and social importance in Brazil; they generate jobs and income throughout its production chain. The South of Brazil accounts for 47% of the Brazilian onion production; the state of Santa Catarina was the largest onion producer in the last 25 years, with 20,000 ha of onion, representing one third of the Brazilian production (ACATE, 2014; IBGE, 2016). These crops are distributed in 18,000 farms, which are mainly managed by family farmers, and most of them are managed using conventional soil tillage system (CTS) (EPAGRI, 2013). The use of CTS in these regions can damage soil quality, considering their soil and environmental characteristics.

The practices carried out in CTS to obtain a suitable environment for

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the crops usually involves the use of plowing and harrowing (Magdoff and Van Es, 2009) or cultivators (Balesdent et al., 2000; So et al., 2009). These practices leave the soil with no or low coverage, favoring erosion processes (Bhatt and Khera, 2006; So et al., 2009), and affects negatively the soil macroporosity, aggregate stability (Franzluebbers, 2002; Paglia et al., 2004; So et al., 2009; Sheehy et al., 2015), and total organic carbon (TOC) and total nitrogen (TN) contents (Busari et al., 2015; Mazzoncinia et al., 2016).

Therefore, the adoption of no-tillage system (NTS) is growing and contributing to improve the soil physical, chemical, and biological characteristics (Busari et al., 2015; Bhatt, 2017). NTS increases the soil TOC (Ussiri and Lal, 2009; Busari et al., 2015; Mazzoncinia et al., 2016) and TN (Busari et al., 2015; Mazzoncinia et al., 2016) contents and, consequently, the soil aggregate stability (So et al., 2009; Sheehy et al., 2015). The use of NTS combined with crop rotation assists in the maintenance or even improves soil fertility, soil organic matter (SOM), and structure, in the control of pests, diseases and weeds (Ball et al., 2005), and increases crop yield (Stanger and Lauer, 2008; Campbell et al., 2011). The soil aggregate stability is improved by the plant species richness, and presence of certain grass and legume species due to their root architecture (Gould et al., 2016).

The use of soil cover crops, especially grasses, protects the soil against climatic events, and increases soil TOC, mainly by rhizodeposition. According to Thivierge et al. (2016), maize, sorghum, and millet root systems contributed to the C contents in the soil at depth of 0.30 m, with higher C accumulation after harvest due to crop residues for maize (243 g C m^{-2}) than for sorghum (197 g C m^{-2}) and millet (131 g C m^{-2}). Most of this C were from the fine roots, with diameters smaller than 0.5 mm. Oat plants have fasciculate root system that reaches depths of up to 0.76 m, average shoot dry matter production of 6 Mg ha^{-1}, and high C/N ratio (average of 31.5). Rye plants have high nutrient cycling capacity, fasciculate root system that reaches depths of up to 1.22 m, average shoot dry matter production of 4.5 Mg ha^{-1}, and high C/N ratio (average of 30.5). Maize plants have an extensive and branched root system, reaching depths of up to 1.8 m, average shoot dry matter production of 6 Mg ha^{-1}, and high C/N ratio (average of 52) (Weaver, 1926; Lima Filho et al., 2014).

Thierfelder and Wall (2010) compared the effect of CTS (monoculture of maize, and maize in succession with cotton – *Gossypium hirsutum* L.) and NTS (two-year and three-year rotations of maize with cotton, and *Crotalaria juncea* as soil cover plant) over four years and found similar results. They found higher water infiltration rates, earthworm population, TOC contents, and aggregate stability in NTS treatments. Several studies have reported positive correlations between SOM and aggregate stability (Amezketa, 1999; Balesdent et al., 2000; Carrizo et al., 2015; Sheehy et al., 2015). Soil turning disaggregates the soil, exposing the SOM that was protected to microbial attack, accelerating its loss (Amezketa, 1999) and, consequently, decreasing aggregate stability.

Evaluating the effects of NTS, CTS, secondary forest, and pasture (*Axonopus compressus*) on the soil aggregation, SOM content in water, TOC, and mineralizable carbon of a Red Nitosol (Alfisol) in Marmeleiro PR, Brazil; Loss et al. (2014) found lower aggregation indices (weighted mean diameter index) and TOC contents in CTS when compared to NTS. Loss et al. (2015) also found similar results when evaluating chemical and physical characteristics of soil aggregates; after five years of NTS with onion in a Humic Distrudept, they compared the effects of different intercrops, and onion crop in CTS for 37 years on the soil aggregation and TOC and found that the use of soil cover crops (single or intercropped) in NTS increases soil aggregation and TOC contents, compared to CTS.

NTS increases aggregate stability, and TOC contents inside the aggregates. So et al. (2009) compared the effect of using CTS and NTS for 14 years on soil physical properties and TOC contents and found lower silt and clay contents dispersed in water and higher aggregation index (WMD) for NTS, i.e., a more stable and better aggregated soil surface layer due to the higher TOC in NTS (33.7 g kg^{-1}), compared to CTS (16.7 g kg^{-1}).

The roots of the plants are temporary agents of macroaggregate stabilization. Several studies have shown improvement in the stability of these structures by the root activity (Amezketa, 1999; Six et al., 2004; Gould et al., 2016). The positive effects of roots on soil aggregation may be due to the fine particles within stable macroaggregates; the drying of the soil around the roots, which reorganizes and approaches clay particles that are parallel to the root axis; the input of decomposable organic residues to the soil; the supporting to a high microbial population in the rhizosphere; the provision of food for the soil fauna; and the release of polyvalent cations, which increases ion concentration in the soil solution. Pérès et al. (2013) evaluated the soil aggregate stability with 60 native plant species of four functional groups – 16 grasses, 12 small herbs, 20 large herbs, and 12 legumes – in a pasture in Jena, Germany and found a significant increase in aggregate stability in soils with intercrops of species, and grasses, and a decrease with legume species, compared to areas with single species; however, the effects varied depending on the measures of stability of the aggregates –rupture by humidity, mechanical rupture, and microcracks.

Plant community characteristics such as diversity of plant species and the presence of grasses and legumes can affect soil aggregate stability. It can be connected to changes in root biomass, TOC, soil microbial biomass, and earthworm biomass. Although legumes assist in essential ecosystem processes, such as primary production, by increasing TN availability, they may disfavor soil aggregate stability. However, mixtures of plants with higher proportion of grasses increase aggregate stability by increasing root biomass, TOC, and soil microbial biomass (Pérès et al., 2013; Lange et al., 2015).

In this study, we hypothesized that (a) maize/onion succession in CTS reduces soil quality compared to NTS; (b) grasses in succession or rotation with onion in NTS increases TOC content; (c) treatments that do not use cover crops in winter reduces SOM content and soil aggregation compared to treatments using winter cover crops for onion cultivation. In this context, the objective of this work was to evaluate the TOC and TN contents, aggregation index, and aggregate mass distribution of a Humic Cambisol cultivated with onions in succession or rotation with other species for seven years.

2. Material and methods

2.1. Location of the experiment and treatments

The experiment was carried out in April 2007, in Ituporanga, Santa Catarina State, Brazil, at the Experimental Station of the Research and Agricultural Extension Company of Santa Catarina (27°24′52″S, 49°36′9″W, and altitude of 475 m). The soil of the region was classified as dystrophic Humic Cambisol (EMBRAPA, 2013), or Humic Distrudept (Soil Survey Staff, 2006), and derived from Permian sediments of the Guatá Group (EMBRAPA, 2004). Its physical and chemical attributes in the 0-0.10 m layer presented 410, 264 and 326 g kg^{-1} of sand, silt and clay, respectively (EMBRAPA, 1997); pH in H_2O of 6.1; 23.08 g kg^{-1} of TOC, exchangeable Ca, Mg and Al of 6.4, 2.7 and 0.0 $cmol_c\ dm^{-3}$, respectively (extracted by KCl 1 mol L^{-1}); and available P and K of 42 and 208 mg dm^{-3}, respectively (extracted by Mehlich-1).

According to the Köppen classification, the climate of the region is Cfa, subtropical mesothermal humid, with hot summers, infrequent frosts, and no defined dry season; it presents average annual temperature of 17.6 °C and average annual precipitation of 1400 mm. A randomized complete block design, with eight treatments, five replications, and plots of 8.7 m^2 was used. The treatments were the management systems for onion crops, with different soil cover plant species. Oat, vetch, and oilseed radish were used in 2007, when experiment was implemented with eight treatments, using cover plants and commercial crops (Table 1).

Table 1
Species used in the crop rotation treatments for onion crops in soil different management systems from 2007 to 2010, Ituporanga, Santa Catarina State, Brazil.

T	2007			2008			2009		2010		
	Winter		Summer	Winter		Summer	Winter	Summer	Winter		Summer
T1	Oat + Vetch + Oilseed radish		Maize	Fallow	Onion	Maize	Fallow Onion	Maize	Fallow	Onion	Maize
T2	Oat + Vetch + Oilseed radish		Maize	Oat + Oilseed radish + Rye	Onion	Sunflower	Oat + Vetch + Oilseed radish	Common Bean	Rye + Oilseed radish	Onion	Maize
T3	Oat + Vetch + Oilseed radish		Maize	Oat + Oilseed radish	Onion	Maize	Vetch	Maize	Rye	Onion	Maize
T4	Oat + Vetch + Oilseed radish		Maize	Oat + Oilseed radish + Rye	Onion	Velvet bean	Rye	Maize	Oilseed radish	Onion	Velvet bean
T5	Oat + Vetch + Oilseed radish	Onion	Pearl Millet	Oilseed radish	Onion	Pearl Millet	Oat + Vetch + Oilseed radish	Maize	Cevada	Onion	Pearl Millet
T6	Oat + Vetch + Oilseed radish	Onion	Jack bean	Rye	Onion	Velvet bean	Onion	Velvet bean	Rye	Onion	Velvet bean
T7	Oat + Vetch + Oilseed radish	Onion	Jack bean + Pearl Millet	Oat	Onion	Showy rattlebox	Rye	Maize	Oat	Onion	Showy rattlebox
T8	Oat + Vetch + Oilseed radish	Onion	Sunflower	Oat + Rye	Onion	Sunflower + Velvet bean + Pearl Millet	Vetch	Maize	Rye + Oat + Oilseed radish	Onion	Pearl Millet + Velvet bean + Sunflower

Species: Oat (*Avena strigosa*), Onion (*Allium cepa*), Rye (*Secale cereale*), Showy rattlebox (*Crotalaria spectabilis*) Vetch (*Vicia villosa*), Common Bean (*Phaseolus vulgaris* L.), Jack bean (*Canavalia ensiformis*), Sunflower (*Helianthus annuus*), Maize (*Zea mays*), Pearl Millet (*Pennisetum americanum*), Velvet bean (*Stizolobium aterrimum*) and Oilseed radish (*Raphanus sativus*). T1 = succession of onion and maize in no-tillage system (NTS); T2 = rotation of soil cover plants (winter), and biennial onion in NTS; T3 = rotation of maize, winter grasses, and annual onion in NTS; T4 = succession of velvet bean, and annual onion in NTS; T5 = rotation of millet, soil cover plants (winter), and annual onion in NTS; T6 = succession of velvet bean, rye, and annual onion in NTS; T7 = succession of maize, and onion in CTS; T8 = succession of intercrops of soil cover plants (summer), and annual onion in NTS. T = Treatments.

Table 2
Species used in the crop rotation treatments for onion crops in soil different management systems from 2011 to 2013, Ituporanga, Santa Catarina State, Brazil.

T	2011			2012			2013		
	Winter		Summer	Winter		Summer	Winter		Summer
T1	Fallow	Onion	Maize	Fallow	Onion	Maize	Fallow	Onion	Maize
T2	Vetch		Maize	Rye + Oilseed radish	Onion	Maize	Rye + Oilseed radish		Common Bean
T3	Rye	Onion	Maize	Oat	Onion	Maize	Rye	Onion	Maize
T4	Fallow Onion		Velvet bean	Fallow Onion		Velvet bean	Fallow Onion		Velvet bean
T5	Rye	Onion	Pearl Millet	Oat	Onion	Pearl Millet	Rye	Onion	Pearl Millet
T6	Rye	Onion	Velvet bean	Rye	Onion	Velvet bean	Rye	Onion	Velvet bean
T7	Fallow	Onion	Maize	Fallow	Onion	Maize	Fallow	Onion	Maize
T8	Fallow	Onion	Pearl Millet + Velvet bean + Sunflower	Fallow	Onion	Pearl Millet + Velvet bean + Sunflower	Fallow	Onion	Pearl Millet + Velvet bean + Sunflower

Species: Oat (*Avena strigosa*), Onion (*Allium cepa*), Rye (*Secale cereale*), Showy rattlebox (*Crotalaria spectabilis*) Vetch (*Vicia villosa*), Common Bean (*Phaseolus vulgaris*), Jack bean (*Canavalia ensiformis*), Sunflower (*Helianthus annuus*), Maize (*Zea mays*), Pearl Millet (*Pennisetum americanum*), Velvet bean (*Stizolobium aterrimum*) and Oilseed radish (*Raphanus sativus*). T1 = succession of onion and maize in no-tillage system (NTS); T2 = rotation of soil cover plants (winter), and biennial onion in NTS; T3 = rotation of maize, winter grasses, and annual onion in NTS; T4 = succession of velvet bean, and annual onion in NTS; T5 = rotation of millet, soil cover plants (winter), and annual onion in NTS; T6 = succession of velvet bean, rye, and annual onion in NTS; T7 = succession of maize, and onion in CTS; T8 = succession of intercrops of soil cover plants (summer), and annual onion in NTS. T = Treatments.

In 2011, rotation and succession systems and the sequence of cover plants were modified, and a soil CTS treatment was implemented for comparison with the other treatments in NTS (Table 2). The soil preparation in CTS was carried out using one plowing and two harrowing passes. The sequence of the plants used in each treatment in 2011, 2012 and 2013 (Table 2) was repeated from 2014. The choice of plant species for the experiment (Tables 1 and 2) was carried out considering plants frequently used by the producers of the region, with good adaptation, seed availability in the market, easy handling, and adequate dry matter production for the NTS.

Weed, pest, and disease control were carried out with chemical products registered for onion crops in the Brazilian Ministry of Agriculture. Three herbicide applications with ioxynil, pendimethalin, and fenoxaprop-p-ethyl + clethodim, and a manual weeding was performed for weed control. Pests, especially *Thrips tabaci* Lind., were controlled with three insecticides applications with lambda-cyhalothrin and imidacloprid. Five fungicide applications with metalaxyl + chlorothalonil, metalaxyl + mancozeb, iprodione, and tebuconazole + trifloxystrobin were carried out for fungal disease control, especially mildew (*Peronospora destructor*) and *Alternaria solani.*

The area of the experiment had been cultivated using a conservationist production system since 1995, when the last liming was carried out to raise the pH to 6. Fertilization was carried out during the experiment only for onion and maize crops, according to the recommendations of CQFSRS/SC (2004). Fertilization for onion crops consisted of 75 Kg ha^{-1} of N, 120 Kg ha^{-1} of P_2O_5, and 60 Kg ha^{-1} of K_2O, using the 05-20-10 NPK formulation, or triple superphosphate, potassium chloride, and ammonium nitrate. P and K were applied soon before the onion planting, and N (15 Kg N ha^{-1}) was applied at planting, and as topdressing at 45, 65, and 85 days after transplantation of the onion seedlings using ammonium nitrate. The P rates were very high in 2010 (CQFSRS/SC, 2004), thus, only 50 Mg ha^{-1} of P was used for onion, and 0.08 Mg ha^{-1} in the following crops. P and K was not applied for maize crops because the soil presented high contents in the analysis; nitrogen was applied using 0.09 Mg ha^{-1} of urea, when the maize reached six to eight leaves.

The soil cover plants were killed, and furrows were opened with a machine adapted for the planting of onion in NTS; the seedlings (cultivar Bola Precoce) were manually transplanted, using spacing of 0.40 m between rows and 0.10 m between plants.

2.2. Soil sample collection

Seven years after the implementation of the experiment, in September 2014, undisturbed soil samples were collected for physical analysis, and deformed samples were collected for chemical analysis. A hole of 0.40 × 0.40 x 0.40 m was opened in the soil of each plot using a shovel for collecting the soil samples in the 0.0-0.05, 0.05-0.10, and 0.10-0.20 m layers. The samples were air-dried and manually disaggregated. Undisturbed samples were separated by slits or weakness points and passed through 8.00 mm, and 4.00-mm mesh sieves to evaluate the soil aggregates (EMBRAPA, 1997). Deformed samples were passed through a 2.00-mm mesh sieve to determine the TOC and TN contents.

2.3. Physical and chemical analyzes

Soil aggregates were separated an those retained in the 4.0-mm mesh sieve were used to analyze the wet aggregate stability, and aggregate mass distribution by passing 25 g of aggregates through sieves with decreasing mesh diameters (2.00; 1.00; 0.50; 0.25, and 0.105 mm) (EMBRAPA, 1997). The aggregates were wetted using a water spray and wet sieved through the set of sieves for 15 min in a Yoder device (Yoder, 1936). Then, the material retained in each sieve was retrieved, separated by a water jet, placed on previously weighed and identified Petri dishes, and taken to a forced air circulation oven at 105 °C until constant weight.

The aggregate dry mass was used to determine the aggregate weighted mean diameter index (WMD) (EMBRAPA, 1997), and their distribution in the mean diameter classes: 8.00 > Ø ≥ 2.0 mm (macroaggregates); 2.0 > Ø ≥ 0.25 mm (mesoaggregates), and Ø < 0.25 mm (microaggregates). With the masses of the aggregates retained in the classes of Ø: < 0.105, 0.105-0.25, 0.25-0.50; 0.50–1.00, 1.00–2.00 e 2.00–8.00 mm and the Ø mean of the respective class, it was determined the WMD, using equation:

$$WMD = exp\left[\sum_{i=1}^{n} (pi*\text{ln}di\right]$$

where ***i*** represents the class of soil aggregates (8.00-2.00; 2.00-1.00; 1.00-0.50; 0.50-0.25, 0.25-0.105 and < 0.105 mm); ***pi*** is the proportion of soil aggregates present in the respective class in relation to the total mass of soil aggregates; ***ln*** is the Neperian logarithm; and ***d*** is the mean diameter of the class (respectively, 5.0, 1.5, 0.75, 0.375, 0.065 and 0.0525 mm).

TOC and TN contents were determined in a dry combustion elemental analyzer (FlashEA 1112 Thermo Finnigan) at the Laboratory of Research in Biotransformation of Carbon and Nitrogen (LABCEN) of the Federal University of Santa Maria, Rio Grande do Sul, Brazil.

2.4. Statistical analysis

The results were analyzed using the model general linear, being eight treatments as separate treatment levels (i.e, the eight treatments and replications as the only use inputs). The data were tested for normality and homogeneity by the Lilliefors and Bartlet tests, respectively. The data presented normal distribution, not requiring the use of data transformation. The data were then subjected to analysis of variance and, when the effects were significant, the means were compared by the Scott-Knott test at 5% probability. The use of the Scott-Knott test an efficient alternative when a large number of treatments are evaluated. This test is a method of grouping means, which distinguishes results without ambiguity (Bhering et al., 2008). Statistical analysis were performed using software Sisvar 5.6.

3. Results and discussion

Differences in soil TOC contents between the treatments were found only in the 0-0.05 m layer. The highest TOC was found in T3 (rotation of maize, winter grasses, and annual onion in NTS) and the lowest in T7 (succession of maize, and onion in CTS). T2 ((rotation of soil cover plants (winter), and biennial onion in NTS)), T5 ((rotation of millet, soil cover plants (winter), and annual onion in NTS)) and T6 (succession of velvet bean, rye, and annual onion in NTS) presented higher TOC contents than T1 (succession of onion and maize in NTS), T4 (succession of velvet bean, and annual onion in NTS), and T8 (succession of intercrops of soil cover plants (summer), and annual onion in NTS). Similarly, soil TN contents were different only in the 0-0.05 m layer. The highest TN content was found in T2, T3, T5, T6, and T8, and the lowest was found in T7 (Table 3).

The soil management and lower diversity of soil cover plant species in T7 generated the lowest TOC, and TN contents in the 0-0.05 m layer. Despite the biomass produced by the maize and weeds in T7, the practices used in CTS fragmented the plant residues, accelerated their decomposition, and might cause soil disaggregation, exposing the soil TOC and TN that were protected inside the aggregates, increasing the soil microbiota decomposition. This causes a higher mineralization rate of the SOM and decreases soil TOC and TN contents (Boddey et al., 2010; Busari et al., 2015; Santos et al., 2018). The lower TOC and TN contents in T7 resulted in low proportion of stable macroaggregates in water in the 0.05-0.10 m layer and increased mesoaggregate and microaggregate masses (Fig. 1), with a consequent reduction in the aggregate stability, presenting lower weighted mean diameter index (WMD) in 0.05-0.10 m, compared to the other treatments (Table 4). Similar results were found by Loss et al. (2015) when evaluating the effects of NTS and CTS after five years with onion.

Considering the soil TOC content at the beginning of the experiment (2007) in the 0.0-0.10 m layer (23.08 g kg^{-1}), it increased after seven years in all treatments in the average of 0.0-0.10 m layer, being 28.44

Table 3
Total organic carbon (TOC) and total nitrogen (TN) contents of a Humic Cambisol with onion crops in no-tillage and conventional systems with different crop successions and rotations, Ituporanga, Santa Catarina State, Brazil.

Treatment	TOC 0-0.05 m	TN	TOC 0.05-0.10 m	TN	TOC 0.10-0.20 m	TN
T1	31.48 c	2.70 b	25.40 a	2.07 a	21.93 a	1.62 a
T2	34.30 b	3.12 a	26.26 a	2.08 a	23.16 a	1.64 a
T3	39.64 a	3.27 a	25.69 a	2.23 a	22.91 a	1.66 a
T4	31.91 c	2.76 b	26.43 a	2.15 a	23.76 a	1.64 a
T5	34.85 b	3.11 a	27.70 a	2.23 a	23.62 a	1.75 a
T6	33.88 b	3.30 a	26.74 a	2.17 a	23.18 a	1.67 a
T7	26.46 d	2.26 c	25.02 a	2.22 a	23.42 a	1.75 a
T8	30.47 c	2.95 a	25.16 a	2.09 a	21.32 a	1.58 a
CV (%)	7.31	7.38	5.53	5.04	5.54	8.02

Means followed by the same letter in the column were similar by the Scott-Knott test at 5%. CV = coefficient of variation. T1 = succession of onion and maize in no-tillage system (NTS); T2 = rotation of soil cover plants (winter), and biennial onion in NTS; T3 = rotation of maize, winter grasses, and annual onion in NTS; T4 = succession of velvet bean, and annual onion in NTS; T5 = rotation of millet, soil cover plants (winter), and annual onion in NTS; T6 = succession of velvet bean, rye, and annual onion in NTS; T7 = succession of maize, and onion in CTS; T8 = succession of intercrops of soil cover plants (summer), and annual onion in NTS.

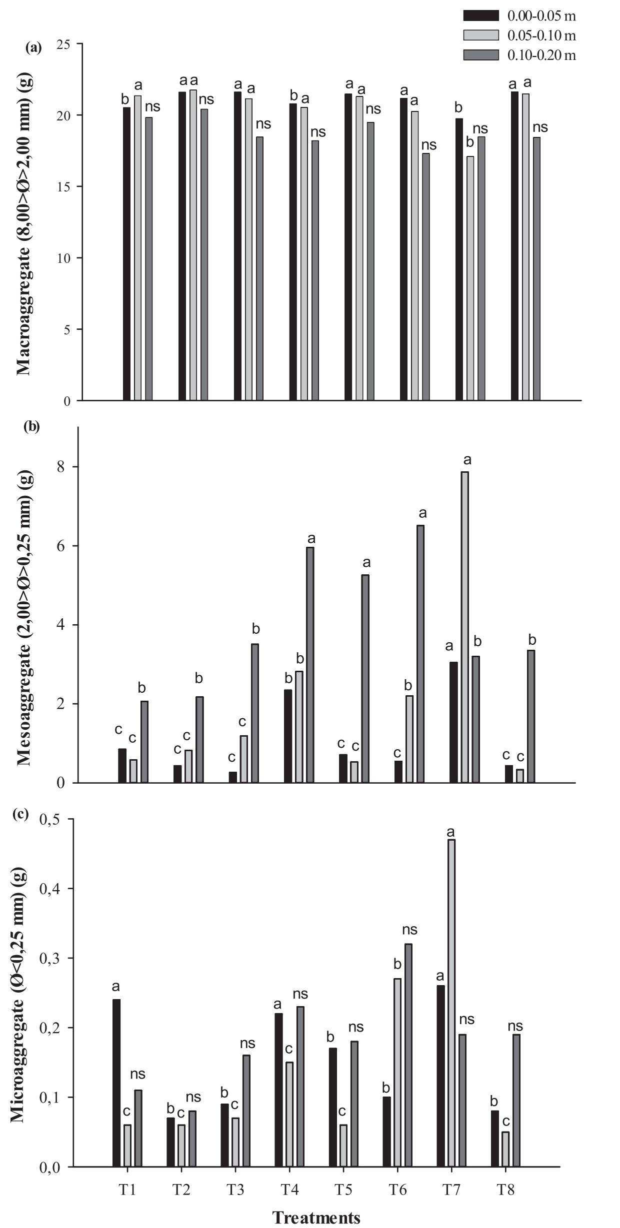

Fig. 1. Microaggregate, mesoaggregate, and macroaggregate mass distributions in the 0.0-0.05, 0.05-0.10, and 0.10-0.20 m layers of a Humic Cambisol with onion crops in no-tillage and conventional systems, using crop successions and rotations, Ituporanga, Santa Catarina, Brazil.
Means followed by the same letter in the bars do not differ by the Scott-Knott test at 5%. ns = not significant by the F test ($p > 0.05$). T1 = succession of onion and maize in no-tillage system (NTS); T2 = rotation of soil cover plants (winter), and biennial onion in NTS; T3 = rotation of maize, winter grasses, and annual onion in NTS; T4 = succession of velvet bean, and annual onion in NTS; T5 = rotation of millet, soil cover plants (winter), and annual onion in NTS; T6 = succession of velvet bean, rye, and annual onion in NTS; T7 = succession of maize, and onion in CTS; T8 = succession of intercrops of soil cover plants (summer), and annual onion in NTS.

Table 4
Weighted mean diameter (WMD) of aggregates of a Humic Cambisol with onion crops in no-tillage and conventional systems using crop successions and rotations. Itupuranga, Santa Catariana State, Brazil.

Treatments	WMD (mm)		
	0-0.05 m	0.05-0.10 m	0.10-0.20 m
T1	4.81^{ns}	4.84 a	4.54^{ns}
T2	4.84	4.70 a	4.55
T3	4.87	4.77 a	4.33
T4	4.76	4.71 a	4.19
T5	4.73	4.83 a	4.48
T6	4.75	4.51 b	4.07
T7	4.63	4.18 c	4.28
T8	4.86	4.83 a	4.36
CV%	3.8	4.5	7.8

Means followed by the same letter in the column were similar by the Scott-Knott test at 5%. CV = coefficient of variation. ns = not significant by the F test ($p > 0.05$). T1 = succession of onion and maize in no-tillage system (NTS); T2 = rotation of soil cover plants (winter), and biennial onion in NTS; T3 = rotation of maize, winter grasses, and annual onion in NTS; T4 = succession of velvet bean, and annual onion in NTS; T5 = rotation of millet, soil cover plants (winter), and annual onion in NTS; T6 = succession of velvet bean, rye, and annual onion in NTS; T7 = succession of maize, and onion in CTS; T8 = succession of intercrops of soil cover plants (summer), and annual onion in NTS.

(T1), 30.28 (T2), 32.66 (T3), 29.17 (T4), 31.27 (T5), 30.31 (T6), 25.74 (T7) and 27.81 (T8) g kg^{-1} of TOC. Among all treatments, T7 (CTS) was the treatment that presented the lower increased in TOC content in the 0–10 cm layer. Lower soil aggregate stability and TOC and TN contents in CTS, compared to the other systems, such as no-tillage system, agroecological no-tillage system, pasture, natural vegetation, and native forest is commonly found in scientific literature (Tivet et al., 2013; Silva et al., 2014; Loss et al., 2009, 2014; 2015; Santos et al., 2018). Plant residues are maintained in the soil surface in NTS; this favors the maintenance or increasing of TOC contents and, consequently, TN contents (Silva et al., 2014; Loss et al., 2009).

The lower TOC contents in the 0-0.05 m layer in T7 (CTS) may be due to the soil disaggregation due to the soil tillage for planting (Balesdent et al., 2000) since aggregate fragmentation is intensified with the use of agricultural implements, and the soil wetting and drying cycles. Microaggregates protected inside the macroaggregates are then exposed and can be disrupted by rainfalls, especially in medium-texture (study area) and sandy soils, making the SOM fraction that was physically protected from biodegradation within microaggregates accessible to microbial decomposition (Amezketa, 1999). Thus, CTS can lower SOM mineralization and decrease soil TOC contents (Busari et al., 2015).

The highest TOC and TN contents found in T3, T2, T5, and T6 may be due to the use of Poaceae species (grasses) in T3 and T5, and the combination of grass and legume species in T2 and T6. T3, which presented the highest TOC content in the 0.0-0.05 m layer, had the grasses oat (*Avena strigosa*), rye (*Secale cereale*), and maize (*Zea mays*); T5 had oat, rye, and millet (*Pennisetum americanum*); T6 had velvet bean (*Stizolobium aterrimum*), and rye; and T2 had a rotation of vetch (*Vicia villosa*), maize, intercrop of rye + oilseed radish (*Raphanus sativus*), and common beans (*Phaseolus vulgaris*). According Weaver (1926) and Lima Filho et al. (2014), the combination of deep, dense root systems, which assists in C deposition, high shoot dry matter production, and high C/N ratio may explain the high TOC contents found in T3. Millet (T5) also has a profuse, deep root system, reaching depths of up to 2.0 m (Norman et al., 1995; Durães et al., 2003). T2 and T6 have combinations of grass and legume species; and crop rotation is used in T2, favoring the C/N ratio balance in the plant that increases TOC and TN contents, according Amado et al. (2001) and Jantalia et al. (2003).

Amado et al. (2001) evaluated the potential of soil cover crops and plants to accumulate carbon and nitrogen in the soil in NTS and found that the use of legumes, and diverse species in succession or rotation increases carbon and nitrogen stocks in the soil. Jantalia et al. (2003) evaluated crop rotations and successions with legume and grass species used for green manuring and mulching and found that systems with greater plant species diversity increase soil carbon and nitrogen stocks in NTS, compared to wheat-soybean succession; and soil cover plants do not increase TOC and TN contents in the CTS. These results may explain the highest TOC and TN contents in treatments with diverse plant species.

Costa et al. (2008) evaluated the TOC stocks in the 0.0-0.20 m layer of soils with cover plants – oat/maize (OM) and vetch/maize (VM) – in NTS and CTS for 18 years, and found decreases of 0.31 Mg ha^{-1} year^{-1} (OM) and 0.10 Mg ha^{-1} year^{-1} (VM) in CTS, and an increase (0.15 Mg ha^{-1} year^{-1}) in NTS only for VM, in relation to the initial TOC content (33.4 Mg ha^{-1}). They emphasized the effect of the legume on the soil TOC accumulation that increases the following grass biomass production due to the input of N.

The similar TOC and TN (0.05-0.10 and 0.10-0.20 m) in NTS and CTS (T7) treatments was due to the soil turning in CTS, which inverts the soil layers and incorporates plant residues of soil surface layer –which presents higher SOM content – into deeper soil layers (Loss et al., 2015). Thus, the nutrient contents change in the soil profile, making them similar to those found in the NTS treatments (Loss et al., 2015; Santos et al., 2018).

The similar TOC and TN in NTS treatments in deeper layers may be due to the material of cover plants and crops in the soil surface layer, and the absence of soil turning. Sisti et al. (2004) evaluated rotation and succession of legume and grass crops in NTS for 15 years and found differences in the TOC and TN contents only in the 0.0-0.05 m layer, concluding that the C and N contents in the soil are connected to the soil tillage system and plant species used.

According to the TOC contents found in the CTS treatment, which was managed under NTS from 2007 to 2010 (Table 1), and the TOC in the NTS treatments (Table 3), the higher TOC contents in NTS are due to the management system and the best interaction between carbon deposition and microbial community in the rhizosphere. Lange et al. (2015) researched the mechanisms that cause positive effects of plant diversity on soil carbon storage in a study using long-term data from an experiment on grassland biodiversity and found that the use of a high plant diversity increases the active microbial community, and carbon stocks due to the accumulation of recently fixed carbon in high-diversity plots; and that plant diversity had less pronounced effects on the decomposition rate of the existing carbon. Thus, carbon storage in high plant diversity conditions is dependent on the microbial community, and the increase in carbon storage is more limited by the input of new carbon into the soil than by the decomposition of the existing soil carbon.

The lower TN content in T7 (CTS) may be due to the lower N uptake and higher mineralization and leaching of mineral N, such as $N\text{-}NO^{3-}$ (Busari et al., 2015). T1 and T4 had higher TN contents than T7, but lower TN than the other treatments. This denotes the benefits of using NTS in T1 and T4, i.e., increasing in TOC and TN contents (Ussiri e Lal, 2009) due to the use of soil cover plants (Fageria et al., 2005). However, the use of greater diversity of soil cover species in T2, T3, T5, T6, and T8 may have contributed to their higher TN contents.

According to the method used in the evaluation of the aggregates stability (Embrapa, 1997), the maximum value of WMD would be 5.00 mm. Then, according to the WMD values presented in Table 4, the aggregate stability was high in all soil layers evaluated and similar between treatments in the 0-0.05 and 0.10-0.20 m layers. The lowest WMD in the 0.05-0.10 m layer were found in T7, followed by T6. The other treatments had higher and similar WMD.

High WMD (stable aggregates) were found in the 0-0.05 and 0.05-0.10 layers in all NTS treatments, except T6 in the 0.05-0.10 m layer (Table 4). The high WMD in the soil surface layer can be due to the combination of NTS with rotation and succession of cover plants.

Contrastingly, the use of CTS for four years (2011–2014) in T7 reduced the WMD (Table 4) due to the lower TOC and TN contents in the 0-0.05 m layer (Table 3).

Loss et al. (2015) compared the soil aggregate stability of onion crops in agroecological NTS – single crops and intercrops with the species *Avena strigosa*, *Secale cereale,* and *Raphanus sativus* – to treatments with weeds, onion in CTS for 37 years, and secondary forest of 30 years. After five years, they found similar WMD in treatments with cover crops in NTS and weeds, which were higher than the WMD in the CTS in the 0-0.05 m, 0.05-0.10 m and 0.10-0.20 m layers. In the forest area, they found similar WMD to those in NTS, except in the 0.10-0.20 m layer, in which the treatment with oilseed radish presented a higher WMD than that in the forest.

The highest proportion of water-stable macroaggregates in the 0-0.05 m layer was found in T2, T3, T5, T6, and T8; and the lowest in T1, T4, and T7. T7 was the only treatment that presented lower proportion of water-stable macroaggregates than the others in the 0.05-0.10 m layer; and no differences between treatments were found in the 0.10-0.20 m layer (Fig. 1).

The lowest masses of stable macroaggregates found in T1, T4, and T7 may be due to their lower soil cover plant species diversity in the onion crop succession. T1 and T7 were conducted with onion/maize/fallow succession with weeds killed before onion planting, however, T7 was managed in CTS since 2011. The biomass of the velvet bean used in succession with onion in T4 can be rapidly decomposed and contribute less to the aggregate stability. T4 also had no soil cover crops in the winter, and the weeds grown in the fallow period was killed before the onion planting. Carrizo et al. (2015) evaluated the effect of crop residues and root activity on aggregation agents and disaggregation mechanisms in soils with different carbon contents and textures, managed in NTS, and found that the plant residues and the presence of plants with active roots increased the aggregation agents, especially soluble carbohydrates, and glomalin-related proteins, which reduced soil disaggregation processes. Moreover, T1, T4, and T7, presented the lowest TOC and TN in the 0-0.05 m layer (Table 3), confirming their lower amount of stable aggregates in water.

Gould et al. (2016) carried out a greenhouse and a long-term field study and found increased soil aggregate stability due to high diversity of plant species in native pastures and emphasized the importance of their root characteristics in determining the effects of species diversity. They found a strong correlation between grasses with thin roots and soil aggregate stability, and low stability of soil aggregates in areas with legumes of thicker roots. However, legumes benefit hydrologic and soil resistance properties, indicating that the combination of plant species can be used to generate complementary effects on soil physical properties, which can be achieved by intercropping in crop rotation systems.

T7 presented higher amounts of stable mesoaggregates and microaggregates in water in the 0.0-0.05 and 0.05-0.10 m layers. T4 presented higher mesoaggregate mass in the 0.0-0.05 layer, compared to the other treatments in NTS. T4 and T6 presented the lowest mesoaggregate mass in the 0.05-0.10 m layer when compared to the other treatments in NTS. The highest microaggregate masses were found in T1, T4, and T7 for the 0.0-0.05 m layer, and in T6 and T7 for the 0.05-0.10 m layer. T4, T5 and T6 presented the highest mesoaggregate mass distributions in the layer of 0.10-0.20 m. The microaggregates mass of the treatments were similar (Fig. 1).

In general, the higher soil cover plant species diversity used in T2, T3, T5, T6, and T8 treatments favored the formation of stable aggregates, which is confirmed by their higher macroaggregate masses (Fig. 1). The lower plant diversity of soil cover species in T1, T4, and T7 decreased macroaggregate stability and increased the proportion of microaggregates in the soil surface layer (Fig. 1). These macroaggregate and microaggregate mass distributions determined the aggregation index (Table 3); the lower WMD in T7 in the 0.05-0.10 m layer was due to the lower macroaggregate and higher microaggregate masses (Fig. 1).

The proportions of mesoaggregates and microaggregates in T7 (CTS) were similar to those found by Loss et al. (2015) in onion crops in an agroecological NTS using single crops and intercrops with oat, rye, and oilseed radish plants, and weeds, compared to onion crops in CTS, and a forest area, in areas adjacent to that of the present work. They found higher proportions of mesoaggregates and microaggregates in CTS in the 0.0-0.05, 0.05-0.10 and 0.10-0.20 m layers.

4. Conclusions

Periodic soil turning in the succession of onion and maize decrease total organic carbon and total nitrogen contents in the soil surface layer when compared to succession and rotation systems with onion crops in no-tillage system. This negative effect on soil quality is associated to reductions in aggregate stability, especially by decreases in the macroaggregate proportion.

The use of no-tillage system for onion crops generates high soil aggregate stability, with predominance of macroaggregates, regardless of the crop succession or rotation system.

The use of grasses in succession or rotation with onion crops in no-tillage system increases total organic carbon content in the soil surface layer, especially in rotations with maize and winter grasses (rye and oat). However, the greatest total nitrogen accumulation in the soil surface layer is found in treatments with great diversity of soil cover crop species in rotation or succession with onion in no-tillage system.

The management of onion crops without using soil cover plants in winter (T1, T4, and T7) having lower soil organic carbon and the mass of stable macroaggregates in water and increases the amount of microaggregates in the soil surface layer.

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