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Organic carbon and nitrogen contents and their fractions in soils with onion crops in different management systems

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Abstract. The use of plant species in rotation or succession of crops can increase C and N contents and their fractions in the soil. The objective of this study was to evaluate the effect of using soil cover crops in succession and rotation with onion crops in different soil management systems on the total organic carbon (TOC), total nitrogen (TN), and C and N fractions in soil aggregates, and bulk soil. The experiment was implemented in April 2007 with eight treatments: succession of onion and maize in a no-tillage system (NTS) (T1); rotation of soil cover crops (winter) and biennial onion in a NTS (T2); rotation of maize, winter grasses, and onion in a NTS (T3); succession of summer legume and annual onion in a NTS (T4); rotation of summer grass, winter grasses, and annual onion in a NTS (T5); succession of summer legume, winter grass, and annual onion in a NTS (T6); succession of maize and onion in a conventional tillage system (CTS) (T7); and succession of intercrops of soil cover crops (summer), and annual onion in a NTS (T8). Undisturbed soil samples were collected in the 0.0–5.0, 5.0–10.0, and 10.0–20.0 cm soil layers in July 2014, and their aggregate (8.0 to 2.0 mm) and bulk soil (<2 mm) fractions were separated to evaluate their TOC, TN, particulate organic carbon and particulate organic nitrogen (OC_P and ON_P respectively), and mineral-associated organic carbon and mineral-associated organic nitrogen (OC_M and ON_M respectively). Soil turning due to the CTS in T7 (0.0–5.0 cm) reduced TOC, OC_P, OC_M, TN, ON_P, and ON_M, in the soil aggregates and in the bulk soil, when compared with the NTS with the use of soil cover crops in succession or rotation with onion crops (T1–T6 and T8). T6 increased the TOC, TN, OC_P, OC_M, ON_P, and ON_M contents in the soil aggregates and bulk soil when compared with the successions with only grasses or only legumes. T1 increased the soil TOC and TN contents in aggregates compared with the same succession in CTS. T8 had higher OC_P (0.0–20.0 cm) and ON_P (5.0–10.0 cm) contents in aggregates than in the bulk soil. In general, aggregates had higher TOC and OC_M contents, and bulk soil had higher TN, OC_P, ON_P and ON_M contents. The main changes resulting from the management systems and soil cover crop combinations used were observed in the particulate fraction, especially in the soil aggregates.

Additional keywords: *Allium cepa* L., bulk soil, green manure, no-tillage system, soil aggregates, vegetable.

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Introduction

Onion (*Allium cepa* L.) is a species of the Alliaceae family, which is widely used as human food. China, India, and the United States are the largest onion producers. Brazil is the eighth largest producer, with 1.7 million Mg of onions per year (The Daily Records 2018). The largest onion-producing region in Brazil is in the state of Santa Catarina (SC), which has an annual production of ~500 thousand Mg of onions, representing ~30% of the national production (IBGE 2017).

A significant part of onion crop production in SC is conducted in a conventional tillage system (CTS) with soil turning using plough and harrow, scarifier and harrow, or cultivator (EPAGRI 2013). These managements have caused edaphic degradation (Loss *et al.* 2015, 2017; Santos *et al.* 2017). Therefore, despite its economic and social benefits, the current onion-production system needs to simultaneously meet economic, social, and environmental requirements to be a sustainable production system.

In this context, some studies have been carried out with onion in a no-tillage system (NTS), where soil tuning is restricted to the planting rows, and the use of single or intercropped plant species produces a biomass that is deposited on the soil surface before planting the onion seedlings (EPAGRI 2013; Silva *et al.* 2014). The use of NTS in onion crops enhances soil properties by improving total organic carbon (TOC) content, chemical attributes related to soil fertility (Oliveira *et al.* 2016; Santos *et al.* 2017), and soil aggregation (Loss *et al.* 2015, 2017).

The use of crop rotation or succession and soil cover crops (single or intercropped) from different botanical families are also beneficial practices used in onion crops (Silva *et al.* 2014; Loss *et al.* 2015, 2017). Santos *et al*. (2017) and Loss *et al*. (2017) evaluated chemical and physical attributes of soils cultivated with onion in NTS and CTS with single and intercropped soil cover crops and found that the chemical and physical conditions of the soil in NTS were better when compared with CTS; in addition, there were better edaphic conditions when the onion crops were cultivated on plant residues of intercropped plants from different botanical families, such as intercrops of oilseed radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin) with rye (*Secale cereale* L.) or oats (*Avena strigosa* Schreb.)

Therefore, the use of soil cover crops is necessary for an efficient NTS, since they protect the soil from erosion, participate in the cycling of nutrients, add C and N to the soil, and improve soil aggregation (Santos *et al.* 2011; Lima Filho *et al.* 2014; Loss *et al.* 2015; Vezzani *et al.* 2018). The plant species used in the NTS will determine the dynamics of production and decomposition of plant material and the soil coverage over time (Oliveira *et al.* 2016).

NTS improves soil quality compared with CTS (Winck *et al.* 2014; Vezzani *et al.* 2018) due to the absence of soil turning, presence of soil physical protection (plant residues), particulate organic matter maintenance (Loss *et al.* 2012; Winck *et al.* 2014). However, this improvement in soil quality depends on the crop system used, since the number and alternation of plant species in rotation or succession determines the amount, quality, and form of C and N additions to the soil (Santos *et al.* 2011; Thivierge *et al.* 2016; Vezzani *et al.* 2018). The temporal arrangement of plant species and the amount of shoot and root biomass produced by the soil cover crops (Janzen *et al.* 1998) can affect the soil C and N contents and stocks in granulometric fractions of organic matter (Six *et al.* 2004; Sisti *et al.* 2004; Loss *et al.* 2012; Winck *et al.* 2014).

According to Loss *et al*. (2012) and Winck *et al*. (2014), the quality of soils subjected to NTS is dependent on the crop system and can be evaluated by their particulate organic matter content due to the function of this fraction in the soil and its sensitivity to different soil management systems. Moreover, it is expected that large aggregates accumulate different amounts of these C and N fractions due to greater biological activity, or have total C and N contents dependent on the management system adopted.

Therefore, the use of NTS with different soil cover crops in rotation or succession with onion crops can increase TOC, total nitrogen (TN), and their fractions in the soil when compared with CTS. In this context, the objective of this study was to evaluate the effect of using soil cover crops in succession and rotation with onion crops in different soil management systems on the TOC, TN, and their fractions in the soil aggregates (2.0–8.0 mm) and bulk soil (<2.0 mm).

Material and methods

The experiment was implemented in April 2007 at the Co. of Agricultural Research and Rural Extension of Santa Catarina, in Ituporanga SC, Brazil. The soil of the region was classified as dystrophic Humic Cambisol (EMBRAPA 2013) or Humic Distrudept (Soil Survey Staff 2006), and its physical and chemical attributes in the 0–10 cm layer were as follows: 410 g kg^{-1} of sand, 264 g kg^{-1} of silt, and 326 g kg^{-1} of clay; pH in H_2O of 6.1; exchangeable Ca, Mg, and Al of 6.4, 2.7 and 0.0 cmolc dm^{-3} respectively; available P and K of 42 and 208 mg dm^{-3} respectively; and 23.08 g kg^{-1} of TOC (EMBRAPA 1997).

According to the Köppen classification, the climate of the region is Cfa, i.e. subtropical mesothermal humid with hot summers, infrequent frosts, and no defined dry season; it has an average annual temperature of 17.6°C and average annual precipitation of 1400 mm.

The experiment was conducted in a randomised block design with eight treatments and five replications, with 8.7 m^2 plots. The treatments consisted of soil management systems for onion crops based on NTS with rotations and successions with different soil cover plant species used to produce biomass, and a CTS.

Oat (*A. strigosa* Schreb cv. EMBRAPA 139), vetch (*Vicia villosa* cv. comum), and oilseed radish (*R. raphanistrum* cv. IPR 116) were sown in the area in 2007, when the experiment was implemented; subsequently, eight treatments (T1–T8) were used with soil cover crops and commercial crops (Table 1).

From 2011, the soil of T7 was prepared using conventional tillage system, with plough and harrow, or cultivator, with succession of maize and onion. The treatments used in 2011, 2012, and 2013 were repeated from 2014 (Table 2).

The plant species chosen for the experiment (Tables 1 and 2) were plants frequently used by regional producers that have good adaptation, seed availability in the market, easy handling, and adequate biomass production for NTS. Thus, the commercial and technical aspects were considered; the experiment was implemented with treatments that could be used by the farmers of the region, making it possible to acquire information about edaphic aspects affected by using NTS in onion crops.

Weed, pest, and disease control were carried out using chemical products that are registered in the Brazilian Ministry of Agriculture, Livestock, and Food Supply for onion crops. Approximately 14 days before onion planting, weeds were killed with glyphosate herbicide (360 g L^{-1}) at 4 L ha^{-1}. Weed control during the onion cycle was carried out with three applications of herbicides, two of ioxynil (250 g L^{-1}) at 1 L ha^{-1} at 35 and 65 days after seedling transplantation (DAT) and one of clethodim (240 g L^{-1}) at 0.4 L ha^{-1} at 85 DAT. The control of pests, especially *Thrips tabaci* Lind., was carried out with three applications of insecticides, one of imidacloprid (700 g L^{-1}) at 0.1 kg ha^{-1} at 30 days after planting and two of lambda-cyhalothrin (50 g L^{-1}) at 0.1 L ha^{-1} approximately at 60 and 81 DAT. The control of fungal diseases, mainly mildew (*Peronospora destructor*) and *Alternaria solani* was carried out with six applications of fungicides, four of metalaxyl (40 g L^{-1}) + mancozeb (640 g L^{-1}) at 35, 50, 65 and 80 DAT and two of tebuconazole (200 mL L^{-1}) + trifloxystrobin (100 mL

Table 1. Species used in rotation or succession with onion crops in different soil tillage systems from 2007 to 2010. Ituporanga SC, Brazil

Species are as follows: oat (*Avena strigosa* Schreb), onion (*Allium cepa* L.), rye (*Secale cereale* L.), showy rattlebox (*Crotalaria spectabilis* Roth), vetch (*Vicia villosa* Roth), common bean (*Phaseolus vulgaris* L.), jack bean (*Canavalia ensiformis* (L.) DC.), sunflower (*Helianthus annuus* L.), maize (*Zea mays* L.), pearl millet (*Pennisetum glaucum* (L.) R.Br.), velvet bean (*Mucuna pruriens* var. *utilis* (Wall. ex Wight) L.H. Bailey), oilseed radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin), and barley (*Hordeum vulgare* L.). T1, succession of onion, and maize in no-tillage system (NTS); T2, rotation of soil cover crops (winter), and biennial onion in NTS; T3, rotation of maize, winter grasses, and onion in NTS; T4, succession of summer legume and annual onion in NTS; T5, rotation of summer grass, winter grasses, and annual onion in NTS; T6, succession of summer legume, winter grass, and annual onion in NTS; T7, succession of maize and onion in conventional tillage system (CTS); T8, succession of intercrops of soil cover crops (summer), and annual onion in NTS

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	Barley	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

Table 2. Species used in rotation or succession with onion crops from 2011 to 2013. Ituporanga SC, Brazil

Species are as follows: oat (*Avena strigosa* Schreb), onion (*Allium cepa* L.), rye (*Secale cereale* L.), Vetch (*Vicia villosa* Roth), common bean (*Phaseolus vulgaris* L.), sunflower (*Helianthus annuus* L.), Maize (*Zea mays* L.), pearl millet (*Pennisetum glaucum* (L.) R.Br.), velvet bean (*Mucuna pruriens* var. *utilis* (Wall. ex Wight) L.H. Bailey) and oilseed radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin). T, treatment; T1, succession of onion, and maize in no-tillage system (NTS); T2, rotation of soil cover crops (winter), and biennial onion in NTS; T3, rotation of maize, winter grasses, and onion in NTS; T4, succession of summer legume and annual onion in NTS; T5, rotation of summer grass, winter grasses, and annual onion in NTS; T6, succession of summer legume, winter grass, and annual onion in NTS; T7, succession of maize and onion in conventional tillage system (CTS); T8, succession of intercrops of soil cover crops (summer), and annual onion in NTS

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	Oilseed radish + Rye		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

Table 3. Shoot dry weight of soil cover crops, onion bulb yield in 2014, and annual average of onion bulb yield in 2008 to 2014

T1, succession of onion, and maize in no-tillage system (NTS); T2, rotation of soil cover crops (winter), and biennial onion in NTS; T3, rotation of maize, winter grasses, and onion in NTS; T4, succession of summer legume and annual onion in NTS; T5, rotation of summer grass, winter grasses, and annual onion in NTS; T6, succession of summer legume, winter grass, and annual onion in NTS; T7, succession of maize and onion in conventional tillage system (CTS); T8, succession of intercrops of soil cover crops (summer), and annual onion in NTS; *, virtually no common bean plant residues were found in the evaluation period; **, there was no onion production in 2014 (biannual onion crops)

	T1	T2	T3	T4	T5	T6	T7	T8
	Shoot dry weight (kg ha^{-1})							
	1652	*	4000	5196	3684	5508	1516	8328
	Onion bulb yield (Mg ha^{-1})							
2014	27.2	**	28.6	23.1	29.5	30.8	18.8	26.2
2008 to 2014	30.6	34.9	34.7	34.1	34.8	33.5	28.1	34.4

L^{-1}) at 80 and 94 DAT. All applications were performed using personal protective equipment.

The soil of the experiment area had been cultivated using a conservationist production system since 1995, when the last liming was carried out to raise the pH to 6.0 using dolomitic limestone. It was incorporated by ploughing and harrowing the soil to a depth of 20 cm. Since then, it was managed in NTS, with soil preparation restricted to the planting rows, except T7, which was managed in CTS (Table 2).

Fertilisation was carried out only for onion and maize crops based on soil analyses during the experiment and according to recommendations for these crops (CQFSRS/SC, 2004). Fertilisation for onion crops consisted of 75 kg ha^{-1} of N, 120 kg ha^{-1} of P_2O_5, 60 kg ha^{-1} of K_2O, using the 05–20–10 NPK formulation, or triple superphosphate, potassium chloride, and ammonium nitrate. The P rates were very high in 2010 (CQFSRS/SC, 2004); thus, only 50 kg ha^{-1} of P was used for the first, and 80 kg ha^{-1} for the following onion crops. P and K were applied to the onion crops at planting, and N was applied at planting (15 Kg N ha^{-1}) and at 45, 65, and 85 days after transplantation (topdressing) of the onion seedlings, using ammonium nitrate. Thirty kilograms per hectare of sulfur (calcium sulfate) were applied in 2014 at 45 days after the transplant of the onion seedlings. P and K were not applied to maize crops because the soil presented high contents of these nutrients; nitrogen was applied using 90 kg ha^{-1} of urea when the maize reached six to eight leaves.

The soil cover crops were killed, and furrows were opened with a machine adapted for onion planting in NTS; the seedlings (cultivar Bola Precoce Empasc-352) were manually transplanted with 0.40 m between rows and 0.10 m between plants. There were seven rows of onion per plot and 30 plants per row.

The shoot dry weight (SDW) of the commercial plants and soil cover plants, and the onion bulb yield of the eight treatments were evaluated in 2014 (Table 3). The SDW was evaluated in July 2014; therefore, it was the plant residues of commercial crops and soil cover crops implemented in the summer of 2013 and winter of 2014 (Table 3). Table 3 shows the average onion bulb yield of 2008 to 2014. T1, T4, T7, and T8 had winter fallow (Table 2); consequently, the shoot dry biomass added was from weeds, crop residues, and soil cover crops from the summer of 2013. The main weed families found were Amaranthaceae, Apiaceae, Asteraceae, Caryophyllaceae, Convolvulaceae, Cyperaceae, Euphorbiaceae, Lamiaceae, Malvaceae, Oxalidaceae, Plantaginaceae, Poaceae, Polygonaceae, and Rubiaceae.

Seven years after the implementation of the experiment in July 2014, undisturbed soil samples were collected; a hole of $40 \times 40 \times 40$ cm was opened between the rows of each onion plot using a spade for collecting the soil samples in the 0.0–5.0, 5.0–10.0, and 10.0–20.0 cm layers. The samples were then placed in plastic bags and sent to the laboratory for analyses.

The soil samples were air-dried and manually disaggregated by following slits or weak points and passed through 8.00-, 4.00-, and 2.00-mm mesh sieves, according to the methodology adapted by EMBRAPA (1997). The soil aggregates that passed through the 8.00-mm mesh sieve and were retained in the 4.00-mm mesh sieve were used to evaluate the soil aggregates. The bulk soil that passed through the 4.00-mm mesh sieve was air-dried, disaggregated, and sieved in a 2.00-mm mesh sieve to obtain the air-dried fine earth (ADFE) from the soil (bulk soil with Ø <2.0 mm).

Soil aggregates that were retained in the 4.00-mm mesh sieve were air-dried, disaggregated, and sieved in a 2.00-mm mesh sieve to obtain the ADFE from the aggregates (8.00 mm > Ø ≥ 2.0 mm), which was used to determine the C, N, and granulometric fractions of organic matter in the aggregates. TOC and TN contents in the ADFE from the bulk soil (Ø <2.0 mm) and ADFE from the soil aggregates (8.00 mm > Ø ≥ 2.0 mm) were determined using a dry combustion elemental analyser CHN (FlashEA 1112, Thermo Finnigan).

The granulometric fractionation of the soil aggregates and bulk soil was performed according to Cambardella and Elliott (1992) to obtain the particulate organic carbon (OC_P) and particulate organic nitrogen (ON_P), which are fractions with sizes smaller than 0.053 mm. The contents of mineral-associated organic carbon (OC_M) and mineral-associated organic nitrogen (ON_M) were determined by the difference between the TOC-to-TN ratio and the OC_P-to-ON_P ratio.

The results were analysed for normality and homogeneity of the data by the Lilliefors (Lilliefors 1967) and Bartlett (Bartlett 1937) tests respectively. The data were subjected to analysis of variance (*F* test) and, when the effects were significant, the means were compared by the Scott–Knott test at 5% probability using the Sisvar program. Statistical analyses were performed for the eight treatments, soil aggregates, and bulk soil. Subsequently, the data of each treatment were subjected to statistical analysis independently, comparing the results of the soil aggregates and bulk soil by the Student's *t*-test (l.s.d.) at 5%.

Results

TOC and TN contents in the bulk soil and soil aggregates

The TOC contents were 20.6–43.4 g kg^{-1} in the bulk soil and 21.3–39.6 g kg^{-1} in the soil aggregates. The TN contents were 1.7–4.6 g kg^{-1} in the bulk soil and 1.5–3.3 g kg^{-1} in the soil aggregates. T7 presented the lowest TOC in bulk soil (0.0–20.0 cm) and aggregates (0.0–5.0 cm), as well as the lowest TN in bulk soil (0.0–10.0 cm) and aggregates (0.0–5.0 cm). T6 had the highest TOC (0.0–5.0 cm) and TN (0.0–10.0 cm) in bulk soil (Table 4).

The aggregates had the highest TOC and TN contents in T2, T3, T5, and T6 treatments. The soil TOC content was higher in T3 than in T2, T5, and T6. TOC in aggregates (5.0–10.0 and 10.0–20.0 cm) and TN in bulk soil (10.0–20.0 cm) and aggregates (5.0–10.0 and 10.0–20.0 cm) in the NTS and CTS treatments were similar (Table 4).

TOC in bulk soil and aggregates presented low differences between treatments, with few variations in the 5.0–10.0 and

Table 4. Total organic carbon (TOC) and total nitrogen (TN) in soil bulk and soil aggregates of a Humic Cambisol subjected to no-tillage and conventional tillage systems with onion crops using crop rotations and successions. Ituporanga SC, Brazil

Means followed by the same uppercase letter in the column did not differ significantly between treatments for soil bulk and aggregates by the Scott–Knott test at 5%. Means followed by the same lowercase letter in the row did not differ significantly between soil bulk and aggregates for each treatment by the Student's *t*-test (l.s.d.) at 5%. CV, coefficient of variation; T1, succession of onion, and maize in no-tillage system (NTS); T2, rotation of soil cover crops (winter), and biennial onion in NTS; T3, rotation of maize, winter grasses, and onion in NTS; T4, succession of summer legume and annual onion in NTS; T5, rotation of summer grass, winter grasses, and annual onion in NTS; T6, succession of summer legume, winter grass, and annual onion in NTS; T7, succession of maize and onion in conventional tillage system (CTS); T8, succession of intercrops of soil cover crops (summer)

	TOC (g kg^{-1})			TN (g kg^{-1})		
	Soil bulk	Aggregates	CV%	Soil bulk	Aggregates	CV%
			0.0–5.0 cm layer			
T1	32.92Ba	31.48Ca	4.31	3.27Ca	2.70Bb	2.05
T2	34.37Ba	34.30Ba	7.71	3.72Ba	3.12Ab	4.99
T3	34.13Bb	39.64Aa	13.25	3.01Ca	3.27Aa	8.55
T4	29.63Cb	31.91Ca	4.56	3.52Ca	2.76Bb	6.43
T5	30.96Cb	34.85Ba	2.78	3.22Ca	3.11Aa	5.72
T6	43.49Aa	33.88Bb	5.14	4.66Aa	3.30Ab	10.82
T7	24.96Db	26.46Da	4.54	2.37Da	2.26Ca	3.26
T8	33.86Ba	30.47Cb	3.86	3.48Ca	2.95Ab	7.70
CV%	6.71	7.10		10.32	7.38	
			5.0–10.0 cm layer			
T1	25.69Aa	25.40Aa	7.39	2.34Ba	2.07Ab	5.75
T2	27.50Aa	26.26Aa	6.07	2.40Ba	2.08Ab	5.35
T3	26.09Aa	25.69Aa	7.51	2.41Ba	2.23Ab	3.11
T4	28.10Aa	26.43Aa	4.52	2.46Ba	2.15Ab	4.57
T5	27.47Aa	27.70Aa	5.54	2.49Ba	2.23Ab	3.16
T6	25.15Ab	26.74Aa	2.96	2.59Aa	2.17Ab	3.40
T7	20.64Bb	25.02Aa	3.39	1.81Cb	2.22Aa	6.08
T8	26.58Aa	25.16Aa	4.16	2.52Ba	2.09Ab	7.91
CV%	5.48	5.53		7.34	5.04	
			10.0–20.0 cm layer			
T1	22.08Ba	21.93Aa	5.78	1.81Aa	1.62Ab	4.13
T2	23.56Aa	23.16Aa	6.89	1.85Aa	1.64Ab	6.17
T3	23.39Aa	22.91Aa	4.23	1.86Aa	1.66Ab	5.81
T4	22.17Ba	23.76Aa	5.61	1.77Aa	1.64Aa	9.08
T5	23.73Aa	23.62Aa	3.89	1.94Aa	1.75Aa	6.97
T6	24.39Aa	23.18Aa	4.65	1.92Aa	1.67Ab	3.78
T7	20.67Ca	23.42Aa	6.51	1.73Aa	1.75Aa	8.87
T8	22.83Ba	21.32Aa	5.28	1.88Aa	1.58Ab	5.05
CV%	5.28	5.54		2.03	8.02	

10.0–20.0 cm layers. However, T3, T4, T5, and T7 stood out in the 0.0–5.0 cm layer. T6 and T7 stood out in the 5.0–10.0 cm layer with higher TOC in aggregates, compared with that found in bulk soil. T6 and T8 had higher TOC contents in bulk soil (0.0–5.0 cm) compared with aggregates. The highest TN contents were found, in general, in bulk soil when compared with aggregates (Table 4).

Granulometric fractionation of the bulk soil and soil aggregates

The OC_P contents were 4.67–13.55 g kg^{-1} in bulk soil and 2.51–12.72 g kg^{-1} in aggregates. The OC_M contents were 14.42–29.94 g kg^{-1} in bulk soil and 15.80–26.96 g kg^{-1} in aggregates. The lowest OC_P content in bulk soil and aggregates (0.0–5.0 cm) and the lowest OC_M content in bulk soil (0.0–10.0 cm) were found in T7. The lowest OC_M contents in aggregates were found in the 0.0–5.0 cm layer in T4 and T8. The highest OC_P (0.5–10.0 cm) and OC_M (0.0–5.0 cm) in aggregates were found in T3. The highest OC_P contents in bulk soil (0.0–5.0 cm) were found in T3 and T6. The highest OC_M in bulk soil (0.0–5.0 cm) was found in T6 (Table 5).

The ON_P contents were 0.04–0.78 g kg^{-1} in bulk soil, and 0.05–0.48 g kg^{-1} in aggregates. The ON_M contents were 1.60–3.88 g kg^{-1} in bulk soil and 1.48–2.96 g kg^{-1} in aggregates. The lowest ON_P contents in bulk soil (0.0–10.0 cm) and aggregates in 0.0–5.0 cm and lowest ON_M in bulk soil (0.0–20.0 cm) were found in T7. However, this treatment had the highest ON_P contents in aggregates in the 5.0–10.0 cm layer and in bulk soil in the 10.0–20.0 cm layer. The highest ON_P contents were found in bulk soil in the 0.0–5.0 cm layer and in aggregates in the 10.0–20.0 cm layer; and the highest ON_M contents in bulk soil (0.0–5.0 cm) were found in T6 (Table 6).

Table 5. Particulate organic carbon (OC_P) and mineral-associated organic carbon (OC_M) in soil bulk and soil aggregates of a Humic Cambisol subjected to no-tillage and conventional tillage systems with onion crops using crop rotations and successions. Ituporanga SC, Brazil

Means followed by the same uppercase letter in the column did not differ significantly between treatments for soil bulk and aggregates by the Scott–Knott test at 5%. Means followed by the same lowercase letter in the row did not differ significantly between soil bulk and aggregates for each treatment by the Student's *t*-test (l.s.d.) at 5%. CV, coefficient of variation; T1, succession of onion, and maize in no-tillage system (NTS); T2, rotation of soil cover crops (winter), and biennial onion in NTS; T3, rotation of maize, winter grasses, and onion in NTS; T4, succession of summer legume and annual onion in NTS; T5, rotation of summer grass, winter grasses, and annual onion in NTS; T6, succession of summer legume, winter grass, and annual onion in NTS; T7, succession of maize and onion in conventional tillage system (CTS); T8, succession of intercrops of soil cover crops (summer)

	OC_P (g kg^{-1})			OC_M (g kg^{-1})		
	Soil bulk	Aggregates	CV%	Soil bulk	Aggregates	CV%
			0.0–5.0 cm layer			
T1	10.64Ba	7.54Cb	10.60	22.28Bb	23.93Ba	4.20
T2	10.66Ba	9.23Ba	7.86	23.71Bb	25.07Ba	8.13
T3	12.88Aa	12.72Aa	11.63	21.25Cb	26.96Aa	8.01
T4	9.66Bb	11.29Aa	12.26	19.97Ca	20.62Ca	4.16
T5	10.36Bb	11.54Aa	5.96	20.60Cb	23.31Ba	*5.89*
T6	13.55Aa	11.40Ab	7.38	29.94Aa	22.48Bb	5.49
T7	7.90Ca	3.79Db	16.19	17.06Db	22.66Ba	5.88
T8	10.88Bb	12.05Aa	11.47	22.98Ba	18.42Cb	5.79
CV%	8.72	12.29		6.02	6.54	
			5.0–10.0 cm layer			
T1	6.89Aa	7.24Ca	6.22	18.80Ba	18.16Ca	5.21
T2	7.40Aa	5.57Da	19.19	20.09Aa	20.69Ba	5.70
T3	6.01Ab	9.22Aa	8.89	20.07Aa	16.47Db	5.83
T4	7.30Aa	2.81Eb	9.64	20.80Ab	23.62Aa	5.04
T5	7.28Aa	2.95Eb	11.15	20.19Ab	24.75Aa	7.01
T6	6.33Aa	5.50Da	7.39	18.82Bb	21.23Ba	3.80
T7	6.23Aa	3.27Eb	13.54	14.42Cb	21.74Ba	5.75
T8	5.95Ab	9.02Ba	11.00	20.62Aa	16.13Db	6.97
CV%	11.98	10.45		6.20	5.37	
			10.0–20.0 cm layer			
T1	4.99Aa	3.28Bb	12.08	15.83Cb	18.65Aa	6.65
T2	4.69Aa	3.48Bb	15.13	20.55Aa	19.68Aa	3.71
T3	5.01Aa	5.91Aa	15.29	18.38Aa	17.00Ba	8.07
T4	4.69Aa	2.51Bb	15.02	17.48Bb	21.24Aa	5.56
T5	4.67Aa	3.08Bb	6.22	19.07Ab	20.53Aa	4.94
T6	4.69Ab	5.83Aa	8.08	19.70Aa	17.35Bb	5.29
T7	4.90Aa	3.39Bb	5.97	15.77Cb	20.03Aa	4.02
T8	4.65Ab	5.51Aa	2.01	18.18Ba	15.80Bb	8.46
CV%	10.78	13.40		4.35	6.32	

Discussion

TOC and TN contents in the bulk soil and soil aggregates

The lowest TOC and TN contents found in bulk soil and aggregates in T7 were due to the soil management and the lower plant diversity used in this treatment. T7 received biomass from the maize residues and weeds in the fallow (Table 3). However, the soil preparation practices caused fragmentation of these residues and accelerated their decomposition. They also caused rupture of aggregates, exposing the organic C and N that were previously protected and favouring their decomposition by soil microbiota. CTS increase the organic matter mineralisation rate, which decreased the TOC and TN contents (Boddey *et al.* 2010; Busari *et al.* 2015). The lowest onion bulb yields were found in T7 (Table 3), which confirms the lower TOC and TN contents found this treatment (Table 4).

Loss *et al*. (2015) evaluated chemical and physical attributes in soil aggregates and found similar results. They evaluated the effects of using soil cover crops (single and intercropped) for onion crops in NTS for 5 years on the soil aggregation and TOC in the soil aggregates, compared with the use of onion crops in CTS for 37 years. They found that the use of soil cover crops with onion in NTS increased soil aggregation, the amount of macroaggregates, and the soil TOC content in the aggregates (0.0–5.0 cm soil depth).

Considering the soil TOC content at the beginning of the experiment in 2007 (23.08 g kg^{-1} in the 0.0–10.0 cm layer), the TOC in bulk soil (0.0–10.0 cm) increased in all treatments, except in T7 (5.0–10.0 cm). Treatments in NTS had more pronounced increases than that in CTS. Studies have reported reductions of soil TOC and TN contents in CTS when compared with NTS, reduced soil tillage, pasture, natural vegetation, and native forest (Tivet *et al.* 2013; Silva *et al.* 2014; Loss *et al.* 2015; Santos *et al.* 2017). Treatments in NTS have constant

Table 6. Particulate organic nitrogen (ON_P) and mineral-associated organic nitrogen (ON_M) in soil bulk and soil aggregates of a Humic Cambisol subjected to no-tillage and conventional tillage systems with onion crops using crop rotations and successions. Ituporanga SC, Brazil

Means followed by the same uppercase letter in the column did not differ significantly between treatments for soil bulk and aggregates by the Scott–Knott test at 5%. Means followed by the same lowercase letter in the row did not differ significantly between soil bulk and aggregates for each treatment by the Student's *t*-test (l.s.d.) at 5%; CV, coefficient of variation. T1, succession of onion, and maize in no-tillage system (NTS); T2, rotation of soil cover crops (winter), and biennial onion in NTS; T3, rotation of maize, winter grasses, and onion in NTS; T4, succession of summer legume and annual onion in NTS; T5, rotation of summer grass, winter grasses, and annual onion in NTS; T6, succession of summer legume, winter grass, and annual onion in NTS; T7, succession of maize and onion in conventional tillage system (CTS); T8, succession of intercrops of soil cover crops (summer)

	ON_P (g kg^{-1})			ON_M (g kg^{-1})		
	Soil bulk	Aggregates	CV%	Soil bulk	Aggregates	CV%
			0.0–5.0 cm layer			
T1	0.30Db	0.45Aa	14.11	2.98Ca	2.25Bb	3.25
T2	0.37Ca	0.34Ba	16.04	3.36Ba	2.78Ab	4.84
T3	0.31Da	0.31Ba	13.75	2.70Ca	2.96Aa	9.47
T4	0.48Ba	0.28Ba	21.06	3.04Ca	2.47Bb	3.82
T5	0.38Ca	0.25Bb	8.70	2.94Ca	2.85Aa	6.37
T6	0.78Aa	0.48Ab	6.85	3.88Aa	2.81Ab	6.18
T7	0.16Ea	0.06Db	7.93	2.14Da	2.20Ba	4.48
T8	0.49Ba	0.13Cb	16.94	2.97Ca	2.82Aa	8.75
CV%	13.21	13.68		4.36	8.38	
			5.0–10.0 cm layer			
T1	0.15Ca	0.08Db	12.75	2.49Ba	1.99Ab	3.10
T2	0.17Ba	0.08Db	11.53	2.57Ba	1.99Aa	6.16
T3	0.13Ca	0.12Ca	12.18	2.54Ba	2.11Ab	2.82
T4	0.16Ca	0.11Cb	14.73	2.62Ba	2.03Aa	5.30
T5	0.20Aa	0.09Db	9.25	2.69Ba	2.12Ab	3.06
T6	0.20Aa	0.10Cb	14.96	2.79Aa	2.06Ab	3.89
T7	0.10Db	0.19Aa	5.99	1.91Ca	2.02Aa	5.76
T8	0.14Cb	0.16Ba	12.41	2.66Aa	1.93Aa	8.15
CV%	11.28	12.88		4.77	5.37	
			10.0–20.0 cm layer			
T1	0.07Ba	0.08Ca	13.98	1.73Aa	1.54Ab	4.85
T2	0.08Ba	0.05Db	15.43	1.77Aa	1.58Aa	6.79
T3	0.05Cb	0.07Ca	14.73	1.83Aa	1.58Ab	5.21
T4	0.04Cb	0.05Da	7.64	1.70Ba	1.59Aa	8.82
T5	0.09Ba	0.08Ca	17.39	1.85Aa	1.67Ab	4.72
T6	0.09Bb	0.16Aa	10.33	1.83Aa	1.51Ab	3.63
T7	0.13Aa	0.09Bb	9.78	1.60Ca	1.65Aa	9.61
T8	0.08Ba	0.10Ba	15.98	1.79Aa	1.48Ab	5.21
CV%	12.41	13.89		4.20	8.29	

deposition of plant residues on the soil surface, favouring the maintenance and increasing of TOC contents and, consequently, increasing the TN contents (Silva *et al.* 2014; Vezzani *et al.* 2018).

The highest TOC (0.0–5.0 cm) and TN (0.0–10.0 cm) contents found in the bulk soil of T6 may be due to the combination of plant species from different botanical families—velvet bean (legume) and rye (grass). The use of velvet bean may explain the high TN, since this species presents a low C : N ratio (average of 16.5), average dry matter of 7.5 Mg ha^{-1}, and great N biological fixation (120 to 210 kg ha^{-1} year^{-1} of N) and nutrient cycling (Lima Filho *et al.* 2014). Rye has a fasciculate and dense root system that develops to depths of up to 122 cm, dry matter with high C : N ratio (average of 30.5), and average dry matter of 4.5 Mg ha^{-1} (Weaver 1926; Lima Filho *et al.* 2014).

The use of soil cover crops, especially grasses, protect the soil against climatic events and favours carbon input, mainly by rhizodeposition (Thivierge *et al.* 2016). Single crops of legumes, and especially intercrops of legumes, can absorb nutrients from deep soil layers (1.0 and 1.5 m) (Gathumbi *et al.* 2003). Rye crops can accumulate 91–100 kg N ha^{-1} (Fageria *et al.* 2005; Oliveira *et al.* 2016), but with slow N mineralisation. Thus, the high amount of dry matter produced by the velvet bean combined with the high C : N ratio of the rye dry matter can explain the higher TOC and TN contents in bulk soil in T6. The higher onion bulb yield in T6 in 2014 (Table 3) confirms its higher TOC and TN contents (Table 4).

According to Giacomini *et al*. (2003), intercrops with different plant species produce biomass with an intermediate C : N ratio to that of single crops. Doneda *et al*. (2012) evaluated rye intercropped with oilseed radish, and oat intercropped with oilseed radish and found a slower decomposition rate of plant residues when compared with single crops and an intermediate C : N ratio of the biomass. Thus, the decomposition rate of plant residues can be altered to simultaneously provide more efficient and lasting soil coverage and better synchronisation between supply and demand of nutrients of the crops in succession, especially N (ASHS, 2010). Boddey *et al*. (2010) evaluated TOC stocks in three long-term soybean experiments using NTS and CTS with crop rotation in Latosols in southern Brazil and found significant increases in TOC stocks in NTS when compared with CTS, and in areas with legumes in the crop rotation. These results confirm those found in the present study, especially considering the bulk soil of T6, which denotes the importance of N as a component of the soil organic matter (SOM) humification process and soil carbon retention (Christopher and Lal 2007).

The highest TN and TOC contents in soil aggregates of T3, T2, T5, and T6 can be attributed to the use of species of the family Poaceae (grasses) in T3 and T5 and the combination of grass and legume species in T2 and T6. T2 is a crop rotation—vetch, maize, rye intercropped with oilseed radish, and common bean. Oats stood out because of its fasciculate root system that generally reaches a depth of 76 cm, producing on average 6 Mg ha^{-1} of dry matter with a high C : N ratio (average of 31.5). Rye has a high nutrient cycling capacity, fasciculate root system that develops to a depth of 122 cm, and an average dry matter yield of 4.5 Mg ha^{-1} with a high C : N ratio (average of 30.5). Maize has a very extensive and branched root system, reaching depths of 1.8 m, producing ~6 Mg ha^{-1} of dry matter with a high C : N ratio (average of 52) (Weaver 1926; Lima Filho *et al.* 2014). Therefore, the combination of deep and dense root systems that perform C deposition and large dry matter yields with high C : N ratio can explain the higher TOC contents found in T3. T5 had oat, rye, and millet, which also has a profuse and deep root system, reaching 200 cm (Norman *et al.* 1995). T2 and T6 had combinations of plant species, grasses, and legumes, and T2 had a crop rotation. These combinations favour the balance of C : N ratio of the plant biomass with a consequent increase of TOC and TN contents.

The input of C and N in the soil occurs not only via decomposition of the shoot of the soil cover crops, but also via rhizodeposition. Thivierge *et al*. (2016) evaluated the contribution of the root systems of maize, sorghum, and millet to the soil C contents, and found that the inputs of C from maize crop residues after harvest (243 g C m^{-2}) was higher than those of the sorghum (197 g C m^{-2}) and millet (131 g C m^{-2}), and large part of this C was derived from fine roots with a diameter of less than 0.5 mm.

Amado *et al*. (2001) evaluated the potential of soil cover crops and plants to accumulate C and N in NTS and found that the use of legumes, combined with a greater diversity of species in succession or rotation, significantly increased the C and N retention in the soil. This confirms the highest TOC and TN contents in treatments with combination of plant species from different families. Jantalia *et al*. (2003) evaluated crop systems with rotation and succession including legume and grass species used as green manuring and mulching. They found higher C and N stocks in NTS with crop rotation systems using plant species from different families compared with CTS with succession of wheat and soybean; there were no TOC and TN stock increases due to soil cover plants in the CTS.

The absence of differences in TOC in aggregates (5.0–10.0 and 10.0–20.0 cm) and TN in bulk soil (10.0–20.0 cm) and aggregates (5.0–10.0 and 10.0–20.0 cm) between treatments in NTS and CTS was due to soil turning in the CTS, which inverts the soil layers. Thus, plant residues in the soil surface layer, which present high SOM contents, are incorporated into deeper soil layers in CTS (Loss *et al.* 2015), changing the nutrient contents of the soil profile and equating them to those found in NTS (Loss *et al.* 2015; Santos *et al.* 2017). The absence of differences in TOC and TN in deeper layers of the treatments in NTS is probably due to the higher contribution of soil cover plants and crops to the soil surface layer and the absence of soil turning. Sisti *et al*. (2004) conducted a long-term experiment (15 years) with crop rotation and succession with legumes and grasses in NTS and found differences in TOC and TN contents only in the 0.0–5.0 cm layer; they reported that the soil C and N stocks are dependent on the soil tillage system and soil cover crop species used.

The physical and chemical protection of the SOM by the soil aggregates explains the higher TOC contents in soil aggregates, compared with bulk soil, in T3, T4, T5, and T7 treatments in the 0.0–5.0 cm layer, and of T6 and T7 in the 5.0–10.0 cm layer. The physical protection of the SOM by occlusion due to the soil aggregates makes it difficult for microorganisms and their enzymes to interact with the organic substrate; it is a physical barrier that reduces the O_2 availability for the oxidative processes of decomposition (Baldock *et al.* 1992; Balesdent *et al.* 2000).

Zhong *et al*. (2017) found similar results and reported that soil aggregates present less accessibility to microorganisms to organic substrates, decreasing the soil microbial activity and physically protecting the C and N from decomposition. These authors conducted an experiment on a Red Latosol in forest plantation (*Schima* sp.) in south-western China, evaluating the physical protection of organic C by soil aggregates and reductions in TOC loss considering TOC, TN, and C and N of microbial biomass, dissolved organic C, and hot water extractable organic C in aggregates and bulk soil. They found 61.79% to 69.86% less N of microbial biomass in aggregates than in bulk soil; 20.69%, 15.74%, and 13.36% less C of microbial biomass in aggregates of 1–2, 2–5, and 5–8 mm respectively; and 41.02%–66.40%, and 91.30%–104.45% higher concentrations of dissolved organic C and hot water extractable organic C in aggregates than in bulk soil respectively. These results denote the decreased microbial activity due to the physical protection of the organic matter by the soil aggregates, which prevents organic C decomposition and results in higher concentrations of dissolved organic C and hot water extractable organic C, compared with bulk soil.

Granulometric fractionation of the bulk soil and soil aggregates

The lowest OC_P contents in bulk soil and aggregates (0.0–5.0 cm), and the lowest OC_M contents in bulk soil (0.0–10.0 cm) in T7 were due to the soil management adopted in this treatment, which was conducted using plough and harrow, or cultivator, which ruptured and fragmented the soil aggregates. This management exposed the SOM that was protected within the aggregates to microbial decomposition (Meurer 2012; Loss *et al.* 2014), decreasing the OC_P, which confirms that the CTS changes the soil aggregation and increases the SOM decomposition rate, causing a decrease in OC_P and OC_M contents when compared with NTS. These results explain the lower TOC contents in bulk soil (0.0–10.0 cm) and aggregates (0.0–5.0 cm) in this treatment.

The higher OC_P (5.0–10.0 cm) and OC_M (0.0–5.0 cm) contents in aggregates in T3 is explained by the soil cover crops (rye, oat, and maize) used, which resulted in high amount of shoot dry matter with high C : N ratio, and the decomposition of organic compounds (Thivierge *et al.* 2016; Lima Filho *et al.* 2014). These results confirm the higher TOC content in aggregates (0.0–5.0 cm) in this treatment.

The highest OC_P and OC_M contents in bulk soil (0.0–5.0 cm) in T6 is explained by the high amount of dry matter produced by the velvet bean combined with the high C : N ratio of the rye dry matter (Weaver 1926; Lima Filho *et al.* 2014). These results confirm the higher TOC contents in bulk soil (0.0–5.0 cm) in this treatment.

Compared with T7, the T1 treatment (succession of onion and maize in NTS) presented higher TOC contents in bulk soil (0.0–20.0 cm) and aggregates (0.0–5.0 cm), TN in bulk soil (0.0–10.0 cm) and in aggregates (0.0–5.0 cm), OC_P in bulk soil (0.0–5.0 cm) and aggregates (0.0–10.0 cm), OC_M in bulk soil (0.0–10.0 cm), ON_P in bulk soil (0.0–10.0 cm) and aggregates (0.0–5.0 cm), and ON_M in bulk soil (0.0–20.0 cm). Since the same succession (onion and maize) was used in both systems, these results denote the importance of conservationist management practices, such as NTS, to improve soil chemical attributes (TOC and TN) and granulometric fractions of SOM when compared with CTS. Moreover, T1 had higher onion yield than T7 (Table 3).

The results obtained in T6, compared with the results of T3 and T5 (both with grass species only) and T4 (with legume species only) showed higher TOC in bulk soil (0.0–5.0 cm), TN in bulk soil (0.0–10.0 cm), OC_P in bulk soil (0.0–5.0 cm, except T3), OC_P in aggregates (10.0–20.0 cm, except T3), OC_M in bulk soil (0.0–5.0 cm), ON_P in bulk soil and in aggregates (0.0–5.0 and 10.0–20.0 cm respectively), and ON_M in bulk soil (0.0–10.0 cm). These results indicate the importance of using plant species of different botanical families, such as grasses and legumes, for the improvement of soil chemical attributes and granulometric fractions of the SOM.

T8 presented, in general, similar or greater TOC and TN contents than T1, T2, T4, and T5 in the 5.0–10.0 and 10.0–20.0 cm layers in aggregates and bulk soil. However, the OC_P contents in these layers differed between treatments only in aggregates, with higher OC_P contents in T8 compared with T1, T2, T3, and T4. The ON_P contents in bulk soil and aggregates of T1, T2, T3, T4, and T8 were different. However, T8 presented higher ON_P contents in the aggregates when compared to T1, T2, T4, and T5 (5.0–20.0 cm). Therefore, using plant species of different botanical families (pearl millet, velvet bean, and sunflower) is important to increase the soil particulate C and N fractions. The greater variation of OC_P and ON_P in the treatments in aggregates, compared with bulk soil, confirms the importance of particulate organic matter for nucleation and formation of soil aggregates, especially macroaggregates (Golchin *et al.* 1994; Six *et al.* 2004).

Winck *et al*. (2014) evaluated soil TOC and TN stocks and granulometric fractions of the SOM in six soil management systems with different crop rotations in NTS. They found that soil TOC and TN stocks, and granulometric fractions of the SOM increased with an increase in the number of species in the rotation that have longer cycles and high organic matter input to the soil, consequently favouring the soil functions by increasing soil quality.

Regarding the C and N contents in bulk soil and aggregates of each treatment, the OC_M was, in general, higher in aggregates; and OC_P, ON_P and ON_M were, in general, higher in bulk soil. T8 had higher OC_P (0.0–20.0 cm) and ON_P (5.0–10.0 cm) in aggregates than in bulk soil. The highest OC_M contents in aggregates were due to the physical and chemical protection of the SOM by the aggregates. The highest OC_P and ON_P contents in aggregates in T8 may be due to the higher biomass produced in this treatment compared with the others (Table 3).

Conclusions

Succession of maize and onion in CTS reduced TOC, OC_P, OC_M, TN, ON_P, and ON_M in soil aggregates and bulk soil when compared with NTS for onion crops in the topsoil. Velvet bean and rye in these successions increased the TOC, TN, OC_P, OC_M, ON_P, and ON_M contents in aggregates and bulk soil when compared with the successions with only grasses or only legumes. Succession of maize and onion crops in NTS increased TOC and TN contents, and the granulometric fractions of the organic matter when compared with CTS with the same succession. Succession of intercrop of pearl millet, velvet bean, and sunflower (summer) in NTS increased the OC_P and ON_P contents in the soil aggregates when compared with succession of maize and onion in CTS, rotation of crops with winter soil cover crops in NTS, succession of summer legumes in NTS, and rotation of summer grass, winter grasses, in NTS.

In general, TOC and OC_M contents were higher in soil aggregates, whereas TN, OC_P, ON_P, and ON_M contents are higher in bulk soil. The main changes due to management systems and combinations of soil cover crops were observed in the particulate fractions, mainly in the soil aggregates.

Conflicts of interest

The authors declare no conflicts of interest.

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