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KATIUÇA SUEKO TANAKA

SOIL QUALITY AND GRAIN YIELD AS A FUNCTION OF CROP ROTATION IN LONG-TERM

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TÍTULO DA TESE: SOIL QUALITY AND GRAIN YIELD AS A FUNCTION OF CROP ROTATION IN LONG-TERM

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I dedicate this thesis to my parents Elio and Marilza, to my sisters Hidemi, Satiko and Hana, to my nieces Sophia and Lívia, and to my grandfather Shigueru Tanaka (*in memory*).

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“Everybody is a genius. But if you judge a fish by its ability to climb a tree, it will live its whole life thinking it is stupid”

Albert Einstein

RESUMO

O solo é um recurso não renovável, sendo fundamental na sustentabilidade do ambiente e para o bem-estar humano. O seu manejo inadequado pode afetar a qualidade e intensificar a sua degradação, podendo provocar a perda da capacidade produtiva do solo. Uma das estratégias utilizadas para minimizar a degradação do solo é adotar um sistema conservacionista, como o sistema plantio direto. Entretanto, o baixo aporte de resíduos culturais na superfície do solo tem comprometido o sucesso deste sistema em regiões tropicais. Além disso, a baixa precipitação durante a estação outono/inverno na região do Cerrado brasileiro pode afetar o desempenho das culturas e/ou das plantas de cobertura durante a entressafra, levando ao aumento do período do pousio. Desse modo, estudos de longa duração sobre a influência dos sistemas de produção na qualidade do solo, são necessários para adotar a melhor estratégia para um sistema de produção mais sustentável no Cerrado brasileiro. O experimento foi instalado em outubro de 2006 no município de Botucatu, São Paulo, com o objetivo de escolher manejo adequado para a estação de inverno seco buscando melhorar a qualidade do solo em sistema plantio direto. Os sistemas de produção foram constituídos com diferentes espécies cultivadas durante o inverno (pousio, segunda safra, adubo verde e forragem) para cada cultura de verão cultivada entre 2007 e 2017. No primeiro capítulo, o objetivo foi investigar o efeito dos sistemas de produção na estrutura e propriedades bioquímicas do solo. No segundo capítulo, o objetivo foi determinar como a escolha da cultura de inverno impacta nas propriedades físicas do solo. No último capítulo, o objetivo foi avaliar o efeito dos sistemas de produção na fertilidade do solo. A inclusão de forrageira e adubo verde durante o inverno tem se mostrado favorável não somente para evitar períodos de pousio, mas também melhorar a qualidade do solo e a produtividade de grãos das culturas de verão.

Palavras-chave: Física do solo. Fertilidade do solo. Sistema de produção. Propriedades bioquímicas do solo.

ABSTRACT

Soil is a non-renewable resource that play a fundamental role on environmental quality and to human well-being. Unsuitable land use and management practices trigger a decline in soil quality, which can lead to soil degradation and lose the capability to grow plants. A strategy to minimize soil degradation is to adopt conservation soil management, such as no-till system. However, the lack of sufficient residues to cover soil surface are compromising the success of no-till system in tropical regions. Furthermore, low precipitation during the autumn/winter season in the Brazilian Cerrado, may affect performance of crops and cover crops during the off-season, and leading to bare fallow periods. Therefore, long-term studies on how cropping systems influence soil quality properties are needed to design the most suitable strategies for more sustainable crop production in the Brazilian Cerrado. An experiment was established in October 2006 on a clayey Rhodic Hapludox soil in Botucatu, São Paulo, Brazil, to investigate choice of winter dry-season management on environmental quality under no-tillage. Cropping systems were with different species cropped during the winter season each year of the summer crop from 2007 to 2017 (fallow, second crop, cover crop, and forage crop). In the first chapter, our objective was to investigate the effects of cropping systems on soil structure and soil biochemical properties. In the second chapter, our objective was to determine how the choice of winter crop/cover crop impacts soil physical properties. And in the last chapter, we aimed to evaluate the effects of cropping systems on soil fertility. The inclusion of forage and cover crops during the winter season has been shown favorable to not only avoid bare fallow periods, but also enhance soil quality and grain yield of the summer crops.

Keywords: Soil physics. Soil fertility. Cropping system. Soil biochemical properties.

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SUMMARY

INTRODUCTION

To attend food demand by 2050, there will need an increase of approximately 60% in global food production (FAO, 2019). However, agricultural production is constrained by the decline in soil quality (Lal, 2015). The loss of soil quality impacts on ecosystem degradation and in human well-being through the quantity and quality of food production (Lal, 2009). According to Blanco-Canqui and Lal (2010), since the 1970s, approximately one-third of the world's soils have become unproductive. Leading factors responsible for poor soil quality are excessive soil plowing, soil surface unprotected and low carbon (C) inputs (plant residues and animal manures) (Franzluebbers and Gastal, 2019). Soil degradation can be minimized with adopting conservation agriculture management, such as no-till, that compromises minimal or no soil disturbance, high plant biomass to maintain soil surface covered and adopt crop rotation (Lal, 2009).

Conservation agriculture management of degraded land can restore soil functions, enhance soil organic matter (SOM), increase soil biological activity and carbon sequestration, and improve soil fertility and physical properties (Lal, 2015; Franzluebbers, 2010). As the main key component of soil quality, soil organic matter is a source of energy and substrates to support biological activity, and affect plant-available nutrient supply, water retention, and soil structure (Franzluebbers, 2002). Further, it minimizes agricultural impact on the environment through carbon sequestration (Six et al., 2002). Primary source of soil organic matter is through decomposition of plant residues, in which the decomposition must be lower than organic inputs (Paul, 2016). Accumulation of soil organic matter is also influenced by climatic conditions. Generally, its stocks decrease under drier and warmer weather conditions (Wiesmeier et al., 2019). According to Sanchez and Logan (1992), soil organic matter decomposition in the tropics was five times faster than in temperate region. Therefore, quantity and quality of plant residues play a fundamental role to agricultural sustainability in the tropics.

The fast turnover of soil organic matter and the lack of sufficient plant residues on the soil surface are compromising soil quality under tropical conditions. Summer crops do not produce sufficient biomass to cover the soil (Pacheco et al., 2011) and low plant biomass production during the autumn/winter season due to low water availability in

Cerrado regions, are allowing extending periods of winter fallow. Long periods of winter fallow can enhance weed infestation, in which some weeds have allelopathy potential that lead to impact negatively on main-crop production (Jabran et al., 2015). Furthermore, low C inputs by weeds in the system and the soil exposure, increase soil degradation over the years (Derpsch et al 2014; Crusciol et al. 2015), and no income is produced during this period (Balbinot Junior et al., 2011).

Growing grain crop that present fast development and resistant to water stress right after harvesting summer crop is a strategy to maximize productivity of the land, and also to avoid bare fallow period. Another alternative is the inclusion of cover crops in the system. Cover crops can improve yield of the following crop by their impact in soil chemical, physical and biological properties (Fageria et al., 2005). However, time of sowing is one of the challenges to grow cover crop properly because of adverse climate conditions during the dry-winter season. In recent years, tropical forage *Urochloa* has been introduced in cropping system into Cerrado region, and stands out due to provide abundant surface residue as cover crop and their great drought tolerance (Borghi et al., 2013; Gichangi et al., 2017). Hence, this forage can be used to protect soil surface (Crusciol et al., 2015) and/or to feed animals during the off-season in a system called integrated crop-livestock that provide several benefits to soil and water conservation, nutrient cycling and increase land profitability (Franzluebbers and Stuedemann, 2007).

Therefore, the choice of the most suitable cropping system is fundamental to design strategies for enhance soil quality properties and more sustainable crop production in the Brazilian Cerrado. We hypothesized that a cropping system with dry-season forage would improve soil organic matter, soil physical and chemical properties as well as grain yield of summer crops. Our objectives were to investigate the choice of winter dry-season management and their impacts on soil structure, biochemical and fertility properties under no-till system, and identify which tropical cropping system for a more sustainable and profitable agriculture.

CHAPTER 1 - RESPONSE OF SOIL AGGREGATION AND BIOCHEMICAL PROPERTIES TO CROPPING SYSTEM UNDER NO-TILL

1.1 Abstract

The choice of crop and/or cover crop grown during the autumn/winter season is crucial to maintain and enhance soil organic matter (SOM) under tropical conditions. However, the impact on SOM and its different fractions by the adoption of different cropping system have not been thoroughly characterized. An experiment was established in October 2006 on a clayey Rhodic Hapludox soil in Botucatu, São Paulo,Brazil, to investigate choice of autumn and dry-winter season management on environmental quality under no-tillage. Cropping systems were with different species cropped during the winter season each year of the summer crop from 2007 to 2017 (I. Summer-Fallow; II. Summer-Second crop; III. Summer-Cover crop; IV. Summer-Forage). We determined the vertical distribution (0 to 0.1; 0.1 to 0.2 and 0.2 to 0.4 m) of total organic carbon (TOC), total soil nitrogen (TN), soil microbial biomass C (SMBC), particulate organic matter (POM) and potential C and N mineralization. At depths of 0 to 0.1 and 0.1 to 0.2 m, dry and water stable aggregates, stability of mean weight diameter (SMWD), and TOC and TN in aggregate classes were determined. At depth of 0 to 0.1 m, potential C mineralization in microaggregates, crushed macroaggregates, and intact macroaggregates were assessed. At upper depths (0 to 0.1 and 0.1 to 0.2 m) no differences in soil properties analyzed were observed. However, in subsoil layer (0.2 to 0.4 m) SMBC was greater with forage (95 mg kg^{-1}) than cropping system with cover crop (62 mg kg^{-1}) and fallow (66 mg kg^{-1}). Within microaggregates, cropping system with fallow had 69% greater mineralizable C at 3 and 10 days, and 91% at 24 days of incubation compared to cropping system with second crop, cover crop and forage. Few responses on soil properties might be the fast SOM dynamics under tropical conditions associated to obstacle to maintain soil surface covered over the year. On the other hand, the adoption of forage has been shown favorable to achieve biological activity in lower depth.

Key words: crop rotation, aggregates, carbon mineralization

1.2 Introduction

Inappropriate land use and management practices trigger a decline in soil quality, which can lead to soil degradation in the long-term, losing the capability to grow plants and, becoming unproductive (Lal, 2001). Therefore, the loss of soil quality affects not only the environment, but also human health through lower quantity and quality of food production (Lal, 2009). A strategy to minimize soil degradation is to adopt conservation soil management that is capable of increasing soil organic matter, building soil fertility and physical properties, and enhancing soil biological activities (Lal, 2015; Franzluebbers, 2010).

As a key indicator of soil functions, soil organic matter is essential to improve and maintain soil quality, productivity (Carter, 2001), and reduce agricultural impact on the environment through carbon sequestration (Six et al., 2002a). The major pathway to form soil organic matter is through decomposition of plant residues (above and below ground) by soil organisms (Castellano et al., 2015). Soil is the largest terrestrial pool of cycling organic C and nitrogen (N). However, soil organic matter accumulation depends on soil management (no-till system), crop management strategies (crop rotation, choice of crop, crop intensity) (Franzluebbers et al., 1994), the balance between decomposition of plant residues and its mineralization to CO_2 (Cotrufo et al., 2015), mean annual precipitation (Burke et al., 1989) and temperature (Jenny, 1980).

Soil organic matter stabilization is mediated by the action of three mechanisms: chemical stabilization, biochemical stabilization and physical protection (Christensen, 1996; Stevenson, 1994). Chemical stabilization of soil organic matter results from the chemical or physicochemical binding of soil organic matter and primary mineral particles. Biochemical stabilization is due to soil organic matter chemical composition, such as lignin and polyphenols that are recalcitrant compounds. Physical protection occurs through soil aggregation that reduces microbial biomass accessibility to C (Six et al., 2002b). Additionally, the quantity and quality of crop residues inputs (above and below ground) play a fundamental role in soil organic matter stabilization. Roots and crop residues are a great source of C that serves as an energy source for soil microbiota (Briedis et al., 2012). This microbiota releases organic compounds that are highly effective to the development of soil aggregation and consequently, promotes protection of C within aggregates (Six et al., 2001).

Since the balance between organic matter inputs and decomposition directly affects soil organic C storage (Six et al., 2006), tropical climate conditions favor a faster turnover of C than in temperate regions (Six et al., 2002a). Therefore, no-till production practices are critical for agricultural sustainability in the tropics. Low precipitation during the autumn/winter season in most of the regions of Brazil, mainly in the Brazilian Cerrado, may affect performance of crops and cover crops during the off-season (Costa et al., 2016), and consequently, promoting winter fallow. Soil coverage by fallow is low what results in lower C inputs in the system, increase soil chemical, physical and biological degradation over the years and intensify weed infestation in the area leading to abandonment of the land (Balbinot Junior et al., 2009). Furthermore, extended fallow periods and insufficient plant residues to cover soil surface compromise conservation system and can negatively impact in soil resources and the summer crop in succession (Derpsch et al., 2014; Crusciol et al., 2015).

In certain regions, from February to April, right after harvesting summer crop, it is possible to grow grain crops that present fast development and resistant to water stress (Pacheco et al., 2011). Growing grain crop (e.g. wheat, common bean, corn) during dry-season is an alternative to maximize productivity of the land, and also to minimize/avoid fallow period. On the other hand, the use of cover crop contributes to build surface residue protection and provide erosion control during off-season (Torbert et al., 1996). However, time of sowing is one of the challenges to grow it properly due to adverse climate conditions during the autumn/winter season. Another alternative that has been presenting great performance under dry-season is the introduction of forage species (e.g. *Urochloa* spp). These forages are capable to produce >10 Mg ha^{-1} of shoot dry matter with large C:N ratio (Pacheco et al., 2011) to help stabilize the C from rapid decomposition, and they can be used for feed livestock in a system called integrated crop-livestock (Borghi et al., 2013; Crusciol et al., 2012).

Long-term studies on how cropping systems influence soil quality properties are needed to design the most suitable strategies for building soil resilience and more sustainable crop production in the Brazilian Cerrado. Furthermore, knowledge of C mineralization within aggregate classes informs us to where C is being stored and protected to enhance soil organic C sequestration. We hypothesized that a cropping system with dry-season forage would increase soil organic C content, and therefore, soil microbial activity and soil aggregate dynamics. Our objective was to investigate the choice of winter dry-season management on soil structure and soil biochemical properties under no-till system, as well as to determine the soil depth influences of these management approaches.

1.3 Materials and methods

1.3.1 Site characteristics and management

The field experiment was initiated in 2006 on a clayey Rhodic Hapludox soil (USDA Taxonomy) in Botucatu, São Paulo State, Southeastern Brazil (48º 23' W, 22º 51' S, 765 m above sea level). Clay content averaged 439 g kg^{-1}, sand content averaged 462 g kg^{-1} and silt content averaged 100 g kg^{-1} at a depth of 0 to 0.20 m. Monthly average across 50 years of rainfall and temperature are reported in Table 1. The predominant climate is highland tropical, with dry winters and wet, rainy summers. Prior to the experiment, the site was managed with soybean (*Glycine max*) in the summer and black oat (*Avena strigosa* Schreb.) in the autumn/winter under no-till for four years. At the time of experiment initiation, chemical properties in the upper 0.2 m were analyzed according to van Raij et al. (2001) [organic matter = 18 g dm^{-3}; pH = 4.2 (1:2.5 soil/$CaCl_2$ suspension 0.01 mol L^{-1}); P resin = 4 mg dm^{-3}; exchangeable K = 0.8 $mmol_c$ dm^{-3}, Ca = 12 $mmol_c$ dm^{-3}, Mg = 6 $mmol_c$ dm^{-3}; total acidity at pH 7.0 (H+Al) = 54 $mmol_c$ dm^{-3}; base saturation = 24%].

The experimental design since 2006 was arranged in a randomized complete block of four cropping system with different species cropped during the winter season each year of the summer crop from 2007 to 2017 (I. Summer-Fallow; II. Summer-Second crop; III. Summer-Cover crop; IV. Summer-Forage) (Table 2) and four replications. Grain crop choices were according to the majority of cultivated land in the State of São Paulo and in Cerrado region. Cropping system with fallow (System I) was left unseeded and volunteer vegetation was allowed during the winter season. In the system II (Summer-Second crop), common oat (*Avena sativa* L.), common bean (*Phaseolus vulgaris* L.), castor bean (*Ricinus communis* L.), sorghum grain [*Sorghum bicolor* (L.) Moench], crambe (*Crambe abyssinica* Hochst. Ex R.E. Fr.), wheat (*Triticum aestivum*) and triticale (*X. triticosecale Wittmack*) were grown. In the system III (Summer-Cover crop), pearl millet (*Pennisetum glaucum* L.), pigeon pea [*Cajanus cajan* (L.) Huth], sunn hemp (*Crotalaria juncea* L.), lupin bean (*Lupinus albus* L.) and common oat were cropped. The fourth cropping system was with forage ruzi grass (*Urochloa ruziziensis*) and palisadegrass (*Urochloa brizantha*). For the summer grain crop, soybean (*Glycine max*), corn (*Zea mays*), common bean and rice (*Oriza sativa*) were sowed, usually in November and harvested between March to April. After the summer harvest, winter crops were sowed without fertilizer.

All cropping system were managed under no-till for the duration of this study. Each plot covered an area of 54 m^2 (5.4 m x 10 m). One row on each side of the plot and one meter at both edges were considered buffer zones and not sampled. It is noteworthy that it was not possible to grow any crop/cover crop in winter season 2014 due to adverse weather conditions. In 2016, the second crop did not grow because of poor weather conditions.

Table 1. Mean monthly rainfall and maximum and minimum temperatures from 2007 to 2016 at Botucatu, São Paulo State, Brazil.

Climate characteristics	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
	Long-term (50 yr) avg.											
Monthly rainfall (mm)	375	177	136	98	69	70	58	37	69	131	140	237
Mean max. temp. (ºC)	28.9	29.7	28.1	27.1	23.8	22.5	23.6	25.9	27.1	27.8	27.7	28.9
Mean min. temp. (ºC)	18.4	19.1	17.9	16.4	14.2	12.6	12.6	13.4	14.5	15.9	16.9	18.3

Table 2. Crop rotation scheme in Systems I, II, III and IV from 2006 to 2016, Botucatu, São Paulo State, Brazil.

	System I (Fallow)	System II (Second crop)	System III (Cover crop)	System IV (Forage)
	2006			
Winter Season	-	-	-	-
Summer Season	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
	2007			
Winter Season	Fallow	*Avena sativa*	*Pennisetum glaucum*	*Urochloa ruziziensis*
Summer Season	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
	2008			
Winter Season	Fallow	*Phaseolus vulgaris*	*Cajanus cajan*	*U. ruziziensis*
Summer Season	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*
	2009			
Winter Season	Fallow	*Ricinus communis*	*Crotalaria juncea*	*U. ruziziensis*
Summer Season	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
	2010			
Winter Season	Fallow	*Sorghum bicolor*	*Pennisetum glaucum*	*U. ruziziensis*
Summer Season	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
	2011			
Winter Season	Fallow	*Crambe abyssinica*	*Lupinus albus*	*U. ruziziensis*
Summer Season	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*
	2012			
Winter Season	Fallow	*Triticum aestivum*	*Pennisetum glaucum*	*U. brizantha*
Summer Season	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*
	2013			
Winter Season	Fallow	*Triticum aestivum*	*Crotalaria juncea*	*U. brizantha*
Summer Season	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*

	------------------------------------ **2014** ------------------------------------			
Winter Season	-	-	-	-
Summer Season	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
	------------------------------------ **2015** ------------------------------------			
Winter Season	Fallow	*X. triticosecale*	*Avena sativa*	*U. brizantha*
Summer Season	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*
	------------------------------------ **2016** ------------------------------------			
Winter Season	Fallow	-	*Pennisetum glaucum*	*U. brizantha*
Summer Season	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*

Over the 11 years of this experiment, dolomitic lime was applied in October 2006 (before sowing the first crop), October 2011 and October 2015. The dolomitic lime rate (LR) was calculated by the method of base saturation (BS) proposed by van Raij et al. (1997), which used a calculation to increase bas saturation to 70%:

$$LR\ (Mg\ ha^{-1}) = (BS_2 - BS_1) \times CEC / (ECCE \times 10) \quad (1)$$

Where, BS_2 is the target base saturation (70%), BS_1 is the base saturation determined by the soil chemical analysis, CEC is cation exchange capacity, and ECCE is the effective calcium carbonate equivalent of the dolomite lime. Adequate rates of NPK fertilizers were applied for summer crops according to soil chemical analyses conducted each year.

1.3.2 Soil sampling and analyses

Eleven years after treatment establishment (in 2017), a trench measuring 0.5 m wide, 0.6 m deep and 0.6 m long was dug in each plot. Soil was sampled at depths of 0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m. A composite sample of three clod (0.05 m height, 0.10 m width and 0.15 m length) was collected in the trench profile. Soil was dried at 55 ºC for 48 h and then gently crushed to pass through a sieve with openings of 4.75-mm.

Potential C mineralization was determined from two 50-g subsamples of soil in 60 mL glass jars that were moistened to 50% water-filled pore space and placed in a 1-L canning jar along with 10 mL of 1 mol L^{-1} NaOH to trap CO_2 and a vial of water to keep it humid (Franzluebbers et al., 1999). Soil samples were incubated at 25 ± 1 ºC for 24 days. Alkali traps were replaced at 3 and 10 days and removed at 24 days.

The quantity of CO_2-C absorbed in the alkali was determined by titration with 1 mol L^{-1} HCl in the presence of excess $BaCl_2$ to a phenolphthalein endpoint. At 10 days of incubation, one of the subsamples was removed from the incubation jar, fumigated with $CHCl_3$ under vacuum. After 24 h, vapors were removed and then soil samples were placed into a separate canning jar along with vials of alkali and water, and incubated at 25 ºC for 10 days. Potential C mineralization was calculated from cumulative emission of CO_2 during 24 days of aerobic incubation. Soil microbial biomass C was determined with the chloroform fumigation-incubation method and was calculated as the quantity of CO_2-C evolved following fumigation divided by an efficiency factor of 0.41 (Voroney and Paul, 1984; Franzluebbers et al., 1999).

Potential N mineralization was calculated from the difference in inorganic N concentration between 0 and 24 days of incubation. Inorganic N (NH_4-N + NO_2-N + NO_3-N) was determined from the filtered extract of a 10-g subsample that was dried (55 ºC for 48 h) and passed through a sieve with openings of 2 mm, shaken with 20 mL of 2 mol L^{-1} KCl for 30 min, and then analyzed using salicylate-nitroprusside and hydrazine autoanalyzer techniques (Bundy and Meisinger, 1994).

Subsamples of whole soil were ground in a ball mill for 5 min and analyzed for total organic C and N using dry combustion at 1350 ºC (Leco CNS-2000, St. Joseph, MI) (Franzluebbers and Stuedemann, 2008).

Particulate organic matter was determined from 50 g of dried soil shaken with 100 mL of 0.1 mol L^{-1} $Na_4P_2O_7$ for 16 h. The soil-solution was passed over a sieve with 0.053 mm openings to collect coarse material on the top of the sieve followed by washing for a minute with a stream of water (Cambardella and Elliott, 1992; Franzluebbers et al., 1999). Samples were dried at 55 ºC for 48 h past visual dryness, weighed, ball milled, and analyzed for C and N concentration with dry combustion.

For all aggregate distribution and stability analyses, soil started from the condition of oven dried (55 ºC) and sieved through 4.75 mm screen. Dry aggregate distribution was determined by weighing a 100 g (0 to 0.1 and 0.1 to 0.2 m depths) portion of soil on top of a nest of sieves (200 mm diameter with openings of 1.0, 0.25 and 0.053 mm) and shaking for 1 min at Level 6 on a CSC Scientific Sieve Shaker (Catalogue no. 18480, CSC Scientific Co., Fairfax, VA). After shaking, soil retained on the 1.0, 0.25 and 0.053 mm screens and what passed through 0.053 mm screen was weighed. Water-stable aggregate fractions were determined from the same reconstituted soil sample used for dry aggregate distribution. Soil was placed on a nest of sieves (17.5

cm diameter with openings of 1.0 and 0.25 mm). Soil was immersed directly in water and the sieves raised and lowered for 10 min (20 mm stroke length, 31 cycles min^{-1}). Then, the two sieves were removed and placed in an oven to dry and water containing soil passing the 0.25 mm sieve was poured over a 0.053 mm sieve. The contents remaining on the top of the sieve were washed with a gentle stream of water, and then were transferred into a drying bottle with a small stream of water. All fractions were oven dried at 55 ºC for 72 h following visual dryness, and then weighed. The fraction 1.0 to 4.75 mm was defined as large macroaggregates. The fraction 0.25 to 1.0 mm was defined as small macroaggregates and the fraction 0.053 to 0.25 mm was defined as microaggregates. Calculation of the mean-weight diameter of dry and water stable aggregates was according to the following equation proposed by Franzluebbers et al. (2000a):

MWD (mm) = [g of 1.0-4.75 mm fraction x 2.875 mm] + [g of 0.25-1.0 mm x 0.625 mm] + [g of 0.053-0.25 mm fraction x 0.1515 mm] + [g of <0.053 mm fraction x 0.0265 mm] / initial mass (100 g) (2)

Stability of mean-weight diameter was calculated as water-stable mean-weight diameter divided by dry-stable mean-weight diameter.

Carbon mineralization from water-stable aggregates classes was determined from 10 to 20 g subsamples (0-0.1 m depth), depending on availability of soil. 25 g subsamples of large macroaggregates (1.0 to 4.75 mm) and small macroaggregates (0.25 to 1.0 mm) were crushed to microaggregate size. Whole aggregates and crushed aggregates were incubated for 24 days to determine C mineralization as described above.

1.3.3 Statistical analyses

The experimental design was a randomized complete block with four replications. Analysis of variance was used to evaluate the effects of crop rotation system and means were compared using least significant difference (LSD) ($p \le 0.1$). All statistical analyses were performed using SAS (SAS Institute, Cary, NC).

1.4 Results

1.4.1 Whole soil

After 11 years of management, cropping rotation under no-till system had little influence on soil properties measured in any of the three soil layers. Total organic C and total N were not different among cropping systems at depths of 0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m, but they were greater at 0 to 0.1 m than at lower depths (Table 3). Soil microbial biomass carbon was affected by cropping system only at depth of 0.2 to 0.4 m. It was greater under cropping system with forage (94.7 mg kg^{-1}) than cropping system with fallow (66.0 mg kg^{-1}), second crop (86.6 mg kg^{-1}) and cover crop (61.6 mg kg^{-1}) (Table 3). Soil microbial biomass C under the second crop (depth of 0.2 to 0.4 m) was 32% and 40% greater than fallow and cover crop, respectively. Depth distribution of soil microbial biomass C was stratified, with declining concentration with increasing soil depth. Mean soil microbial biomass C was 415 mg kg^{-1} at 0-0.1 m, 176 mg kg^{-1} at 0.1-0.3 m, and 77 mg kg^{-1} at 0.2 to 0.4 m.

Table 3. Total organic carbon (TOC), total soil nitrogen (TN) and soil microbial biomass carbon (SMBC) as affected by cropping system at three depths (0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m) at the end of 11 years experiment at Botucatu, São Paulo State, Brazil.

Cropping System (CS)	TOC			TN			SMBC		
	------------------- g kg^{-1}			----------------			------ mg kg^{-1} -----		
	0-0.1 m	0.1-0.2 m	0.2-0.4 m	0-0.1 m	0.1-0.2 m	0.2-0.4 m	0-0.1 m	0.1-0.2 m	0.2-0.4 m
Fallow	14.9	10.9	9.7	1.25	0.94	0.76	502	170	66 c[a]
Second crop	12.9	10.4	9.4	1.14	0.91	0.86	348	191	87 b
Cover crop	12.7	11.6	10.5	1.11	0.92	0.87	378	129	62 c
Forage	13.8	11.6	9.5	1.19	0.95	0.79	430	215	95 a
LSD	2.38	2.01	1.20	0.17	0.09	0.11	165.30	61.95	20.85

[a]Means followed by different letters in the same column are significantly different at $P \leq 0.1$

Particulate organic C, particulate organic N, and potential N mineralization were unaffected by cropping system at all depths (0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m) (Table 4). There was no difference in potential C mineralization under cropping system at depths of 0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m (Figure 1). Despite no difference among treatments, it is noteworthy the cropping system with fallow (251 mg kg^{-1} $[24\ d]^{-1}$) had higher mineralizable C than cropping system with forage (214 mg kg^{-1} $[24\ d]^{-1}$), cover crop (188 mg kg^{-1} $[24\ d]^{-1}$) and second crop (171 mg kg^{-1} $[24\ d]^{-1}$) at the first depth (0 to 0.1 m).

Table 4. Particulate organic carbon (POC), particulate organic nitrogen (PON) and potential nitrogen mineralization (Potential Nmin) as affected by cropping system at three depths (0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m) at the end of 11 years experiment at Botucatu, São Paulo State, Brazil.

Cropping System (CS)	POC			PON			Potential Nmin		
	------------------- g kg^{-1} ----------------						------ mg kg^{-1} [24d]$^{-1}$ -----		
	0-0.1 m	0.1-0.2 m	0.2-0.4 m	0-0.1 m	0.1-0.2 m	0.2-0.4 m	0-0.1 m	0.1-0.2 m	0.2-0.4 m
Fallow	2.0	0.8	0.6	0.11	0.03	0.02	28.2	18.5	14.5
Second crop	1.3	0.7	0.7	0.06	0.03	0.02	23.4	18.9	20.4
Cover crop	1.2	0.6	0.5	0.06	0.02	0.02	22.4	19.5	17.9
Forage	1.7	1.0	0.6	0.09	0.05	0.02	29.3	19.8	16.3
LSD	0.91	0.37	0.25	0.06	0.03	0.007	10.15	7.68	5.02

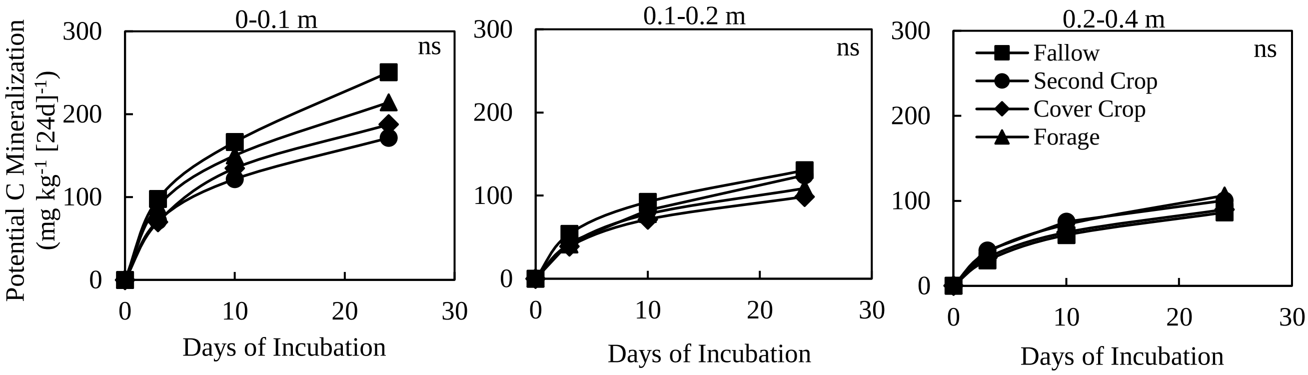

Figure 1. Carbon mineralized in 24 days from whole soil of water-stable aggregates (WSA) as affected by cropping system at three depths (0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m) at the end of 11 years experiment at Botucatu, São Paulo State, Brazil. ns: not significant.

1.4.2 Aggregates

Dry-stable mean weight diameter, water-stable mean weight diameter and stability of mean weight diameter did not vary greatly among cropping system under long-term no-till (Table 5). Dry-stable mean weight diameter was greater than water-stable mean weight diameter at depth 0 to 0.1 m. For the second depth (0.1 to 0.2 m), the difference in dry-stable mean weight diameter was greater than water-stable mean weight diameter (Table 5). Furthermore, the depth of 0 to 0.1 m had greater dry-stable mean weight diameter, water-stable mean weight diameter and stability of mean weight diameter than at the depth of 0.1 to 0.2 m.

Table 5. Dry-stable mean weight diameter (Dry MWD), water-stable mean weight diameter (Water MWD) and stability of mean weight diameter (SMWD) as a function of cropping system at depths of 0 to 0.1 and 0.1 to 0.2 m at the end of 11 years experiment at Botucatu, São State, Brazil.

Cropping System (CS)	**Dry MWD**		**Wet MWD**		**SMWD**	
	---------- mm ----------				mm (wet) mm (dry)$^{-1}$	
	0-0.1 m	0.1-0.2 m	0-0.1 m	0.1-0.2 m	0-0.1 m	0.1-0.2 m
Fallow	1.88	1.75	1.31	0.92	0.70	0.53
Second Crop	1.86	1.80	1.16	0.90	0.62	0.50
Cover Crop	1.77	1.68	1.11	0.82	0.63	0.47
Forage	1.94	1.79	1.24	0.94	0.64	0.52
LSD	0.18	0.26	0.26	0.17	0.14	0.07

The use of different cropping system had no impact on the quantity of total organic C in large macroaggregates, small macroaggregates and microaggregates at depths 0 to 0.1 and 0.1 to 0.2 m (Figure 2). Total organic C in large macroaggregates at depth of 0 to 0.1 m averaged 18 g kg^{-1} and 15 g kg^{-1} at depth of 0.1 to 0.2 m and concentrations were greater than in small macroaggregates (12 g kg^{-1} for 0 to 0.1 m and 10 g kg^{-1} for 0.1 to 0.2 m) and microaggregates (10 g kg^{-1} for 0 to 0.1 m and 9 g kg^{-1} for 0.1 to 0.2 m) at both depths. Overall, Total organic C in aggregates classes was more pronounced at 0 to 0.1 m than at 0.1 to 0.2 m. Just as total organic C in aggregates classes, cropping system did not affect total soil N in large macroaggregates, small macroaggregates and microaggregates and, neither at depths of 0 to 0.1 and 0.1 to 0.2 m (Figure 3).

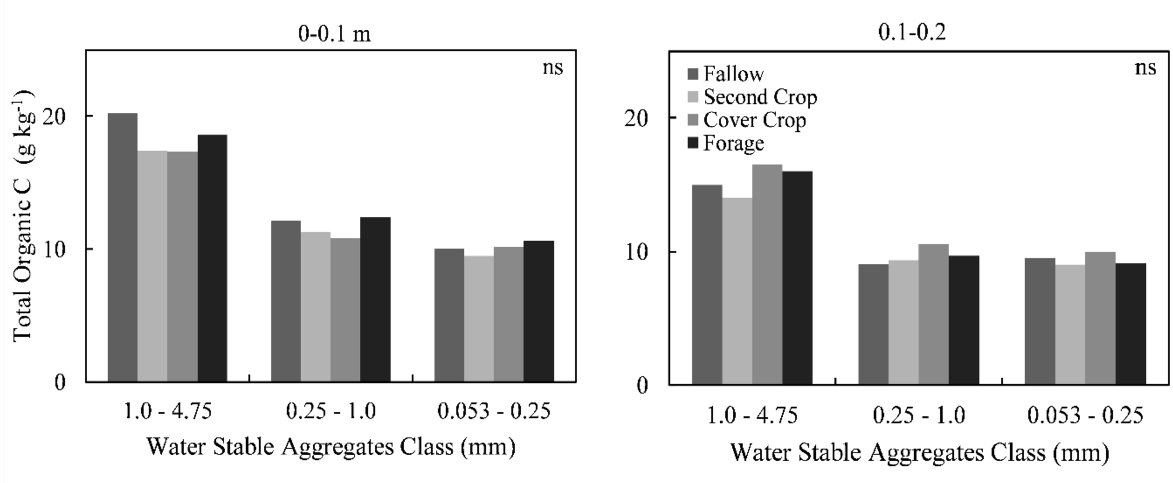

Figure 2. Total organic carbon (TOC) of water-stable aggregates (WSA) classes as affected by cropping system at depths of 0 to 0.1 and 0.1 to 0.2 m at the end of 11 years experiment at Botucatu, São Paulo State, Brazil. ns: not significant.

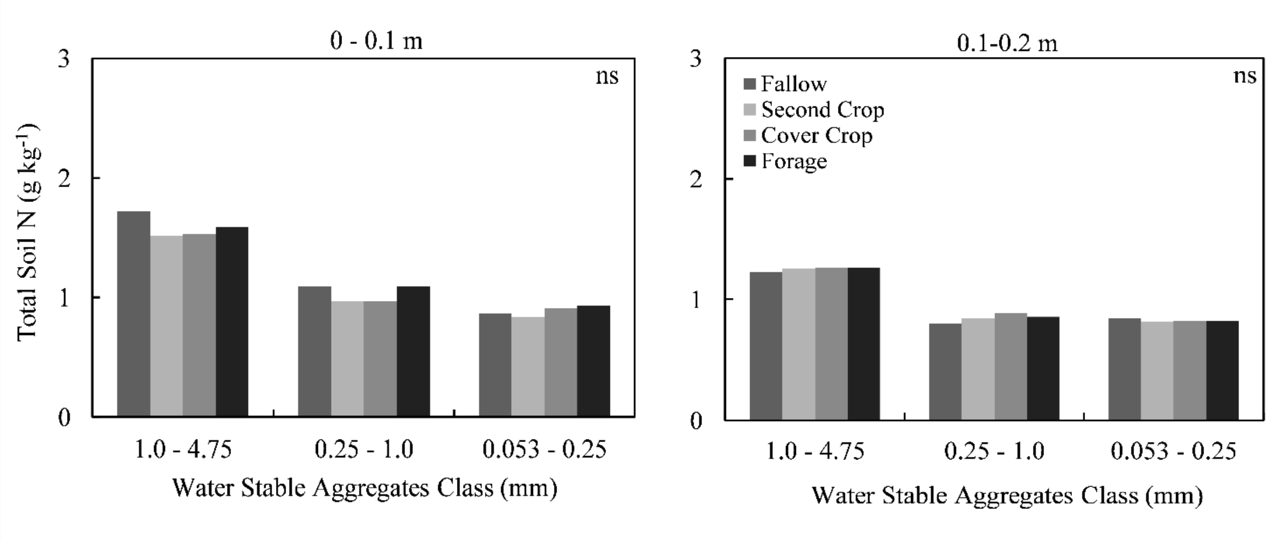

Figure 3. Total soil nitrogen (TN) of water-stable aggregates (WSA) classes as affected by cropping system at depth of 0 to 0.1 and 0.1 to 0.2 m at the end of 11 years experiment at Botucatu, São Paulo State, Brazil. ns: not significant.

Potential C mineralization in water-stable aggregate classes was analyzed only at depth of 0 to 0.1 m. The sum of C mineralized in 24 d from whole soil was lower than the water stable aggregate classes. C mineralization was generally greater in both macroaggregate classes than in microaggregate, regardless if macroaggregates were intact or crushed. However, microaggregates of cropping system with fallow (396 mg kg^{-1} $[24\ d]^{-1}$) had greater C mineralization than intact small macroaggregates (356 mg kg^{-1} $[24\ d]^{-1}$). Crushed large macroaggregate (520 mg kg^{-1} $[24\ d]^{-1}$) had greater mineralizable C than intact large macroaggregate (467 mg kg^{-1} $[24d]^{-1}$) for only cropping system with fallow. On the other hand, cropping system with second crop, cover crop and forage had lower mineralizable C in crushed large macroaggregates than intact large macroaggregate (Figure 4). However, averaged across treatments, mineralizable C in crushed small macroaggregate was 21% greater than in intact small macroaggregate.

Mineralizable C in microaggregate was different among cropping system at 3 days, 10 days and 24 days (Figure 4). Cropping system with fallow was 69% greater at 3 and 10 days and 91% greater at 24 days than cropping system with second crop, cover crop and forage. Despite the large difference in potential C mineralization, there was no difference in total organic C among cropping system in microaggregates (Figure 4).

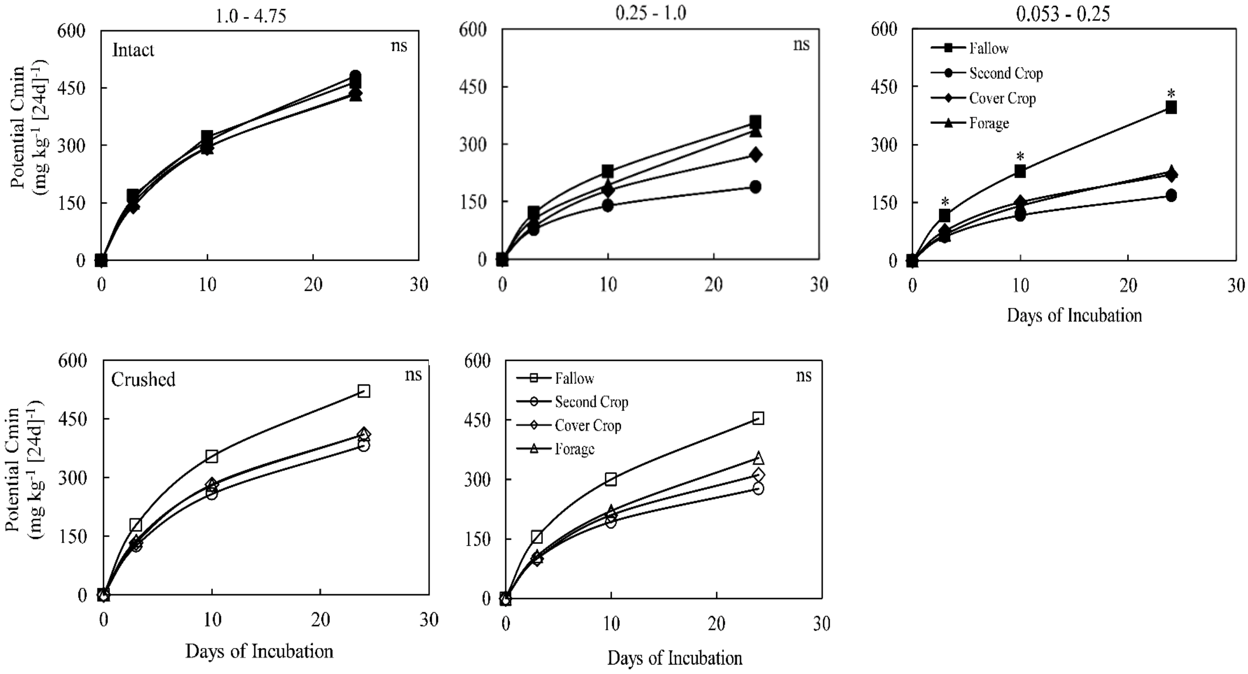

Figure 4. Carbon mineralized in 24 days from intact and crushed large and small macroaggregates of water-stable aggregates (WSA) and intact microaggregates as affected by cropping system at depth of 0 to 0.1 m at the end of 11 years experiment at Botucatu, São Paulo State, Brazil. *Significant at $P \leq 0.1$. ns: not significant.

1.5 Discussion

1.5.1 Whole soil

Concentrations of soil organic C and total soil N changes in long-term depends on cropping management and the quality and quantity of crop residues input (Kong et al., 2005; Franzluebbers et al., 1995a). Contrary to our hypothesis, there was no difference in total organic C and total soil N among cropping system after 11-year experiment at all depths measured (Table 3). In a previous study at the same area developed by Castro et al. (2015), the authors could not observe difference in organic C stock (~11.8 g kg^{-1}) by the crop rotation at depth of 0 to 0.2 m. However, they could notice greater particulate organic C concentrations at depth of 0 to 0.05 m in crop rotation with forage than crop rotation with fallow. The lack of difference in soil organic C suggest a fast turnover of soil organic matter due to the high decomposition under higher moisture and temperature regimes (Six et al., 2002a) associated to adequate amounts of plant residue inputs. The decrease in total organic C with lower depths (Table 3) is consistent with Franzluebbers and Stuedemann (2013). The authors observed differences between soil management only at the first depth (0 to 0.2 m).

The greatest soil microbial biomass C at depth of 0.2 to 0.4 m in the cropping system with forage than other systems (Table 3) suggest a higher input of organic material, such as roots, once *Urochloa* spp. have a deep root system what can reach 1 m deep and they are in continuous activity as these forages have potential to deposit great amounts of biomass (Crusciol et al., 2015). Furthermore, as soil microbial biomass is related to decomposition of organic inputs and they are the most labile C in soils (Moore et al., 2000), changes in soil environment, such as cropping rotation, can influence short-term nutrient availability and microbial activity and growth (Franzluebbers and Stuedemann, 2008). Cenciani et al. (2009) found greater soil microbial biomass C and total organic C in an area with pasture than in tropical forest and fallow. Authors attributed this to different inputs of organic matter quality by the forest and grasses. The decrease of soil microbial biomass C with lower depths was also reported by Franzluebbers and Stuedemann (2008; 2015) due to the lower inputs of organic material at deep layers.

The quality and quantity of plant residues inputs, decomposition rates and soil management are factors that can affect particulate organic matter (Bayer et al., 2002). However, we could not notice difference in particulate organic C and N and potential N mineralization among cropping systems (Table 4), even though the amount of straw during the 11 years of cropping system management with forage was greater than systems with second crop, cover crop and fallow. Moreover, potential N mineralization also changes depending on the accumulation and the decomposition of organic materials on the soil held by soil microbial biomass (Wilson et al., 2001; Franzluebbers et al., 1995b) and it can vary from one season to the next (Bonde and Rosswall, 1987).

Increasing mineralizable C and soil biological activity by forage were reported by Franzluebbers et al. (2000b), but the difference was not significant when we compared four cropping system. The lack of effects in this study might be attributed to adverse weather conditions to grow during the winter season associated to fast decomposition of the straw mainly in spring and summer season.

1.5.2 Aggregates

Deposition of plant residues above ground as well as below ground in a no-till system plays a fundamental role in improving soil aggregation, a factor necessary for soil to remain productive (Franzluebbers et al., 2000b; Six et al., 1998). However, the effect of cropping system was not observed on mean weight diameter (dry and wet sieving) for both depths (0 to 0.1 and 0.1 to 0.2 m) (Table 5). The small difference between values of mean weight diameter when it was analyzed dry than by wet sieving (Table 5) is supported by Sainju (2006). The author observed the difference between sieving in the amount of large macroaggregates (2.00-4.75 mm). According to Kemper and Rosenau (1986), the wetting process in aggregates can be highly disruptive because of the ion hydration and osmotic swelling forces cause a rupture of weak water-stable aggregates.

The aggregate hierarchy concept proposed by Tisdall and Oades (1982) describes that microaggregation is stabilized by organic substances and then, these microaggregates are bound together into macroaggregates by fungal hyphae and microbial by-products. Therefore, to improve soil structure it is fundamentally important to adopt management practices that enhance soil organic matter. The lower concentrations of total organic C in microaggregates than in macroaggregates was also observed by Carmeis Filho et al. (2016) and Elliott (1986).

Greater potential C mineralization from water-stable aggregates than from whole soil is supported by results from Franzluebbers and Arshad (1997). The authors attributed greater potential C mineralization from crushed than intact aggregates as a consequence of removing physical protection when crushed through greater exposure of C substrates to microorganisms. In general, we observed lower mineralizable C in microaggregates than in macroaggregates. Elliot (1986) reported that organic matter associated with macroaggregates (>0.25 mm) was easier mineralized than with microaggregates, because organic matter within microaggregates is a humified recalcitrant fraction.

The effect of cropping system on potential C mineralization within aggregates classes was observed only in microaggregates (0.053-0.25 mm) (Figure 4). Cropping system with fallow had the greatest mineralizable C in microaggregates, even though the total organic C and total soil N concentrations (Figures 2 and 3) were similar to cropping system with second crop, cover crop and forage. Pulleman and Marinissen (2004) evaluated C mineralization of crushed and intact samples of macroaggregates under a permanent pasture (>70 years) and, did not see a significantly increase on C mineralization. Therefore, our study suggests that C stored within microaggregates under second crop, cover crop and forage might be a recalcitrant or ‘stable’ C, since the recalcitrant C comprises the greater proportion of total organic C than labile C (Davidson and Janssens, 2006). Furthermore, soil organic C concentration in aggregates is defined by the amount of organic matter that is dependent on the quality and quantity of plant residues above and below ground (Blanco-Canqui and Lal, 2004). Nevertheless, how the mechanism of organic C protection within aggregate classes is not well understood, mainly inside the microaggregates.

1.6 Conclusions

A cropping system with *Urochloa* forage enhanced soil microbial biomass C at a depth of 0.2-0.4 m compared with fallow, cover crop and second crop. However, in contrast to our hypothesis, there was no difference in C and N contents among the cropping systems, and consequently, soil aggregation was not affect by cropping system. Within aggregate size classes, results of our study suggest that cropping system with second crop, cover crop and forage resulted in more recalcitrant C in microaggregates than in a cropping system with fallow at depth of 0 to 0.1 m.

Few differences in soil structural and biochemical properties among cropping system were observed in this study. The lack of difference might be due to the fast turnover of soil organic matter under tropic conditions and the adverse conditions to maintain soil surface covered during the year. We expected *Urochloa* forage to provide more benefits to soil properties, but the effect was limited to soil microbial biomass at 0.2-0.4 m depth. Summer crop yields have responded positively to *Urochloa* forage and cover crop in the cropping system, so the lack of difference in soil properties was unexpected.

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CHAPTER 2 - CHANGES IN SOIL PHYSICAL PROPERTIES WITH TROPICAL CROPPING SYSTEMS UNDER LONG-TERM NO-TILL CONDITIONS

2.1 Abstract

Sustainability of no-till systems in tropical regions can be compromised by the lack of sufficient residue to cover the soil surface. The type of crop/cover crop during the autumn and dry winter season may play a fundamental role to keep the soil surface covered and avoid bare fallow periods. How these off-season crops/cover crops impact soil physical properties over time have not been comprehensively studied. An experiment in Botucatu, São Paulo State, Brazil on a clayey Rhodic Hapludox soil was conducted from 2007 to 2017 to compare the effects of cropping systems with different winter season species (fallow, second crop, cover crop, and forage crop) and the same summer crop on soil physical properties. Accumulated above-ground biomass, soil bulk density (BD), total porosity (TP), macroporosity (Mac), microporosity (Mic), mean-weight diameter of water-stable aggregates (MWD), geometric-mean diameter (GMD) and aggregate stability index (ASI) were assessed at 5 and 11 years from initiation of the study at depths of 0-0.1, 0.1-0.2, and 0.2-0.4 m. Accumulated above-ground biomass was greater with the use of forage during the winter dry-season than with a second crop or with fallow. Soil bulk density did not change over the years under any of the cropping systems managed with no-till. At the end of 5 years of cropping, macroporosity was greater in the system with forage as winter cover than with fallow, second crop or traditional cover crop at a depth of 0.1-0.2 m. Mean-weight diameter of water-stable aggregates was greater at the end of 11 years than at 5 years across cropping systems at all depths. These data support the use of forage and traditional cover crops during the winter season to stimulate additional biomass production, which was needed to promote improvements in soil physical properties under these tropical conditions.

Key words: winter cover crops, soil structure, *Urochloa*.

2.2 Introduction

Unsustainable agricultural management has been responsible for significant soil degradation that leads to exhaustion of soil functions (Franzluebbers et al., 2006). The extent of soil health decline depends on the gravity and type of soil degradation, but operating costs often rise to maintain fertility or production remains low and stagnant without sufficient costly inputs (Gomiero, 2016). Continuous soil disturbance, low carbon inputs via plant residues, and an uncovered soil surface are practices leading to soil degradation (Franzluebbers and Gastal, 2019). Conservation management with a no-till system is the most important agricultural practice to rebuild and maintain soil productivity (Bruce et al., 1995) and minimize soil erosion (Lal, 2007) in highly weathered soils. However, negative impacts of no-till on soil physical properties have been found in some situations, such as an increase in bulk density (Martínez et al., 2008; Zuber et al., 2015), evidence of soil compaction (Munkholm et al., 2013; Moraes et al., 2014), and low oxygen diffusion rates (Russell, 1988). Equally important, long-term no-till systems often leads to more stable aggregates and greater total porosity in surface soil due to greater soil organic carbon concentration (Busari et al., 2015), all of which helps control soil erosion (Blanco-Canqui and Ruis, 2018) compared with conventionally tilled systems.

A successful no-till system demands an appropriate crop rotation and soil surface that remains covered with crop residues throughout the year (Derpsch et al., 2014). In a no-till system with large above and below ground crop residue inputs, soil structure is improved, particularly as measured by soil aggregation (Tisdall and Oades, 1982). Soil aggregation plays a fundamental role to keep soil productive, since it allows water to infiltrate rather than runoff, and avoids soil erosion (Franzluebbers et al., 2000). Crop residues are a source of energy for the development of soil biological activity, which releases polysaccharides and proteins effective for improving soil aggregation (Oades, 1984; Briedis et al., 2012a). Soil physical properties, such as water infiltration, pore size distribution and soil aggregation, can be influenced by the type of crop species due to differences in rooting patterns, and the quantity and quality of above and below ground biomass (Blanco-Canqui et al., 2010). Moreover, the nature of organic inputs may affect aggregate stability (Abiven et al., 2009).

In the tropics with high temperature and abundant moisture, grain crop residues in simple cropping systems decompose fast even under no-till systems (Crusciol et al., 2008; Castro et al., 2017). Particularly in the Brazilian Cerrado with low autumn/winter precipitation, off-season production of second crops and cover crops can be risky (Costa et al., 2016) leading to fallow periods. Long periods of winter fallow can enhance weed infestation, leading to reduced main-season crop productivity and potential allelopathy (Jabran et al., 2015). Biomass produced by weeds are usually insufficient to cover the soil surface (Miguel et al., 2018), and no income is produced during this period (Balbinot Junior et al., 2011). Hence, soil exposure with the lack of plant residue cover results in poor aggregation, low organic matter, crusting of soil surface, enhanced soil erosion, and low plant-water availability (Franzluebbers, 2002a). With this in mind, introduction of secondary grain crops or cover crops would be hypothesized to enhance soil organic carbon, and as a consequence, improve soil physical properties to enhance crop establishment and production (Blanco-Canqui and Ruis, 2018).

The type of crop species may affect soil structure differently because of different rooting patterns and organic inputs (Ball et al., 2005). Deep-rooted cover crops (i.e. brassicas) can break through compacted soil layers (Rosolem et al., 2002) and increase water infiltration under no-till (Blanco-canqui et al., 2011). Villamil et al. (2006) reported an increase in soil aggregate stability, total porosity, and water availability with winter cover crops of hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) in a no-till corn (*Zea mays*)-soybean (*Glycine max*) rotation on a silt loam in Illinois. In contrast, on a silt loam in North Dakota, Liebig et al. (2004) found no difference in soil bulk density among cropping systems with continuous spring wheat, spring wheat-millet, spring wheat-sunflower-fallow, spring wheat-sunflower-rye, and spring wheat-fallow. In recent years, the tropical forage *Urochloa* has been introduced into Cerrado cropping systems to provide livestock feed during the off-season and/or to produce plant residues for the following crop (Crusciol et al., 2015; Tanaka et al., 2019). Various tropical forages have been shown to impart positive effects on soil properties (Costa et al., 2015).

The impacts of soil management with different tillage systems on soil physical attributes have been well investigated (Liebig et al., 2004; Alvarez and Steinbach, 2009; Blanco-Canqui et al., 2017). However, only a few studies have assessed changes in soil physical properties with different cropping systems under tropical climate conditions. Long-term experiments are essential for accurately assessing changes in soil physical properties as affected by cropping systems, since crops do not disturb soil like tillage tools (Benjamin et al., 2007). Therefore, the objective of this study was to determine how the choice of winter crop/cover crop impacts soil physical properties under a long-term no-till system.

2.3 Materials and methods

2.3.1 Site characteristics and management

The experiment was located in Botucatu, São Paulo State, Brazil (48°23’ W, 22°51’ S; 765 m above sea level) on a clayey Rhodic Hapludox (USDA Taxonomy) with 440 g kg^{-1} of clay, 469 g kg^{-1} of sand, and 91 g kg^{-1} of silt at a depth of 0 to 0.20 m. According to Köeppen's classification the climate is Cwa, with dry winters and wet, rainy summers. Mean monthly rainfall, maximum and minimum temperatures from 2007 to 2017 are reported in Table 1. Prior to establishing the experiment in 2006, the field experiment was managed with soybean (*Glycine max*) in the summer and black oat (*Avena strigose* Schreb.) in the autumn/winter under no-till for four years. At the time of experiment initiation, chemical and physical properties were determined (0-0.2 m), according to methodology proposed by van Raij et al. (2001) [organic matter = 18 g dm^{-3}; pH = 4.2 (1:2.5 soil/$CaCl_2$ suspension 0.01 mol L^{-1}); P resin = 4 mg dm^{-3}; exchangeable K = 0.8 $mmol_c$ dm^{-3}, Ca = 12 $mmol_c$ dm^{-3}, Mg = 6 $mmol_c$ dm^{-3}; total acidity at pH 7.0 (H+Al) = 54 $mmol_c$ dm^{-3}; base saturation = 24%] and Embrapa (1997) and Kiehl (1979) [soil bulk density = 1.40 Mg m^{-3}; total porosity = 0.39 m^3 m^{-3}; microporosity = 0.32 m^3 m^{-3}; macroporosity = 0.07 m^3 m^{-3}, mean weight diameter = 2.9 mm; geometric mean diameter = 2.8 mm; aggregate stability index = 99%], respectively.

Table 1. Mean monthly rainfall and maximum and minimum temperatures from 2007 to 2017 at Botucatu, São Paulo State, Brazil.

Climate characteristics	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
	Long-term (50 yr) avg.											
Monthly rainfall (mm)	370	174	137	94	83	73	58	37	69	131	140	237
Mean max. temp. (ºC)	28.9	29.7	28.1	27.0	23.9	22.5	23.6	25.9	27.1	27.8	27.7	28.9
Mean min. temp. (ºC)	18.5	19.2	18.0	16.5	14.4	12.7	12.6	13.4	14.5	15.9	16.9	18.3

The field experiment was arranged in a randomized complete block design with four replications of four cropping systems having different treatments during the winter season (fallow, second crop, cover crop, and forage crop) and consistent summer crop from 2007 to 2017 (Table 2). Grain crop choices were according to majority of cultivated land in the State of São Paulo and in Cerrado region. Cropping system with fallow (System I) was left unseeded and volunteer vegetation was allowed during the winter season. In System II with second crop, common oat (*Avena sativa* L.), common bean (*Phaseolus vulgaris* L.), castor bean (*Ricinus communis* L.), sorghum grain [*Sorghum bicolor* (L.) Moench], crambe (*Crambe abyssinica* Hochst. Ex R.E. Fr.), wheat (*Triticum aestivum*) and triticale (*X. triticosecale Wittmack*) were grown in different years and harvested for grain when possible. In System III with cover crop, pearl millet (*Pennisetum glaucum* L.), pigeon pea [*Cajanus cajan* (L.) Huth], sunn hemp (*Crotalaria juncea* L.), lupin bean (*Lupinus albus* L.) and common oat were cropped in different years and not harvested, but left for surface mulch. The fourth cropping system was with forage ruzi grass (*Urochloa ruziziensis*) and palisadegrass (*Urochloa brizantha*). In summer, soybean (*Glycine max*), corn (*Zea mays*), common bean and rice (*Oriza sativa*) were sown in November and harvested between March to April. After the summer harvest, winter crops were sown without fertilizer. It is noteworthy that it was not possible to grow any crop/cover crop in winter season 2014 due to insufficient rainfall. In 2016, the second crop did not grow because of the drought during this season. Each plot covered an area of 54 m^2 (5.4 m x 10 m).

Table 2. Crop rotation scheme in Systems I, II, III and IV from 2006 to 2016, Botucatu, São Paulo State, Brazil.

	System I (Fallow)	System II (Second crop)	System III (Cover crop)	System IV (Forage)
		------ **2006** ------		
Winter	-	-	-	-
Summer	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
		------ **2007** ------		
Winter	Fallow	*Avena sativa*	*Pennisetum glaucum*	*U. ruziziensis*
Summer	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
		------ **2008** ------		
Winter	Fallow	*Phaseolus vulgaris*	*Cajanus cajan*	*U. ruziziensis*
Summer	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*
		------ **2009** ------		
Winter	Fallow	*Ricinus communis*	*Crotalaria juncea*	*U. ruziziensis*
Summer	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
		------ **2010** ------		
Winter	Fallow	*Sorghum bicolor*	*Pennisetum glaucum*	*U. ruziziensis*
Summer	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
		------ **2011** ------		
Winter	Fallow	*Crambe abyssinica*	*Lupinus albus*	*U. ruziziensis*
Summer	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*
		------ **2012** ------		
Winter	Fallow	*Triticum aestivum*	*Pennisetum glaucum*	*U. brizantha*
Summer	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*
		------ **2013** ------		
Winter	Fallow	*Triticum aestivum*	*Crotalaria juncea*	*U. brizantha*
Summer	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
		------ **2014** ------		

Winter	-	-	-	-
Summer	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
		2015		
Winter	Fallow	*X. triticosecale*	*Avena sativa*	*U. brizantha*
Summer	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*
		2016		
Winter	Fallow	-	*Pennisetum glaucum*	*U. brizantha*
Summer	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*

Over the 11 years of this experiment, dolomitic lime was applied in October 2006 (before sowing the first crop), October 2011 and October 2015. Dolomitic lime rate (LR) was calculated by the method of base saturation (BS) proposed by van Raij et al. (1997), which used a calculation to increase base saturation to 70%:

$$\text{LR (Mg ha}^{-1}\text{)} = (BS_2 - BS_1) \times CEC / (ECCE \times 10) \quad (1)$$

Where, BS_2 is the target base saturation (70%), BS_1 is the base saturation determined by the soil chemical analysis, CEC is cation exchange capacity, and ECCE is the effective calcium carbonate equivalent of the dolomite lime. Adequate rates of NPK fertilizers were applied for summer crops according to soil chemical analyses conducted each year.

2.3.2. Plant and soil sampling and analyses

Biomass of winter and summer crops were generally determined by sampling 10 plants at flowering. However, fallow and forage crop biomass were taken before planting the summer crop in the following crop year. From three random locations along a diagonal within each plot, biomass was cut at ground level (0.25 m^2 each), according to Crusciol et al. (2005). Biomass samples were dried by forced-air circulation at 65 °C for 72 h until constant weight and weighed.

Undisturbed soil samples were collected in October 2011 and in May 2017 using a 5 cm tall core cylinder with 4.8 cm internal diameter to determine soil bulk density, total porosity, macroporosity and microporosity. Two undisturbed soil cores were sampled at depths of 0 to 0.1, 0.1 to 0.2, and 0.2 to 0.4 m from trenches (~0.5 m wide, 0.6 m long, and 0.6 m deep) dug in each plot. After extraction, cores were trimmed smoothly at the ends and sealed with a plastic lid to prevent damage during transport. Cores were placed into plastic trays with water up to two-thirds of the cylinder height to saturate core samples. To avoid soil loss, the bottom of each core was wrapped with polyester fabric. Upon 48 h of wetting, cores were weighted to determine saturated mass. Cores were placed on a tension table (Dane and Hopmans, 2002) and subjected to -6 kPa. Upon equilibration 40-72 h later, a second wet mass was recorded. Dry soil mass was determined afterwards in a forced-air oven at 105°C for 48 h.

Bulk density was calculated by dividing the dry soil mass by the volume of the soil cylinder collected. Total soil porosity was assumed equivalent to the measured saturated volumetric water content. Microporosity was calculated as the difference between mass at -6 kPa and oven-dried mass. Macroporosity was calculated as the difference between total porosity and microporosity (de Camargo et al., 2009).

Water-stable aggregates were determined from an undisturbed soil monolith dried in a forced-air oven at 50 °C until constant weight. Soil retained on a 4-mm sieve after passed through 8-mm sieve was used. A 25-g aliquot of the retained dried aggregate fraction was pre-wetted (with a spray bottle) and subjected to a wet-sieving procedure for 15 min using nested sieves with 4, 2, 1, 0.5, 0.25, and 0.105-mm openings linked to mechanical equipment adjusted to 30 vertical oscillations min^{-1} (Yoder, 1936). Soil retained on each sieve was transferred to aluminum dishes, dried in a forced-air oven at 105 °C for 48 h, and weighed. Aggregate stability index, mean weight diameter, and geometric mean diameter were calculated based on equations below proposed by Kemper and Chepil (1965):

$$ASI\% = [(y_i - z_i)/ y_i] \times 100 \quad (2)$$

$$MWD = \sum_{i = 1,\ n}(x_i . w_i) \quad (3)$$

$$GMD = exp\ [(\sum w_i \ln x_i)/ (\sum w_i)] \quad (4)$$

Where y_i is the weight of dry soil sample, z_i is the weight of aggregates <0.25 mm, x_i is the mean diameter of the size class (mm), and w_i is the weight of the aggregates of each size class.

2.3.3. Statistical Analyses

The experimental design was a randomized complete block with four replications. Analysis of variance was used to evaluate the effects of crop rotation system and means were compared using least significant difference (LSD) ($p \leq 0.1$). All statistical analyses were performed using SAS (SAS Institute, Cary, NC).

2.4. Results

2.4.1 Accumulated above-ground biomass, soil bulk density and soil porosity

Accumulated above-ground biomass was greater in the cropping system with winter forage, regardless of the period (Table 3). Cropping system with fallow and second crop had lowest above-ground biomass inputs. In general, above-ground biomass production varied by cropping system: forage > cover crop > second crop = fallow.

At the end of five years (2011), soil bulk density and macroporosity were influenced by cropping system at 0.1-0.2-m depth, but not at other depths (Table 4). Soil bulk density was lower in the cropping system with forage (1.38 Mg m^{-3}) than with fallow (1.42 Mg m^{-3}), second crop (1.45 Mg m^{-3}) and cover crop (1.46 Mg m^{-3}). Macroporosity was greater in the cropping system with forage than all other cropping systems. No cropping system effects were detected at other soil depths for bulk density and macroporosity and at any depth for microporosity and total porosity.

At the end of 11 years (2017), microporosity was influenced by cropping system at all three soils layers and macroporosity was affected at 0.1-0.2-m and 0.2-0.4-m depths (Table 4). At all three soil layers, microporosity was lower in the cropping system with cover crop than with fallow, second crop, and forage. This effect was counteracted with greater macroporosity in the cropping system with cover crop than with fallow, second crop and forage at 0.1-0.2-m and 0.2-0.4-m depths. Total porosity and bulk density were not affected by cropping system at any soil depth.

Soil bulk density at the beginning of the experiment (1.40 Mg m^{-3} at depth of 0 to 0.2 m) did not change over the course of this experiment (1.40 Mg m^{-3} at 5 years and 1.40 Mg m^{-3} at 11 years when averaged across treatments and two depths). As an average across cropping systems, macroporosity increased at all three soils layers from 5 to 11 years. The change was 50% at 0-0.1-m depth, 60% at 0.1-0.2-m depth, and 80% at 0.2-0.4-m depth (Table 4). Consequently, microporosity declined from 2011 to 2017 by 6, 9, and 19% at depths of 0-0.1, 0.1-0.2, and 0.2-0.4 m, respectively.

Table 3. Accumulated above-ground biomass production in period 1 (1-5 years) and period 2 (6-11 years) as a function of cropping management at Botucatu, São Paulo State, Brazil.

Cropping System	Period 1 (1-5 years)	Period 2 (6-11 years)
	-------------- Mg ha^{-1}	----------------
Fallow	54.6 d*	45.1 c
Second crop	58.9 c	37.3 d
Cover crop	68.4 b	56.3 b
Forage	75.5 a	64.4 a
LSD	3.90	3.47

*Values followed by the same letter are not significantly different ($p \leq 0.1$).

Table 4. Bulk density (BD), total porosity (TP), microporosity (Mic) and macroporosity (Mac) as a function of cropping system at depths of 0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m after five and 11 years of cropping management at Botucatu, São Paulo State, Brazil.

Cropping System	2011				2017			
	BD	TP	Mic	Mac	BD	TP	Mic	Mac
	Mg m^{-3}	----- cm^3 cm^{-3} -----			Mg m^{-3}	----- cm^3 cm^{-3} -----		
	0 - 0.1 m							
Fallow	1.40	0.34	0.26	0.08	1.33	0.45	0.33 a*	0.12
Second crop	1.37	0.43	0.35	0.07	1.37	0.42	0.31 a	0.11
Cover crop	1.40	0.40	0.34	0.07	1.34	0.44	0.27 b	0.18
Forage	1.33	0.42	0.35	0.08	1.41	0.41	0.33 a	0.08
LSD	0.09	0.10	0.11	0.04	0.10	0.04	0.04	0.07
	0.1 - 0.2 m							
Fallow	1.42 a	0.38	0.34	0.04 b	1.44	0.40	0.33 a	0.07 b
Second crop	1.45 a	0.39	0.35	0.05 b	1.44	0.40	0.31 a	0.08 b
Cover crop	1.46 a	0.37	0.33	0.04 b	1.42	0.40	0.26 b	0.13 a
Forage	1.38 b	0.39	0.32	0.07 a	1.48	0.38	0.32 a	0.05 b
LSD	0.05	0.03	0.03	0.02	0.07	0.02	0.02	0.04
	0.2 - 0.4 m							
Fallow	1.39	0.42	0.36	0.06	1.38	0.42	0.34 a	0.08 b
Second crop	1.40	0.44	0.38	0.06	1.38	0.41	0.32 a	0.09 b
Cover crop	1.34	0.45	0.40	0.05	1.34	0.42	0.27 b	0.14 a
Forage	1.35	0.42	0.38	0.04	1.39	0.40	0.33 a	0.06 b
LSD	0.07	0.03	0.03	0.01	0.06	0.02	0.02	0.02

*Values followed by the same letter are not significantly different ($p \leq 0.1$).

2.4.2 Mean-weight diameter, geometric-mean diameter and aggregate stability index

At the end of 5 years, mean-weight diameter of water-stable aggregation at 0-0.1-m depth in cropping systems with second crop (2.16 mm) and forage (1.95 mm) was greater than with fallow (1.75 mm) and cover crop (1.38 mm) (Table 5). Geometric-mean diameter followed the same pattern as mean-weight diameter. At depth of 0.1-0.2 m, mean-weight diameter of water-stable aggregates and geometric-mean diameter were also greater in the cropping system with forage than with fallow, second crop, and cover crop. Below 0.2 m, no differences due to cropping system occurred in all aggregation responses. Aggregate stability index was not affected by cropping system at any soil depth.

At the end of 11 years, mean-weight diameter of water-stable aggregates at 0-0.1-m depth was greater in cropping systems with fallow (3.60 mm) and forage (3.56 mm) than with second crop (2.80 mm) and cover crop (3.03 mm) (Table 5). Geometric-mean diameter was also greater in cropping systems with fallow and forage than with second crop and cover crop at the upper depth. Cropping system effects were not significant for any aggregation response at deeper layers. Aggregate stability index was not affected by cropping system at any soil depth.

Averaged across cropping systems, mean-weight diameter of water stable aggregates increased 80, 86, and 98% from 5 to 11 years at depths of 0-0.1, 0.1-0.2, and 0.2-0.4 m, respectively. Geometric-mean diameter also increased 72, 61, and 63% from 5 to 11 years at depths of 0-0.1, 0.1-0.2, and 0.2-0.4 m, respectively. Aggregate stability index in 2011 (82-86%) and 2017 (85-90%) were lower than at initiation (99%).

Table 5. Mean-weight diameter (MWD), geometric-mean diameter (GMD) and aggregate stability index (ASI) as a function of cropping system at depths of 0 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m after five and 11 years of cropping management at Botucatu, São Paulo State, Brazil.

Cropping System	2011			2017		
	MWD	GMD	ASI	MWD	GMD	ASI
	----- mm -----		%	----- mm -----		%
	------------------------ 0 – 0.1 m --------------------					
Fallow	1.75 b*	1.11 b	84	3.60 a	2.44 a	92
Second crop	2.16 a	1.43 a	87	2.80 b	1.50 b	87
Cover crop	1.38 b	0.85 b	84	3.03 b	1.76 b	89
Forage	1.95 a	1.31 a	89	3.56 a	2.40 a	92
LSD	0.38	0.33	4.59	0.61	0.70	4.02
	----------------------- 0.1 – 0.2 m ---------------------					
Fallow	1.28 b	0.75 b	81	2.31	1.21	86
Second crop	1.00 b	0.62 b	81	2.33	1.16	86
Cover crop	1.09 b	0.67 b	83	2.15	1.13	85
Forage	1.63 a	0.98 a	85	2.48	1.36	87
LSD	0.26	0.14	4.95	0.33	0.23	2.62
	---------------------- 0.2 – 0.4 m ---------------------					
Fallow	1.13	0.75	86	1.95	1.11	84
Second crop	1.17	0.79	79	2.17	1.15	88
Cover crop	0.98	0.63	83	2.31	1.37	86
Forage	0.91	0.61	86	1.87	0.92	83
LSD	0.52	0.41	7.92	0.53	0.43	4.09

*Values followed by the same letter are not significantly different ($p \leq 0.1$).

2.5 Discussion

2.5.1 Accumulated above-ground biomass, soil bulk density and soil porosity

Greater accumulation of above-ground biomass in the cropping system with forage was expected (Table 3) as *Urochloa* species have the potential for large production [e.g. 6-10 Mg ha^{-1} (Crusciol and Soratto, 2007; Menezes et al., 2009; Simidu et al., 2010; Pacheco et al. 2013; Tanaka et al. 2019)]. Plants with vigorous root systems can minimize the effects of soil compaction by reducing bulk density (Williams and Weil, 2004). In this sense, the introduction of forage (*Urochloa* spp.) into the cropping system alleviated soil bulk density and enhanced macroporosity at 0.1-0.2-m depth early in this study (Table 4). Lal et al. (1978) also reported lower soil bulk density under cover crops (grasses and legumes) than under weed fallow at depths of 0-0.1 and 0.1-0.2 m in a no-till system. However, Cunha et al. (2007) found no difference in soil bulk density with inclusion of forage into the cropping system.

Cropping system with cover crop had lower microporosity and greater macroporosity than cropping systems with fallow, second crop and forage at all three depths (Table 4). According to Rosolem et al. (2002), cover crops such as *Pennisetum glaucum* L. and *Sorghum bicolor* L. have the potential to improve soil properties, since cover crops have great root length density that allow them to grow in compacted soil and create biopores into deeper soil layers. Additionally, the assemblage of diversified plants species over time in this study could have had a positive impact on soil physical properties (Gould et al., 2016).

Depending on the climate, soil type, and length of time of no-till management, untilled soil may be oxygen limited compared with tilled soil (Russell, 1988) due to an increase in soil bulk density and overall compaction (Martinez et al., 2008). According to Stone and Silveira (2001), it is possible to observe an increase in soil bulk density and microporosity and a decrease on macroporosity and total porosity compared to conventional soil management during the first 3-4 years after implementation of a no-till system, due to farm equipment traffic. However, our results indicate that soil bulk density did not vary from 2006 to 2017 at depth of 0 to 0.2 m. Blanco-Canqui and Ruis (2018) analyzed 62 studies on soil bulk density under no-till system for the past 10 years, and there was no effect on soil bulk density in 24 of these studies and there was a significantly negative effect in 12 studies. It is equally possible that a diversity of plants species over time with cover cropping could enhance soil organic matter, which could increase macroporosity and decrease microporosity under long-term no-till system.

Although a critical soil bulk density value has not yet been established, Camargo and Alleoni (1997) considered 1.6 Mg m^{-3} as a critical value for soil bulk density for a range of sandy to clay soils. In contrast, restrictions on root system growth with soil bulk density greater than 1.2 Mg m^{-3} in Oxisols was reported by De Maria et al. (1999). Reeves et al. (1984) observed lower wheat root growth in soil with bulk density of 1.52 Mg m^{-3} than with 1.32 Mg m^{-3} in depth of 0-0.2 m. Macroporosity (0.10-0.16 m^3 m^{-3}), microporosity (>0.33 m^3 m^{-3}) and total porosity (~0.59 m^3 m^{-3}) in this study were at the adequate range for plant cultivation based on literature (Baver et al., 1972; Kiehl, 1979). Therefore, the choice of cover crops/grain crops with expansive root systems would be ideal to improve soil physical properties, since low resistance pathways (biopores) by cover crop roots have been shown to benefit the root system of the following crop (Cresswell and Kirkegaard, 1995). Moreover, a larger soil water retention capacity can be achieved with an enhancement of total pore space (Franzluebbers, 2002).

2.5.2 Mean-weight diameter, geometric-mean diameter and aggregate stability index

The effect of cropping system on soil aggregation occurred mostly in the upper soil layers (Table 5), since the soil surface is where there is the greatest root concentration and plant residue accumulation (Franzluebbers, 2002). Additionally, large quantities of organic compounds are produced by plant residues and developing plant roots that promote soil microbial biomass, and as a consequence of their activity, they produce polysaccharides that increase soil aggregation (Briedis et al., 2012b). Thus, with better soil aggregation, other improvements in soil physical properties (i.e. soil bulk density, porosity, aeration and soil water-holding capacity) can develop (Tisdall and Oades, 1982).

Forages can improve soil aggregation due to their vigorous and dense root systems (Salton et al., 2008) and potential for large above-ground biomass inputs (Table 3) (Marchão et al., 2007). Further, forage species such as *Urochloa* have an aggressive root system that can penetrate more than 1 m deep (Pacheco et al., 2011; Nascente and Crusciol, 2012), thereby improving soil physical properties and biological activity (Crusciol et al., 2014). Furthermore, increases in soil organic matter with above- and below-ground biomass production can play an important role in soil aggregation (Anders et al., 2012). In fact, improved soil aggregation in the cropping system with forage was observed at depths of 0-0.1 and 0.1-0.2 m after five years of cropping management (Table 5). After 11 years of cropping management, growing forage during the autumn/winter season continued its positive effect on soil aggregation. Garcia et al. (2013) observed an improvement in soil aggregates (> 2 mm) by forage (*Urochloa* sp.), pearl millet (*P. glaucum* L.) and sorghum (*Sorghum* sp.) due to enhancement of biomass inputs. In addition, Liu et al. (2005) reported an increase in soil aggregate stability under non-leguminous cover crops in intensively cultivated soils.

The impact of cropping systems on soil physical properties may not have been affected at all depths (Table 4 and 5) because distribution of effects is not nearly as dramatic as soil tillage, and effects on soil physical properties are not as dynamic as on soil fertility (Blanco-Canqui et al., 2010). Benjamin et al. (2007) studied three cropping systems [(i) wheat/corn/fallow; (ii) wheat/corn/sunflower; and (iii) wheat/corn/millet] under no-till on a silt loam soil after 15 years of management and found no difference in soil bulk density, pore size distribution, and soil water retention. Moreover, after 33 years of cropping management (sorghum/fallow, continuous sorghum, wheat/sorghum/fallow, wheat/fallow, and continuous wheat) under no-till, Blanco-Canqui et al. (2010) reported that the most significant changes in soil physical properties occurred near the soil surface. The authors related these improvements in soil properties to continuous cropping systems, in which crop residue input was greater than in crop-fallow systems. Despite our results show only a few differences among cropping systems, it is noteworthy that improvement of soil physical properties did actually occur under no-till over the years (Table 4 and 5).

2.6 Conclusions

Cropping systems with forage and cover crop accumulated large amounts of above-ground biomass over the years in this study. Both above- and below-ground inputs were considered important in affecting change in soil physical properties. A diversity of cover crops over the 11 years of management may have imparted different rooting patterns that influenced microporosity at all depths and macroporosity at depths of 0.1-0.2 and 0.2-0.4 m. Despite the cover crop sytem produced great quantity of biomass, it did not affect soil aggregation. In contrast, cropping system with forage produced the highest amount of above-ground biomass and improved soil aggregation at depth of 0-0.1 and 0.1-0.2 m at the end of 5 years, and only at the first depth at the end of 11 years. Soil bulk density did not change over time in this no-till system. Significantly, there were a few improvements in soil physical properties with the introduction of forage and cover crops into the cropping system. In conclusion, growing forage or cover crops during the autumn/winter season are beneficial to soil physical properties and are great choices to avoid fallow periods under tropical conditions.

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CHAPTER 3 - TROPICAL CROPPING SYSTEM IMPACTS ON SOIL FERTILITY UNDER LONG-TERM NO-TILL MANAGEMENT

3.1 Abstract

Extended periods of fallow during autumn/winter in tropical climate regions are compromising the sustainability of no-till management systems. Growing a second crop/cover crop is an alternative to keep the soil surface covered and avoid bare fallow periods. Inclusion of these plants may alter soil properties and nutrient cycling, thereby influencing soil fertility and summer grain yield over time. This study aimed to evaluate the long-term effect of winter crops/cover crops on soil nutrient levels and grain yield of summer crops. The experiment was stablished in 2006, on a clayey Rhodic Hapludox to compare the effects of cropping systems with different winter season species (fallow, second crop, cover crop, and forage crop) and the same summer crop (soybean) on soil fertility. Soil pH, soil organic matter, phosphorus (P), exchangeable potassium (K), calcium (Ca) and magnesium (Mg), and base saturation were assessed at 4 and 9 years from initiation of the study at depths of 0-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.4, and 0.4-0.6 m. Long-term no-tillage created nutrient stratification in the soil profile. Growing forage during the off-season improved soil organic matter concentration at 4 years of cropping management. At 9 years of cropping management, the system with fallow had greater levels of P, Ca, Mg and base saturation in the surface 0.2 m compared with other winter management systems. These data suggest low extraction of nutrients by the weedy vegetation. Despite greater soil nutrient concentrations with fallow, grain yield of summer crops was lower than with second crop, cover crop, and forage crop. The autumn/winter forage crop is a recommended improvement for enhancing soil organic matter and summer crop yield over time.

Key words: Nutrients budget. Winter crop. Winter cover crops. Crop rotation.

3.2 Introduction

To feed a world population of almost 10 billion people in 2050 implies the need to double food production and prevent environmental degradation (FAO, 2019). Conservation agricultural practices, such as using no-till management, often lead to an increase in crop production and preservation of natural resources. Diversification through crop rotation and crop residue on the soil surface is a key component of a successful no-till system (Derpsch et al., 2014). However, no-till systems have been hindered in regions with dry winters and hot and rainy summers, such as the Brazilian Cerrado, because of low plant biomass production during the winter and fast decomposition of crop residues (Costa et al., 2016). As a consequence, volunteer vegetation grows in these uncovered soils leading to weed establishment and proliferation (Borghi et al., 2008), and eventually to soil degradation (McGuire et al., 1998).

Replacing bare fallow periods with a cover crop can increase land profitability and sustainability (Holman et al., 2018). The inclusion of a cover crop in a no-till system can lead to improved soil quality by stimulating soil microbial activity and increasing soil organic matter content (Franzluebbers et al., 2014; Mbuthia et al., 2015), promoting nutrient cycling (Assmann et al., 2017), reducing chemical inputs (Fageria et al., 2005), improving soil physical properties (Calonego et al., 2017), and enhancing the yield of following crops (Costa et al., 2016). *Urochloa* grasses are well-suited for the tropical region with dry winters because these grasses have vigorous and deep roots, high tolerance to water deficit stress (Fisher and Kerridge, 1998; Gichangi et al., 2017), high biomass production potential, and efficiency in nutrient cycling (Momesso, et al., 2019). Moreover, these grasses can be cut for cattle fodder or grazed, as well as to protect soil resources, all of which lead to greater food production without expanding to new cropping areas (Borghi and Crusciol, 2007; Pacheco et al., 2011; Crusciol et al., 2014).

Choice of cover crop species can play a fundamental role in soil fertility. Legume cover crops generally have greater uptake of Ca, Mg and K (Li et al., 2013). Nitrogen-fixing legumes are capable of fixing more than 200 kg N ha^{-1} (Calegari et al., 2008). Phosphorus dynamics also can change with cultivation of different plant species (Horst et al., 2003). According to Rheinheimer and Anghinoni (2003), a cropping system of oat (*Avena strigosa* Schreb)/corn (*Zea mays*) had lower level of organic P than a cropping system of oat + vetch (*Vicia* sp.)/corn + cowpea (*Vigna unguiculata*) and cropping system of pigeon pea (*Cajanus cajan*) + corn. Pear millet (*Pennisetum glaucum*) can extract a large quantity of K from the soil and accumulate it in biomass, with subsequent rapid release during decomposition of the straw (Crusciol and Soratto, 2007).

Long-term experiments play a fundamental role to assess the most suitable cropping management (Johnston and Poulton, 2018). Growing different plant species leads to different soil nutrient extraction strategies that can influence nutrient cycling and soil fertility in a no-till system (Tiecher et al., 2017). Therefore, our objective was to evaluate the impact of different cropping systems on soil fertility responses, in search of more sustainable agriculture approaches under tropical climate conditions.

3.3 Materials and methods

3.3.1 Site characteristics and management

The experiment was initiated in 2006 in Botucatu, São Paulo State, Southeastern Brazil (48º 23’ W, 22º 51’ S, 765 m above sea level), on a clayey Rhodic Hapludox (USDA Taxonomy), with 440 g kg^{-1} of clay, 469 g kg^{-1} of sand and 91 g kg^{-1} of silt at a depth of 0 to 0.2 m. Mean monthly rainfall and temperature are reported in Table 1. Characteristic climate condition is highland tropical, with dry winters and wet, rainy summers. Prior to the experiment, the site was managed with soybean (*Glycine max*) in the summer and black oat (*Avena strigose* Schreb.) in the autumn/winter under no-till for four years. At the time of experiment initiation, chemical properties in the upper 0.2 m were analyzed according to van Raij et al. (2001) [organic matter = 18 g dm^{-3}; pH = 4.2 (1:2.5 soil/$CaCl_2$ suspension 0.01 mol L^{-1}); P resin = 4 mg dm^{-3}; exchangeable K = 0.8 $mmol_c$ dm^{-3}, Ca = 12 $mmol_c$ dm^{-3}, Mg = 6 $mmol_c$ dm^{-3}; total acidity at pH 7.0 (H+Al) = 54 $mmol_c$ dm^{-3}; base saturation = 24%].

Table 1. Mean monthly rainfall and maximum and minimum temperatures from 2007 to 2017 at Botucatu, São Paulo State, Brazil.

Climate characteristics	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
	Long-term (50 yr) avg.											
Monthly rainfall (mm)	370	174	137	94	83	73	58	37	69	131	140	237
Mean max. temp. (ºC)	28.9	29.7	28.1	27.0	23.9	22.5	23.6	25.9	27.1	27.8	27.7	28.9
Mean min. temp. (ºC)	18.5	19.2	18.0	16.5	14.4	12.7	12.6	13.4	14.5	15.9	16.9	18.3

The experiment was arranged as a randomized complete block design with four replications of four cropping systems differentiated in the winter season (fallow, second crop, cover crop, and forage crop) and the same summer crop from 2007 to 2017 (Table 2). Summer grain crop choices were according to the majority of cultivated land in the State of São Paulo and in Cerrado region - soybean (*Glycine max*), corn (*Zea mays*), common bean (*Phaseolus vulgaris* L.), and rice (*Oriza sativa*). Cropping system with fallow was left unseeded and volunteer vegetation was allowed during the winter season. The second-crop system was planted with common oat (*Avena sativa* L.), common bean, castor bean (*Ricinus communis* L.), sorghum grain [*Sorghum bicolor* (L.) Moench], crambe (*Crambe abyssinica* Hochst. Ex R.E. Fr.), wheat (*Triticum aestivum*) or triticale (*X. triticosecale Wittmack*). The cover-crop system was with pearl millet (*Pennisetum glaucum* L.), pigeon pea [*Cajanus cajan* (L.) Huth], sunn hemp (*Crotalaria juncea* L.), lupin bean (*Lupinus albus* L.) or common oat. The forage-crop system was with ruzi grass (*Urochloa ruziziensis*) or palisadegrass (*Urochloa brizantha*). Summer grain crops were sown in November and harvested between March and April. After the summer harvest, winter crops were sown without fertilizer. Winter crops were harvested between July and August. It is noteworthy that it was not possible to grow any crop/cover crop in winter season 2014 due to adverse weather conditions (low precipitation). In 2016, the second crop did not grow because of insufficient precipitation necessary to development of the crop during this season.

During this study, all cropping systems were managed under no-till. Each plot covered an area of 54 m^2 (5.4 m x 10 m). One row on each side of the plot and one meter at both edges were considered buffer zones and not sampled.

Table 2. Crop rotation scheme in Systems I, II, III and IV from 2006 to 2016, Botucatu, São Paulo State, Brazil.

	System I (Fallow)	**System II (Second crop)**	**System III (Cover crop)**	**System IV (Forage)**
		------------ 2006 ------------		
Winter Season	-	-	-	-
Summer Season	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
		------------ 2007 ------------		
Winter Season	Fallow	*Avena sativa*	*Pennisetum glaucum*	*Urochloa ruziziensis*
Summer Season	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
		------------ 2008 ------------		
Winter Season	Fallow	*Phaseolus vulgaris*	*Cajanus cajan*	*U. ruziziensis*
Summer Season	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*
		------------ 2009 ------------		
Winter Season	Fallow	*Ricinus communis*	*Crotalaria juncea*	*U. ruziziensis*
Summer Season	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
		------------ 2010 ------------		

Winter Season	Fallow	*Sorghum bicolor*	*Pennisetum glaucum*	*U. ruziziensis*
Summer Season	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
		2011		
Winter Season	Fallow	*Crambe abyssinica*	*Lupinus albus*	*U. ruziziensis*
Summer Season	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*
		2012		
Winter Season	Fallow	*Triticum aestivum*	*Pennisetum glaucum*	*U. brizantha*
Summer Season	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*
		2013		
Winter Season	Fallow	*Triticum aestivum*	*Crotalaria juncea*	*U. brizantha*
Summer Season	*Glycine max*	*Glycine max*	*Glycine max*	*Glycine max*
		2014		
Winter Season	-	-	-	-
Summer Season	*Zea mays*	*Zea mays*	*Zea mays*	*Zea mays*
		2015		
Winter Season	Fallow	*X. triticosecale*	*Avena sativa*	*U. brizantha*
Summer Season	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*	*Phaseolus vulgaris*
		2016		
Winter Season	Fallow	-	*Pennisetum glaucum*	*U. brizantha*
Summer Season	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*	*Oriza sativa*

Over the 11 years of this field experiment, dolomitic lime was applied in October 2006 (before sowing the first crop), October 2011 and October 2015 (before sowing summer crop). The dolomitic lime rate (LR) was calculated by the method of base saturation (BS) proposed by van Raij et al. (1997), which used a calculation to increase base saturation to 70%:

$$LR\ (Mg\ ha^{-1}) = (BS_2 - BS_1) \times CEC / (ECCE \times 10) \quad (1)$$

Where, BS_2 is the target base saturation (70%), BS_1 is the base saturation determined by soil chemical analysis, CEC is cation exchange capacity, and ECCE is the effective calcium carbonate equivalent of the dolomitic lime. Adequate rates of NPK fertilizers were applied for summer crops according to soil chemical analyses conducted each year.

3.3.2 Soil sampling and analyses and grain yield

Four (October 2010) and nine (October 2015) years after cropping management, six individual soil samples were randomly collected at depths of 0 to 0.05, 0.05 to 0.1, 0.1 to 0.2, 0.2 to 0.4 and 0.4 to 0.6 m from the experimental area of each plot to form a composite sample. Soil samples were air dried, passed through a 2-mm sieve, and analyzed according to methodology proposed by van Raij et al. (2001).

Summer crops were harvested at maturity. Plants from the usable area were threshed mechanically, grain weighed, and yield calculated (130 g kg^{-1} wet basis).

3.3.3 Statistical analyses

The experimental design was a randomized complete block with four replications. Analysis of variance was used to evaluate the effects of crop rotation system and means were compared using least significant difference (LSD) ($p \leq 0.1$). All statistical analyses were performed using SAS (SAS Institute, Cary, NC).

3.4 Results

3.4.1 Soil chemical characteristics

During the 11 years of the experiment, soil chemical characteristics generally improved with all cropping management systems (Figure 1, 2 and 3). After four (2010) and nine (2015) years of cropping management, pH values were not affected by crop management system at any depth (Figure 1A and 1B).

Introduction of forage into the cropping system increased soil organic matter concentration by 28, 52, 46, 29, and 28% at depths of 0 to 0.05, 0.05 to 0.1, 0.1 to 0.2, 0.2 to 0.4 and 0.4 to 0.6 m, respectively, at 4 years of management as compared to the beginning of the experiment (2006) (Figure 1C). Soil organic matter concentration at 4 years of cropping management was greater with forage than with fallow, second crop and cover crop at depths of 0 to 0.05, 0.05 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m (Figure 1C). However, at 9 years (2015) of cropping management, no significant difference in soil organic matter concentration occurred among cropping system (Figure 1D). Nevertheless, there was an increase in soil organic matter from 2010 to 2015, mainly in the upper 0.2 m of soil, irrespective of cropping system.

From 2006 to 2010, soil P level increased at all depths regardless of the cropping system (Figure 1E). With 9 years of cropping management, fallow (34.6 mg dm^{-3}) had greater P level than second crop (24.3 mg dm^{-3}), cover crop (28.9 mg dm^{-3}) and forage (32.4 mg dm^{-3}) at the upper depth (0 to 0.05 m) (Figure 1F). At depth of 0.05 to 0.1 m, P level was lower with second crop compared with fallow, forage and cover crop. Also, the cropping system with second crop had the lowest P level and with fallow had the greatest P level at depth of 0.1 to 0.2 m (Figure 1F).

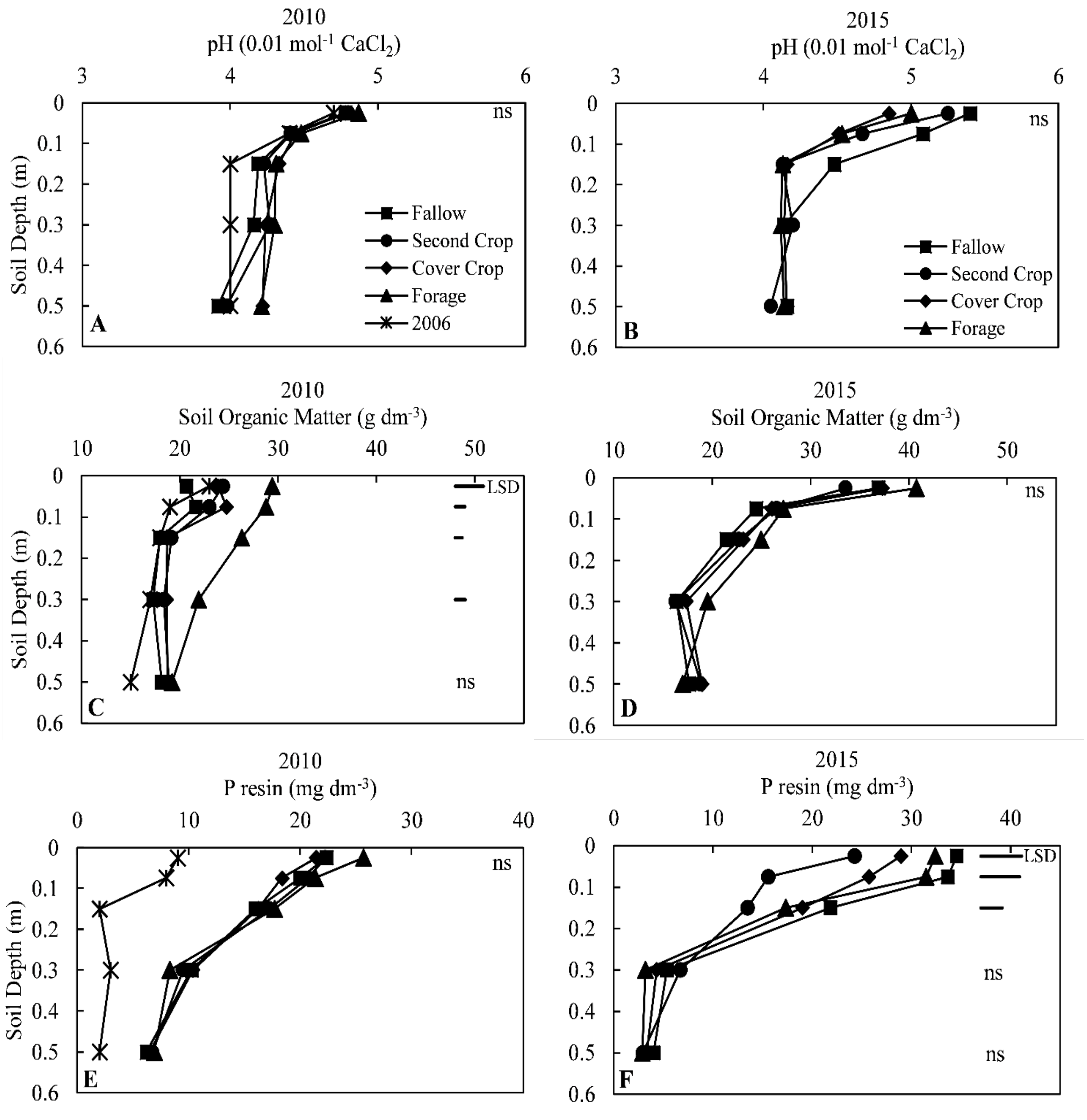

Figure 1. Soil pH (0.01 mol L^{-1} $CaCl_2$), soil organic matter and phosphorus levels as a function of cropping system after four (2010) and nine (2015) years of cropping management at Botucatu, São Paulo State, Brazil. Error bars denote significance (*P* ≤ 0.1) among cropping systems management within a depth. ns: not significant.

Exchangeable K was affected by cropping system only at 9 years of cropping management and at depth of 0 to 0.05 m (Figure 2B). This nutrient was greater under the cropping system with forage (2.29 $mmol_c$ dm^{-3}) than with fallow (1.71 $mmol_c$ dm^{-3}), second crop (1.53 $mmol_c$ dm^{-3}) and cover crop (1.59 $mmol_c$ dm^{-3}). Soil Ca level was not affected by cropping system 4 years after cropping management (Figure 2C), but it was affected 9 years after cropping management (Figure 2D). At depths of 0 to 0.05, 0.05 to 0.1 and 0.1 to 0.2 m, exchangeable Ca^{2+} was greater with fallow than with second crop, cover crop and forage. At depths lower than 0.2 m, fallow and forage had lower Ca levels than cropping system with second crop and cover crop (Figure 2D).

After 4 years of cropping management, Mg level was lower with fallow than with second crop, cover crop and forage at depth of 0.1 to 0.2 m (Figure 2E). Nine years after cropping management, exchangeable Mg^{2+} with fallow was 95, 37, and 39% greater at depth of 0 to 0.05 m and 78, 71, and 64% greater at depth of 0.05 to 0.1 m with second crop, cover crop, and forage, respectively (Figure 2F). At depths lower than 0.1 m, exchangeable Mg^{2+} values were not affected by cropping management system.

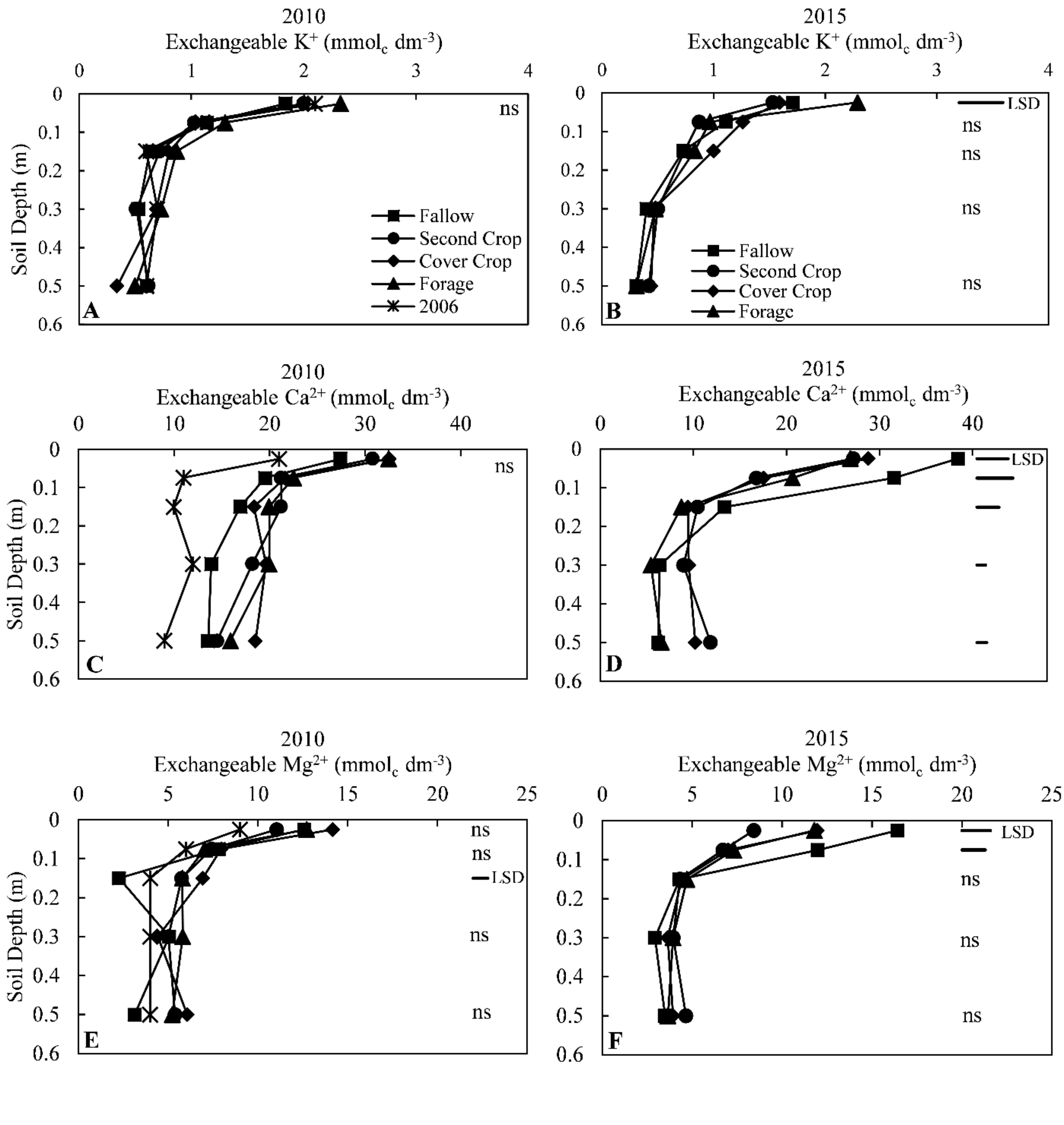

Figure 2. Exchangeable K, Ca and Mg levels as a function of cropping system after four (2010) and nine (2015) years of cropping management at Botucatu, São Paulo State, Brazil. Error bars denote significance ($P \leq 0.1$) among cropping systems management within a depth. ns: not significant.

Over the 11 years of this study, base saturation increased at depths in the upper 0.1 m, but decreased at depths below 0.1 m, regardless of the cropping system (Figure 3A and 3B). Four years after cropping management, base saturation was unaffected by cropping system at any depth (Figure 3A). In the upper 0.1 m of soil at 9 years of cropping management, fallow had greater base saturation than with second crop, cover crop and forage (Figure 3B). However, at depths below 0.2 m, base saturation was lower with fallow than with other winter cropping system.

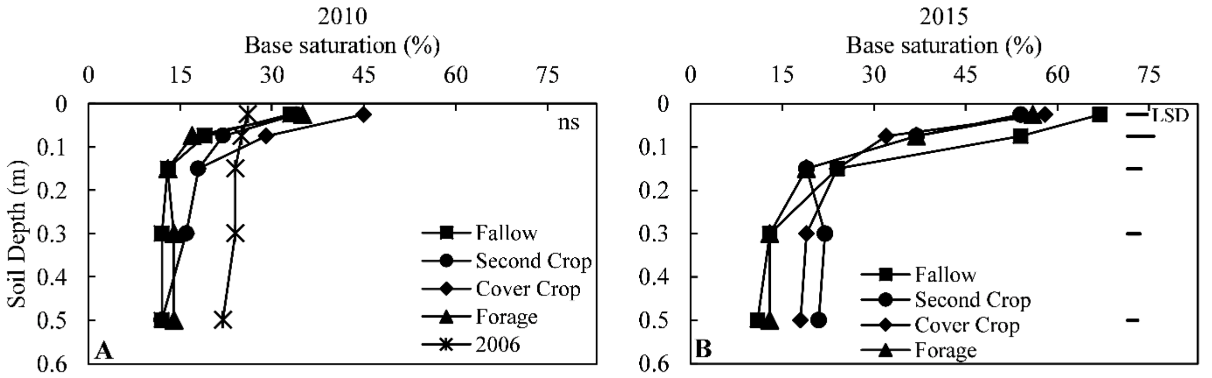

Figure 3. Base saturation level as a function of cropping system after four (2010) and nine (2015) years of cropping management at Botucatu, São Paulo State, Brazil. Error bars denote significance (*P* ≤ 0.1) among cropping systems management within a depth. ns: not significant.

3.4.2 Accumulated grain yield

Across the 11 years, autumn/winter cropping management impacted summer grain yield. Growing forage during the winter dry-season increased summer crop grain yield by 21, 9, and 7% compared with fallow, second crop and cover crop, respectively (Figure 4).

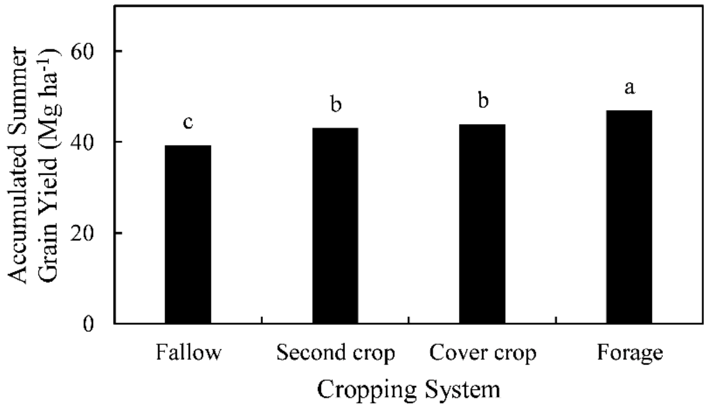

Figure 4. Accumulated summer grain yield as a function of cropping management at Botucatu, São Paulo State, Brazil. Different letters denote significant difference among cropping management ($P \leq 0.1$).

3.5 Discussion

3.5.1 Soil chemical characteristics

Improved soil organic matter with the introduction of forage into a cropping system (Figure 1B) can be attributed to its greater capacity to produce above- and below-ground biomass (Quattrocchi, 2006; Crusciol and Soratto, 2007; Pacheco et al., 2013). Soil organic matter generally increases with greater crop residue inputs (Franzluebbers et al., 1998) and improved environment conditions and management systems (Franzluebbers, 2002). Crusciol et al. (2015) observed greater soil organic matter concentration under corn intercropped with *Urochloa brizantha* than corn alone at all depths assessed (0 to 0.05, 0.05 to 0.1, 0.1 to 0.2 and 0.2 to 0.4 m). Additionally, the authors also reported an increase in soil fertility and grain yield of the system with the inclusion of forage.

Soil chemical properties can be enhanced by growing cover crops (Fageria et al., 2005) and/or forage crops (Crusciol et al., 2015). We found that soil nutrients were affected by cropping systems more after 9 years of cropping management under no-till than after 4 years (Figures 1F, 2B, 2D, 2F and 3B). In this context, long-term experiments play a fundamental role to evaluate changes in soil fertility and the sustainability of crop production (Johnston and Poulton, 2018). The enrichment of soil with nutrients depends on the type of cover crop, amount of biomass inputs, concentration of nutrients in plant residues and the capacity of root system to reach deeper layers and transfer nutrients to upper layer (Fageria et al., 2005).

Phosphorus and exchangeable Ca^{2+} and Mg^{2+} were greater under the cropping system with fallow at depth in the upper 0.2 m than all other cropping systems. In general, this suggests lower extraction of nutrients by weeds than by grain crops, cover crops and forage (Figures 1F, 2D and 2F), as the soil sampling occurred after winter crops and before sowing of the summer crop. Also, this could have also occurred from fast nutrient turnover from volunteer vegetation grown during the off-season, since the availability of nutrients in the soil are affected by biomass production and plant residue decomposition (N'Dri et al., 2018). At depths below 0.2 m, exchangeable Ca^{2+} was lower under cropping system with fallow and forage (Figures 2D). This change in vertical distribution of Ca^{2+} could has been from cultivation of different species that had different root system architecture. Large organic inputs in a no-till system help to create vertical channels to which these channels can physically displace basic cations (Ca^{2+} and Mg^{2+}) (Machado and Silva, 2001).

Greater exchangeable K^+ under the cropping system with forage than with other cropping systems (Figure 2B) could be attributable to the large capacity of *Urochloa* to cycle this macronutrient. Torres et al. (2008), Pacheco et al. (2011, 2013), and Tanaka et al. (2019) reported that K is one of the most extracted nutrients by *Urochloa*. In addition, the fast release of K from biomass occurs because K is not associated with structural components of plant tissue (Marschner, 2012). Therefore, as plants begin to desiccate and degrade upon rupture of the plasma membrane (Malavolta et al., 1997), K concentration dissipates with leaching from rainfall (Khatounian, 1999).

Lower extraction of basic cations, such as Ca^{2+} and Mg^{2+}, by volunteer vegetation during the winter dry-season influenced the availability of these basic cation (Figures 2D and 2F) and base saturation in surface depths (0-0.2 m) (Figure 3B). Carvalho et al. (2014) did not find a difference in sum of bases or base saturation among different cover crops or fallow during the off-season after 6 years under no-till.

3.5.2 Accumulated grain yield

Across 11 years of this experiment, accumulated summer grain yield was greater when forage was grown during the off-season than with second crop, cover crop and fallow (Figure 4). Greater grain yield in the cropping system with forage was also reported by Borghi et al. (2013), Soratto et al. (2013) and Crusciol et al. (2015). This yield enhancement may have been due to greater soil organic matter (Figures 1C and 1D), as several studies have reported correlations between soil organic matter and yield (Culman et al., 2013; Sá et al., 2014; Oldfield et al., 2019). Accumulated summer grain yield in the cropping system with second crop and cover crop was also greater compared to cropping system with fallow. According to Fageria et al. (2005), proper selection and management of cover crops can lead to improved productivity of the land. Contrary to our results, Tiecher et al. (2017) studied several winter cover crop species (*Lupinus angustifolius*, *Vicia villosa* Roth, *Avena strigosa*, *Raphanus sativus* L. and *Triticum aestivum* L.) and fallow during 23 years experiment in a subtropical Oxisol, and did not find a significant difference in summer crop yield (soybean and corn).

3.6 Conclusions

No-tillage for 4 and 9 years of management resulted in an increase in soil fertility of the topsoil. Long-term no-tillage stratified nutrient availability with greatest concentration near the surface and lowest concentration with increasing soil depth. It was particularly noteworthy that soil organic matter under the cropping system with forage increased relative to other cropping systems at 4 years throughout the 0 to 0.4 m soil layer.

Major influence of cropping systems on soil fertility was observed at 9 years of cropping management. Despite the cropping system with fallow had highest levels of P, Ca, Mg and base saturation in the topsoil, grain yield of summer crops was lower compared to other cropping systems. On the other hand, the cropping system with forage had a positive impact on grain yield of summer crops over the 11 years of management. Therefore, growing forage during the winter in tropical areas was the best option to enhance grain productivity and improve soil fertility indicators in a sustainable way. Soil organic matter appeared to be more related to yield responses than individual chemical nutrients.

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GENERAL CONCLUSIONS

Growing cover crops or crops during the dry-season are fundamental to avoid a decline in soil quality and enhance the sustainability of conservational agriculture management in tropical regions. The inclusion of forage in a no-tillage system can lead to improve soil quality by increasing soil organic matter, providing few positive changes in soil physical properties and enhancing grain yield of summer crops over the years. Further, this forage can be used for feed livestock that increase land profitability. Growing cover crops also show as a good strategy to minimize bare fallow periods, maintain soil surface protected, and influence positively on grain yield. Therefore, the inclusion of forage and cover crops in the tropical cropping system are recommended as a suitable option to diversify farming operations, improve crop productivity, and potentially avoid soil quality loss.

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