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Different soil tillage systems influence accumulation of soil organic matter in organic agriculture

Ademir Sergio Ferreira de Araújo[1]*, Luiz Fernando Carvalho Leite[2], Ana Roberta Lima Miranda[1], Luis Alfredo Pinheiro Leal Nunes[1], Ricardo Silva de Sousa[1], Fabio Fernando de Araújo[3] and Wanderley José de Melo[4]

[1]Soil Quality Lab., Agricultural Science Center, Federal University of Piauí, Teresina, PI, Brazil.
[2]Embrapa Mid-North, Av. Duque de Caxias, Teresina, PI, Brazil.
[3]Universidade do Oeste Paulista, Campus II, Presidente Prudente, SP, Brazil.
[4]Universidade Estadual Paulista, Campus de Jaboticabal, Jaboticabal, SP, Brazil.

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As a sustainable method of agriculture, organic agriculture aims to increase the soil organic matter through the use of crop rotation, legume cover crop, animal green manure, and organic compost. These practices add organic residues with high organic Carbon (C) which results in a higher soil organic matter content over time primarily due to the no-tillage practices. However, different soil tillage systems, such as conventional tillage and reduced tillage are also used in organic agriculture, and therefore the accumulation of organic matter does not follow similar trends. The studies under conventional tillage have shown that soil tillage influences negatively the organic matter accumulation in organic agriculture plots, while the results from different studies on organic agriculture showed the potential benefits of reduced or zero tillage for organic matter accumulation.

Key words: Sustainability, soil quality, management systems.

INTRODUCTION

Soil is important to terrestrial ecosystems and represents a balance among physical, chemical, and biological properties. Soil organic matter (SOM) plays a key role in the improvement of these soil properties (Ouedraogo et al., 2007). The increase of SOM is considered critical for sustainable soil management and maintenance of soil productivity (Doran et al., 1996; Fan et al., 2005). In this way, SOM is an important component for the maintenance of sustainable agriculture in the world.

As a sustainable method of agriculture, organic agriculture (OA) aims to increase the SOM through the use of crop rotation, legume cover crop, animal green manure, and organic compost. Usually, these practices add high quantities of organic residues which will be decomposed by soil microorganisms, release nutrients, and increase SOM over time. Globally, OA is regulated

*Corresponding author. E-mail: asfaruaj@yahoo.com.br. Tel: +55-86-3215-5740. Fax: +55-86-3215-5743.

Table 1. The main characteristics of organic farming systems around the world (adapted from Araújo and Melo, 2010).

S/N	Details
1	Protecting the long term fertility of soils by maintaining organic matter levels
2	Encouraging soil biological activity
3	Nitrogen self-sufficiency through the use of legumes and biological nitrogen fixation, as well as effective recycling of organic materials including crop residues and livestock manures
4	Providing crop nutrients indirectly using relatively insoluble nutrient sources which are made available to the plant by the action of soil micro-organisms
5	Weed, disease and pest control relying primarily on crop rotations, natural predators, diversity, organic manuring, and resistant varieties
6	Careful attention to the impact of the farming system on the wider environment and the conservation of wildlife and natural habitats

by the International Federation of Organic Agriculture Movements (IFOAM). This system occupies 37.5 million hectares worldwide distributed over 164 countries (IFOAM, 2014). Oceania has the largest land area under organic farming (approximately 12.2 million hectares), followed by Europe (approximately 11.2 million hectares), Latin America (approximately 6.8 million hectares), Asia (approximately 3.2 million hectares), and North America (approximately 3 million hectares). In 2012, it was estimated that the land under OA increases by 0.2 million hectares that is, 0.5% globally (IFOAM, 2014).

The practices in OA excludes the use of synthetic fertilizers, pesticides, plant growth regulators, livestock feed additives, and genetically modified organisms. The term 'organic' is best thought of as referring to the concept of the farm as an organism, in which all the component parts - the soil minerals, organic matter, micro-organisms, insects, plants, animals and humans - interact to create a coherent and stable whole. The main characteristics of OA around the world are shown in Table 1. Therefore, OA focuses on alternative agricultural practices using farm-derived renewable resources and biological processes and interactions that will provide an acceptable crop yield (Watson, 2006). Crops under OA require about 50% less energy per unit area; although conventional agriculture may produce more per area, their energy efficiency is lower (Mäder et al., 2002). In this context, an OA system represents an important method that improves soil properties, recycles nutrients, promotes biological process, and increases SOM content (Rigby and Caceres, 2001). High levels of SOM are found to be more closely associated with OA as compared with conventional agriculture (Nardi et al., 2004; Kong et al., 2005; Fließbach et al., 2007; Araújo et al., 2008; Leite et al., 2010; Santos et al., 2012). However, two main points should be considered in global OA systems: the SOM accumulation differs according to the quantity and quality of the C input and the different soil tillage practices significantly affect SOM accumulation over time. Some studies have been shown different trends in SOM accumulation over time (Araújo et al., 2008; Sampaio et al., 2008; Leite et al., 2010; Triberti et al., 2008; Santos et al., 2012, Kong et al., 2005; Fließbach et al., 2007). Therefore, this review focuses on the long-term studies under OA system and its effect on SOM accumulation.

SOM ACCUMULATION IN ORGANIC FARMING SYSTEMS

SOM is a critical component of the soil which affects the physical, chemical, and biological processes of soil and regulates a wide range of soil functions (Leite et al., 2010). The role of SOM in the formation of stable soil aggregates has major implications for soil structure, and consequently, on water infiltration, water holding capacity, aeration, resistance to root growth, and surface crusting (Mirsky et al., 2008). The physical protection of SOM within aggregates is an important factor that controls the dynamics and decomposition of organic C. Aggregate disruption is one of the mechanisms proposed for lower SOM in soil tillage system rather than in no-tillage systems (Six et al., 2000; Leite et al., 2003) because tillage disrupts soil aggregates mechanically, thereby increasing the access of microorganisms to SOM (Jiao et al., 2006). SOM is considered as a source of soil cation exchange capacity (CEC) by which the cations are

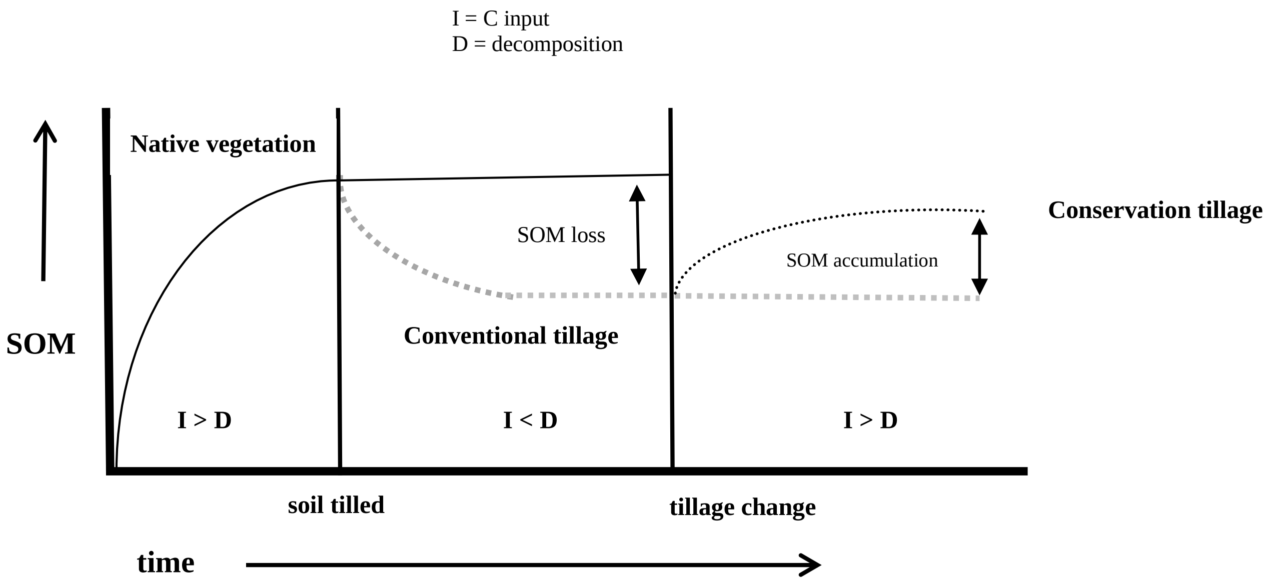

Figure 1. Trend in soil organic matter accumulation from conventional tillage and conservation tillage as compared with native soil.

retained for plant use and can be readily exchanged for other cations. The exchange is quite often made is the intake of a hydrogen ion from plant roots, which replaces one of the cations in the exchange complex. By reducing fixation and leaching losses of the cations, the CEC helps maintain a more constant nutrient supply and potentially increases crop yields (Craswell and Lefroy, 2001; Bot and Benites, 2005). SOM has an intense effect on the number and type of soil organisms. These organisms, consisting of microflora and microfauna, do not just live passively in soil but are affected by one another, either through competition or a symbiotic relationship. They frequently compete with one another for nutrients or energy, much of which is derived from organic matter. Once the organisms have been nourished by organic matter, they may become an energy and nutrient source for other organisms. Most soil organism activities are beneficial to crop plants. In fact, soil fertility is related to the number and diversity of the organisms it can support (Wolf and Snyder, 2003).

More recently, SOM has attracted great interest because of the phenomenon of global warming and the prospects of using soil as a reservoir of carbon released to the atmosphere (CO_2) by human activities. The best strategies to build-up carbon stocks in the soil are basically those that increase the crop residue addition to the soil or decrease the SOM decomposition rate (Lal, 2004). In fact, soil organic carbon (SOC) storage is a balance between C additions from non-harvested portions of crops and organic amendments and C losses. The losses are primarily from organic matter decomposition and the release of respired CO_2 to the atmosphere and, to a lesser extent, by the erosion and leaching of dissolved organic carbon (Kemmit et al., 2008). Organic matter returned to the soil directly from crop residues or indirectly as manure consists of many different organic compounds. The result is a quick formation of microbial compounds and body structures, which are essential for holding particles together to provide structure to the soil and release CO_2 back to the atmosphere through microbial respiration (Liu et al., 2006).

Organic C is a major component in OA systems and has a positive effect on soil C because a significant increase in SOM is correlated with C input (Drinkwater et al., 1998). The input of residues with high organic C results in a higher SOM content over the long-term. Several studies on OA have demonstrated this increase in the SOM content (Araújo et al., 2008; Sampaio et al., 2008; Leite et al., 2010; Triberti et al., 2008; Santos et al., 2012, Kong et al., 2005; Fließbach et al., 2007). The conversion from native soil to agricultural systems, through soil tillage practices, decreases the SOM content in the soil (Rees et al., 2001). It happens because conventional practices, such as soil tillage, stimulate the degradation of SOM, compared to native vegetation, and do not allow organic C to accumulate in soil (Figure 1). The use of soil tillage promotes a strong decline in SOM during the transition from native vegetation to cropland. Thus, selecting a conservation soil tillage may be important for minimizing negative tillage effects on SOM and, therefore, the adoption of conservation tillage tends

Table 2. Main characteristics of long-term organic farming studies.

Crop	Soil amendment	Soil management	Soil type	Reference
Acerola" fruit (Malpighia glabra)	Composted cow manure, rock phosphate, and straw	Zero tillage	Typic Quartzipsamment	Santos et al. (2012)
Maize/bean	Organic compost and straw	No-tillage	Typic Hapludult	Leite et al. (2010)
Tomato, maize	Legume cover crop, chicken and turkey manure, organic compost	Conventional tillage	Typic Xerorthent	Kong et al. (2005)
Maize	Manure and legume cover crop	Conventional tillage	-	Hepperly et al. (2006)
Maize, soybean, potato	Animal manure, compost, turkey litter	Conventional tillage	Typic Udipsamment	Tu et al. (2006)
Potato, wheat	Famyard manure, slurry and organic compost	Conventional tillage	Typic Hapludalf	Fließbach et al. (2007)
Potato, wheat	Cow manure, slurry	Reduced tillage	Eutric Cambisol	Berner et al. (2008)
Cereal, sunflower	Manure compost, slurry	Conventional tillage, Reduced tillage	Eutric Cambisol	Gardemeier et al. (2011)
Maize, wheat	manure, slurry, maize residues	Conventional tillage	Haplic Calcisol	Triberti et al. 2008

to accumulate SOM in long-term.

SOIL TILLAGE SYSTEMS

Soil tillage systems are practices of soil manipulation aiming to improve conditions for germination, seedling establishment and crop growth (Lal and Kimble, 1997). These practices vary in different ways and frequency affecting the biological, physical and chemical properties of the soil (Mathew et al., 2012). Usually, conventional soil tillage practices are used in several agricultural systems and may adversely affect long-term soil productivity due to erosion and loss of organic matter in soils (Leite et al., 2009). These systems generally involve plowing or some other form of intensive tillage. However, conservation soil tillage is defined as a tillage system in which at least 30% of crop residues are left in the field and is an important conservation practice to reduce soil erosion (Uri, 1999). As a specialized type of conservation soil tillage, the no-tillage system consists of a one-pass planting and fertilizer operation in which the soil and the surface residues are minimally disturbed (Šimon et al., 2009). Additionally, zero tillage system has been shown to improve or to maintain organic matter in soil due to reduced soil disturbance (Mangalassery et al., 2015).

Conservation soil tillage are recognized as useful agricultural practices for sustainable agriculture and food system because of the economic, environmental, sustainable benefits (Mangalassery et al., 2015). The positive agricultural practices, such as very little or no soil disturbance, direct drilling into untilled soil, crop rotation, and permanent soil cover, maintain and improve soil properties (Holland 2004; Derpsch 2007). Also, conservation soil tillage practices change many soil properties when implemented for a long term (Chen et al., 2009).

Conservation soil tillage may be characterized by increased SOM due to surface residue accumulation in soil and this permanent increase in SOM in the top soil improves the availability of plant nutrients (Fernández et al., 2007; Lopez-Fando and Pardo, 2009), which are released faster than in conventional tillage (Fernández et al. 2007). Therefore, conservation soil tillage systems affect the accumulation of SOM and the increases in organic matter are normally observed within the surface 10 cm of soil (West and Post, 2002). Also, soil under conservation soil tillage system accumulates greater amounts of total C and a greater proportion of aromatic C (Mangalassery et al., 2015). However, many studies indicate that various soil tillage systems have a strong effect on SOM accumulation and the effects varied depending on regional climate, soil type, residue management practice, and crop rotation (Koch and Stockfisc, 2006; Leite et al., 2009; Šimon et al., 2009; Chen et al., 2009; Mathew et al., 2012; Abdullah, 2014; Mangalassery et al., 2015).

EFFECT OF DIFFERENT SOIL TILLAGE ON SOM ACUMULATION

Conventional and conservation are both used in OA systems (Table 2), and therefore, the accumulation of SOM does not follow similar trends (Table 3). In OA systems, tillage is used to ploughing the soil between crops in order to

Table 3. Organic C input and SOM accumulation in organic farming system over time.

Period (years)	C input (Mg ha^{-1})	SOM accumulation (mg kg^{-1})	Reference
10	8,000	25.6 (+310%)	Santos et al. (2012)
12	8,400	36.2 (+40%)	Leite et al. (2010)
15	6,000	23.6 (+30%)	Kong et al. (2005)
5	10,200	19.2 (+20%)	Tu et al. (2006)
18	5,000	26.5 (-13%)	Fließbach et al. (2007)
7	6,000	40.2 (+14%)	Berner et al. (2008)
6	5,500	44.7 (+19%)	Gardemeier et al. (2011)
34	2,100	11.6 (-12%)	Triberti et al. (2008)

incorporate crop residues and soil amendments, remove weed growth, and prepare a seedbed for planting. In 1978, a long-term study under OA was started comparing organic and conventional agriculture in Switzerland (Fließbach et al., 2007). The main practices used in OA plots are crop rotation (potatoes, wheat, and beetroots, followed by three years of grass-clover), manure, and soil tillage. After 21 years, SOM was found to decrease by 13% and 8% at low intensity and high intensity tillage areas under OA, respectively. According to Fließbach et al. (2007), the organic practices follow a guideline in Switzerland that comprise a variety of management steps, including tillage of soil, thus SOM may fluctuate according to the long-term land use.

The results reported by Fließbach et al. (2007) confirmed that soil tillage influenced SOM accumulation in OA plots. Similarly, a field study, which was a long-term research on agriculturalsustainability at the University of California, Davis, USA, compared a conventional and an organic maize–tomato crop system with legume cover crop, compost and no pesticides (Kong et al., 2005) that had been under standard soil tillage since 1993. After 15 years, the SOM accumulation results showed a marginal increase in the SOM content in OA system over time. The same trend was found in another experiment that had been maintained under organic farming practices since 1981. The Rodale farming system, followed in some parts of Pennsylvania, USA, evaluated OA on the basis of manure and legume coverage required by the crop under conventional tillage. In that system, Hepperly et al. (2006) observed that SOM accumulation increased by 14% under OA over a 20 year period.

In southeastern Italy, a long-term field experiment (1966 to 2000) compared rotational application of organic and mineral fertilizations performed over duration of 2 years under conventional soil tillage: maize and winter wheat with cattle manure, cattle slurry and wheat or corn residues together with an unfertilized control (Triberti et al., 2008). The authors observed that in the year 2000, the SOM content was 12% lower than that in 1966. Thirty-four years after the commencement of the trial, the organic amendment revealed no significant effects on SOM accumulation. According to the authors, plowing the soil caused a dilution of SOM and promoted oxidation, and the adoption of deep soil tillage in an intensive cereal succession caused the decrease in SOM.

Soil tillage is an important factor that influences SOM accumulation because tillage exposes more soil to oxygen and increases the breakdown of organic matter by microorganisms. Although soil tillage may increase soil microbial biomass and its activity (Gadermaier et al., 2011), the SOM accumulation in tilled soils may decrease over time. Although tillage is a very common practice and is recommended for OA mainly to control weeds, suitable crop rotations with a high weed-suppressing capacity may be an alternative to tillage. The use of reduced tillage in organic farming has not yet been successfully implemented and the development of suitable crop rotations and management practices that promote weed control should be investigated to avoid tillage (Peigné et al., 2007). Reduced tillage appears to correlate with an increase in SOM (Gadermeier et al., 2011). For example, Gadermeier et al. (2011) evaluated an OA system from 2002 to 2008 that operated under reduced tillage and found a 19% increase in the SOM. Emmerling (2007) observed a 10% increase in SOM under reduced tillage after 10 years of OA and no differences under tilled soil. Berner et al. (2008) evaluated the effects of reduced soil tillage on SOM accumulation over seven years and found a 14% increase in SOM.

Another option is zero soil tillage which refers to direct seeding and direct drilling with no soil disturbance. Zero soil tillage is the conservation tillage system which may accumulate high amounts of organic residue on the soil surface, and the benefits are most pronounced in dry regions (Car et al., 2013). When the soil is not tilled, SOM accumulation seems to be higher and it favors a fast increase in the SOM content. Organic agriculture without tillage may reduce energy use and CO_2 emissions while increasing C sequestration (Holland, 2004) and system sustainability (Davies and Finney, 2002).

Under no-tillage or zero tillage systems, OA has significantly higher SOM accumulation (Leite et al., 2010; Araújo et al., 2008; Wang et al., 2011; Santos et al., 2012). Leite et al. (2010) evaluated the SOM changes over a long-term (12 years) addition of organic compost under an OA system of a maize/bean intercrop under no-tillage in Brazil. The authors observed that SOM values were approximately 40% higher in the no-tilled organic farming system compared with a conventional system. The magnitude of increase was not high; however, the application of organic compost associated with the no-tillage system favored the accumulation of SOM over time. Compost application has been evaluated with other practices, which can increase the SOM content, such as cover crop, crop rotation, and no-tillage. In Brazilian semi-arid areas, Menezes and Silva (2008) evaluated entisol soil and the effects of compost application (15 t ha^{-1}) and/or a cover crop (rattlepods, *Crotalaria juncea*) on the SOM content over a six-year period. The annual fertilization with compost, with or without *C. juncea,* increased the SOM content.

No-tillage practices in organic farming from tropical or sub-tropical regions is as important practice to avoid high organic matter decomposition as in humid and warm regions there is highest soil microbial activity which is stimulated by tillage practices. The long-term experiment with OA in the USA evaluated during 15 years the cumulative effects of agricultural practices on accumulation of SOC (Wang et al., 2011). The study was established in 1994 comparing tillage and no-tillage practices with chemical or organic inputs. The results showed that the total organic C content was significantly higher (77–83%) in no-tillage than in tillage systems. Also, soil organic C was 44% higher in no-tillage organically managed compared to no-tillage with chemical inputs. Therefore, Wang et al. (2011) showed that OA with no-tillage practices and organic inputs can promote soil C accumulation over time.

In a study of the effects of 40 years of farmyard manure, mineral and mixed fertilizations on the organic properties of a fluvi-calcaric cambisol soil from northeastern Italy, Nardi et al. (2004) also reported a larger influence of the organic practices on the SOM content. A study on OA in sandy soil with fruit production and under no tillage management showed a SOM accumulation > 300% over 10 years (Santos et al., 2012). This SOM accumulation is important because sandy soils present low fertility and the increase in SOM may improve soil properties. Comparing the aforementioned three studies, we found that soil tillage influenced SOM accumulation and the quantity and quality of the C input affected SOM accumulation over time.

Recently, Alvaro-Fuentes et al., (2013) evaluated the long-term effects of different tillage systems on soil organic C levels in the 0 to 50 cm soil layer under dryland semiarid conditions in Spain. The experiment compared three tillage systems: two conservation tillage systems (no-tillage and reduced tillage) and one intensive tillage system (conventional tillage). The highest soil organic C contents were found in the no-tillage system. However, the differences only were found in the soil layer submitted to tillage. It means that the effect of tillage on accumulation of soil organic matter may be restricted to the plough layer.

CONCLUSION

Different soil tillage systems affect strongly the SOM accumulation in organic agriculture. The results from different studies on organic agriculture showed the potential benefits of reduced or zero tillage for SOM accumulation over time. Finally, this higher accumulation of soil organic C found in conservation soil tillage systems may increase soil fertility and can contribute to alleviate atmospheric CO_2 rise.

Conflict of interests

The authors have not declared any conflict of interests.

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