

Long-Term Impacts of Organic and Inorganic Fertilizers on Carbon Sequestration in Aggregates of an Entisol in Mediterranean Turkey

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Abstract: Soil management practices significantly impact soil aggregation and carbon (C) dynamics. Organic fertilizer and mycorrhizal inoculation also affect aggregate stability and soil C pool. Thus, this study was designed to assess the effects of inorganic and organic fertilizer treatments (control, chemical fertilizer, animal manure, compost, and compost + mycorrhizal inoculation) on bulk density (ρ_b), C and N concentrations, soil organic C (SOC) pool, C sequestration, total N, aggregate fractions, water-stable aggregates (WSA), and mean weight diameter (MWD) in the long-term field experiment initiated in 1996 on the Mediterranean coast of Turkey. Disturbed and undisturbed soil samples were collected from the 0- to 0.15-m and 0.15- to 0.30-m depths after wheat (*Triticum aestivum*) harvest in June 2010 to determine the soil physical and chemical characteristics.

Soils that received animal manure, compost, and compost + mycorrhizae contained more C (in percent), N (in percent), SOC, and total N concentrations than control. In comparison with control, chemical fertilizers also affected soil C and N concentrations and pools by increasing plant biomass production. The C/N ratio of soil was less than 10 in control and chemical fertilizer treatments but more than 10 in animal manure, compost, and compost + mycorrhizae treatments. Organic fertilizers significantly reduced ρ_b and increased porosity (in percent). Total amounts and rate of C and N sequestration increased with application of organic fertilizers. The rate ($\text{kg C ha}^{-1} \text{ year}^{-1}$) of C sequestration in 0- to 0.15-m depth was 7.19 for control, 329.6 for animal manure, and 273.4 for the compost + mycorrhizae treatment. Furthermore, organic fertilizers significantly increased the SOC concentrations in different aggregate size fractions. The C and N concentrations in the 0.25- to 1.0-mm aggregate size were higher than those in the less than 0.25-mm fraction. Concentrations of C and N decreased significantly with the decrease in aggregate size less than 0.25 mm ($P < 0.0009$).

Application of organic fertilizers impacted soil ρ_b , WSA, and MWD. Compost + mycorrhizae-treated soil had the highest MWD (3.09 mm), and the control treatment had the least (1.49 mm). Decline in aggregate size decreased WSA in compost and mycorrhizae treatments. The high values of MWD were associated with mycorrhizal inoculation rather than with application of organic fertilizer.

Application of organic fertilizers including mycorrhizal inoculation contributed considerably to soil aggregation and soil C sequestration. There was more C concentration in 1- to 2-mm and 0.5- to 1-mm aggregate sizes than in the less than 0.25-mm size range. Additional research is needed to assess the role of mycorrhizae on macroaggregate

development and C sequestration under long-term soil and crop management systems.

Key words: Carbon sequestration, organic and inorganic fertilizers, mycorrhizae, soil organic carbon, water-stable aggregates.

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The green revolution of the 1960s and 1970s resulted in enhanced agricultural production through intensive use of inputs such as chemical fertilizers, pesticides, tillage, irrigation, and improved varieties. However, crop yields in some soils with low inherent fertility cannot be sustained without use of external inputs. In others, agronomic yields may not be sustained even with input of chemical fertilizers because of other soil-related constraints. Important among these constraints are supraoptimal soil temperatures, high concentrations of CaCO_3 and clay contents, and excessive heavy tillage. Under these conditions, such as those prevalent in the eastern parts of the Mediterranean region of Turkey, the rate of decomposition of soil organic matter (SOM) is high, and soils are prone to a range of degradation processes. Depletion of SOM is exacerbated on continually cropped arable land because of the burning of crop residues. These practices adversely affect soil biological and physical properties and the arbuscular mycorrhizal fungal (AMF) hyphal network, the microbial biomass carbon (MBC), and consequently, the aggregation and soil structure. Total organic C storage in soil is a principal attribute of soil biological and physical quality. Organic compounds (Caravaca et al., 2002) and AMF hyphae are important in binding soil particles (Caravaca et al., 2002; Wilson et al., 2009) into macroaggregates and microaggregates (Singh et al., 2009). Thus, depletion of SOM and the degradation of soil structure can adversely affect soil fertility and crop productivity (Lal, 2009).

Depletion of the SOM content is one of the major causes underlying the declining agronomic productivity in soils of the Mediterranean region (Khesat et al., 2008; Ryan et al., 2008). Excessive tillage and breakdown of soil aggregates exacerbate mineralization of SOM and emission of CO_2 (Lal, 2010; Larionova et al., 2010). With appropriate management, soil can be a sink for atmospheric CO_2 and mitigate the “greenhouse effect” (Lal, 2002). Singh et al. (2009) suggested that management practices involving increased return of crop residues-C would improve aggregate stability and enhance aggregate-associated soil organic C (SOC) levels.

The SOC concentration directly affects production of biomass by improving soil quality (Lal, 2009). Improvement in soil fertility through nutrient management is also important to SOC sequestration (Lal, 2005) because concentrations of SOC and N are key indicators of soil quality and productivity through their favorable effects on physical, chemical, and biological processes (Bauer and Black, 1994), including nutrient cycling, water

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retention, root and shoot growth, and environmental quality (Sainju and Good, 1993). Aggregates encapsulate SOC and reduce the rate of its decomposition (Lal, 2008). Similarly, plant roots and AMF hyphae provide physical protection to soil C against microbial decomposers through aggregation (Golchin et al., 1994; Jastrow et al., 1998). The SOC encapsulated within soil aggregates has a lower decomposition rate than that located outside of aggregates (Oades, 1984; Six et al., 2000). Increase in the SOC pool also enhances soil structure (Celik et al., 2004; Mikha et al., 2010). Soil management exerts a strong influence on the formation and stabilization of aggregates and SOC sequestration (Jastrow et al., 1998; Six et al., 1998). Soil aggregation is one of the important soil characteristics that mediates many soil chemical, physical, and biological properties and improves soil quality and sustainability (Moreno-de las Heras, 2009).

Mycorrhiza is the largest symbiotic association between plant roots and fungi. These associations enhance soil structure and improve uptake of nutrients and water through extension of AMF hyphae into the rhizosphere (Ortas, 2003; Karandashov and Bucher, 2005; Smith and Read, 2008). Elongation of AMF from the mycorrhizal root to soil is a complex and ramifying network into the surrounding soil that can reach up to 30 m of fungal hyphae per gram of soil (Cavagnaro et al., 2005; Wilson et al., 2009). The mycorrhizae mycelia network can bind particles and improve soil structure (Tisdall et al., 1997; Caravaca et al., 2006; Rillig et al., 2010). Andrade et al. (1998) and Bedini et al. (2009) observed that secretion of glomalin by AM fungi contributes to soil stability, quality, and water retention. Jastrow et al. (1998) and Smith and Read (2008) observed that very fine roots and AMF hyphae have significant effects on the geometric mean diameter of water-stable aggregates (WSA), whereas very fine roots had no direct effects.

Sequestration of C and storing it in aggregates are important for enhancing the mean residence time (Six et al., 2000; Lal, 2002; Ussiri et al., 2006; Singh et al., 2009; Wilson et al., 2009; Lal, 2010). Thus, it is prudent to enhance soil aggregation to increase C sequestration, especially within stable microaggregates and macroaggregates. Yet, there is a need to understand aggregate development and C sequestration under long-term field experiments involving inorganic and organic fertilizers and AMF inoculation. Because of their high clay and lime contents, most soils in the Mediterranean region are poor in macronutrient and micronutrient availability, which is also indirectly related to WSA. Consequently, management of soil physical quality (i.e., bulk density, aggregation) can enhance and sustain agronomic production.

Therefore, the objective of this study was to assess the long-term effects of organic and inorganic fertilizers (including mycorrhizal inoculation) application on soil aggregation and SOC concentration and budget under semiarid Mediterranean conditions. The study is based on the hypothesis that organic amendments and AMF inoculation enhance C and N concentrations in soil aggregates and increase WSA.

MATERIALS AND METHODS

Site and Soil Description

The experiment was conducted between 1996 and 2010 for a range of crops suited to the Menzilat soil series (Typic Xerofluvents) located on the Research Farm of the Çukurova University (37°00'54.31"N longitude and 35°21'21.56"E latitude and 34 m above mean sea level) in the eastern part of the Mediterranean region of Adana-Turkey. General soil properties are presented in Table 1. The regional climate is

typical Mediterranean with long-term average annual air temperature of 19.1°C (ranging from 14.2°C in January to February to 25.5°C in July to August) and precipitation of 670.8 mm. As much as 80% of the annual precipitation is received between November and April, with a mean annual humidity of 66% (Anonymous, 2008).

The experiment initiated in 1996 was composed of five treatments × three replicates = 15 plots, each of 10 × 20-m (200-m²) dimensions. The treatments were (i) control; (ii) traditional N-P-K fertilizers (160 kg N ha⁻¹ as (NH₄)₂SO₄, 83 kg K ha⁻¹ as K₂SO₄, and 26 kg P ha⁻¹ as 3Ca (H₂PO₄)₂·H₂O); (iii) compost at 25 Mg ha⁻¹; (iv) animal manure at 25 Mg ha⁻¹; and (v) mycorrhiza-inoculated compost at 10 Mg ha⁻¹. Experimental plots were moldboard ploughed to 0.15- to 0.20-m depth after each harvest. Annually, the organic fertilizers (animal manure, compost, and mycorrhizae) were uniformly spread on the soil surface just before sowing and were incorporated into the surface 0.10- to 0.15-m layer with a disc harrow. Similar tillage practices were followed for the control and fertilizer-treated plots.

Soil Sampling, Preparation, and Analyses

Bulk soil samples were obtained after the harvest of wheat (*Triticum aestivum* L.) during June to July 2010 within each treatment at 0- to 0.15-m and 0.15- to 0.30-m depths. A part of the sample was separated as bulk soil fraction. Soil bulk density (ρ_b) was measured by the core method (Blake and Hartge, 1986). Total porosity (in percent) of soil was calculated using the equation: $[1 - (\rho_b/\rho_s)] \times 100$; where ρ_b is bulk density and ρ_s is particle density (assumed to be 2.65 Mg m⁻³ soil) (Singh et al., 2009).

Soil C and N Analyses

Soil samples were air-dried, gently ground, and passed through a 2-mm sieve. Air-dried bulk soil was further ground and sieved through a 0.25-mm sieve for determining total C and N concentrations by the dry combustion method at 900°C using a C and N elemental analyzer (LECO Corporation, St. Joseph, MI). Inorganic C was determined by measuring total CaCO₃ content by treating 2 g of finely ground soil with 6 M

TABLE 1. Soil Characteristics of Menzilat Soil in 1996

Properties	Unit	Depth	Depth
		0–0.15 m	0.15–0.30 m
Clay	g kg ⁻¹	318.8 ± 30.6	333.4 ± 21.8
Silt		360.9 ± 87	379.5 ± 13.4
Sand		320.3 ± 23.0	287.2 ± 16.4
Organic C soil	g kg ⁻¹ soil	0.88 ± 0.08	0.78 ± 0.08
Inorganic C		3.77 ± 0.35	3.97 ± 0.42
Total N		0.08 ± 0.01	0.07 ± 0.01
Cation exchange capacity	Cmol ⁺ kg ⁻¹	20.50 ± 2.00	17.90 ± 1.64
pH	H ₂ O	7.58 ± 0.66	7.60 ± 0.71
Salt	%	0.05 ± 0.00	0.04 ± 0.00
P	mg kg ⁻¹	22.60 ± 2.16	20.20 ± 2.00
Fe		5.43 ± 0.82	5.66 ± 0.58
Mn		5.74 ± 0.32	5.31 ± 0.59
Zn		0.52 ± 0.05	0.23 ± 0.02
Cu		1.86 ± 0.19	1.56 ± 0.16
No. AMF spores	10 g ⁻¹ soil	64.00 ± 11.70	44.00 ± 2.62
Mean of three replicates ± SD.			

TABLE 2. From Analysis of Variance for Different Soil Parameters Such as Soil C %, Inorganic C%, Organic C%, Nitrogen %, TSN Mg ha⁻¹, TSN Mg ha⁻¹, WSA%, MWD mm ρ_b Mg m⁻³, and f_t (%).

Treatment	df	Soil C	Inorganic C	Organic C	N	SOC	TSN	WSA	MWD	ρ _b	Porosity f _t
		%				Mg ha ⁻¹		%	mm	Mg m ⁻³	%
Depth	1	0.405	0.372	0.6800	0.596	0.283	0.764	0.001	0.232	0.152	0.146
Treatments	4	0.003	0.508	<0.001	0.001	0.012	0.048	<0.001	0.006	<0.001	<0.001
Depth × treatment	4	0.813	0.746	0.682	0.930	0.915	0.887	0.798	0.683	0.789	0.799

df, degrees of freedom.

HCl as per the modified pressure calcimeter method (Sherrod et al., 2002).

The SOC concentration was obtained by subtracting soil inorganic C from total C. Total N concentration was measured by the semi-Kjeldahl method (Jackson, 1973).

Soil WSA Analyses

Air-dried bulk soil samples were gently crushed and sieved through an 8-mm sieve, and 50 g of aggregates (5–8 mm in size) were used for wet sieving (Yoder, 1936; Youker and McGuiness, 1957). Wet sieving was done by using a nest of five sieves (4.75, 2, 1, 0.5, 0.25, and <0.25 mm) after prewetting for 30 min and oscillated in water for 30 min (Nimmo and Perkins, 2002; Lal and Blanco-Canqui, 2007). Aggregates retained on each sieve were backwashed with deionized water to determine WSA. Aggregate size distribution was used to compute the mean weight diameter (MWD) (van Veen and Kuikman, 1990). Each aggregate size fraction was also ground to pass through a 0.25-mm sieve for determination of C and N concentrations.

Calculations of Soil Organic C and N Pools

The SOC and total soil N (TSN) pools were calculated for specific soil depths and fragments (4.75, 2, 1, 0.5, 0.25, and < 0.25 mm) using Eq.(1) (Lal et al., 1998):

$$\begin{aligned} \text{Mg SOC or TSN ha}^{-1} &= \% \text{ C or N} \times \text{soil depth (m)} \\ &\times \rho_b (\text{Mg m}^{-3}) \\ &\times 10^4 \text{ m}^2 \text{ ha}^{-1} / 100 \dots \end{aligned} \quad (1)$$

The SOC and TSN sequestration rates were calculated with reference to the control treatment as baseline by dividing the change in the SOC and TSN pools by the 14 years of the experiment duration.

Data Analysis

All data were analyzed statistically using the analysis of variance procedure in SAS program (SAS, 2009) to assess the effects of different treatments and soil depths on soil properties. Treatment means were compared using the least significant difference test when the analysis of variance showed significant land-use effects ($P \leq 0.05$).

RESULTS

Soil Bulk Density

After 14 years of cropping, ρ_b significantly changed ($P < 0.05$) (Table 2). There was a noticeable trend of higher ρ_b in the plots treated with chemical than organic fertilizers (Table 3). In the 0- to 0.15-m depth, ρ_b was 1.46 Mg m⁻³ in control compared with 1.13 Mg m⁻³ in the compost treatment. In 0.15- to 0.30-m depth, ρ_b was 1.47 Mg m⁻³ in control compared with 1.17 Mg m⁻³ in the compost treatment.

Total porosity (f_t) was calculated and, in the 0- to 0.15-m depth, the highest f_t of 57.23% was in the compost, 51.33%

in compost + mycorrhizae-treated soils, and the lowest of 44.84% was in the control plot (Table 3). Similar trends in f_t were observed for the 0.15- to 0.30-m depth.

Soil Organic C and N and C:N Ratio

Results of inorganic and organic C and N concentrations and total SOC and N pools for different fertilizer treatments are summarized in Table 4. Fertility management treatments significantly impacted ($P < 0.003$) total C concentrations, which in 0- to 0.15-m depth was 4.61% in control compared with 5.04% in the manured treatment. Similar trends were observed in the 0.05- to 0.30-m depth. Apparently, there was no impact of depth on soil inorganic C concentration, which was 3.78% for the 0- to 0.15-m depth and 3.82% for the 0.15- to 0.30-m depth.

The SOC concentration significantly increased with fertilizer treatments ($P < 0.001$), varying from 0.81% to 1.30% in the 0- to 0.15-m depth (\bar{X} 1.09%) and 0.84% to 1.26% (\bar{X} 1.10%) in the 0.15- to 0.30-m depth (Table 4). The most notable increase in SOC concentration occurred in the organic fertilizer plots, where it was higher than that in the control by 140% to 163% at both depths. In general, the SOC concentration increased with application of organic compared with the inorganic fertilizers and control treatments. Animal manure, compost, and compost + mycorrhizae treatments had significantly higher concentrations of SOC (in percent) than mineral fertilizer treatment.

The TSN concentration (in percent) also differed among fertilizers treatments ($P < 0.002$), ranging from 0.08% to 0.12% in the 0- to 0.15-m depth (Table 4). Use of animal

TABLE 3. Effect of Inorganic and Organic Fertilizers on Bulk Density and Porosity of the Soil

Soil Depth, m	Treatments	Bulk Density (ρ _b), Mg m ⁻³	Porosity (f _t), %
0–0.15	Control	1.46 ± 0.02a	44.84 ± 0.84c
	Mineral fertilizer	1.44 ± 0.06a	45.73 ± 2.26c
	Animal manure	1.18 ± 0.03c	55.37 ± 1.04a
	Compost	1.13 ± 0.02c	57.23 ± 0.93a
	Compost + mycorrhizae	1.29 ± 0.06b	51.33 ± 2.35b
0.15–0.30	Control	1.46 ± 0.10a	44.73 ± 4.10b
	Mineral fertilizer	1.46 ± 0.06a	44.93 ± 2.42b
	Animal manure	1.27 ± 0.06bc	52.04 ± 2.29a
	Compost	1.17 ± 0.06c	55.79 ± 2.32a
	Compost + mycorrhizae	1.31 ± 0.08b	50.52 ± 2.94a

Mean of three replicates ± SD. Means in the same column followed by the same letter represent significant differences ($P \leq 0.05$) among treatments at the same depth.

TABLE 4. Initial Soil Inorganic C, SOC, and N Concentration and Effects of Organic and Inorganic Fertilizer Application on Total SOC and Total N Pools

Depth, m	Treatments	Total Soil C, %	Inorganic C, %	SOC, %	N, %	C:N Ratio	SOC Pool, Mg ha ⁻¹	TSN Pool, Mg ha ⁻¹
0-0.15	Control	4.61 ± 0.01b	3.80 ± 0.01a	0.81 ± 0.00b	0.08 ± 0.00b	9.67 ± 0.42	17.69 ± 0.27b	1.83 ± 0.11b
	Mineral fertilizer	4.83 ± 0.10ab	3.86 ± 0.07a	0.97 ± 0.05b	0.10 ± 0.00a	9.32 ± 0.05	20.99 ± 1.83ab	2.25 ± 0.18a
	Animal manure	5.04 ± 0.07a	3.74 ± 0.07a	1.30 ± 0.11a	0.12 ± 0.01a	11.09 ± 0.61	23.08 ± 2.49a	2.09 ± 0.27ab
0.15-0.30	Compost	5.02 ± 0.38a	3.76 ± 0.20a	1.26 ± 0.20a	0.11 ± 0.01a	10.91 ± 0.74	21.40 ± 3.87ab	1.95 ± 0.22ab
	Compost + mycorrhizae	4.86 ± 0.05ab	3.75 ± 0.05a	1.11 ± 0.10a	0.10 ± 0.01ab	11.19 ± 1.21	21.42 ± 1.01ab	1.92 ± 0.17ab
	Control	4.65 ± 0.09b	3.81 ± 0.06a	0.84 ± 0.12b	0.08 ± 0.01b	10.15 ± 0.84	18.43 ± 2.69b	1.82 ± 0.22a
	Mineral fertilizer	4.86 ± 0.06b	3.86 ± 0.12a	1.00 ± 0.10b	0.10 ± 0.01ab	10.22 ± 1.18	21.78 ± 1.87ab	2.15 ± 0.30a
	Animal manure	5.06 ± 0.15a	3.85 ± 0.16a	1.21 ± 0.05a	0.11 ± 0.00a	10.82 ± 0.30	23.01 ± 0.77a	2.13 ± 0.12a
	Compost	4.99 ± 0.23a	3.73 ± 0.15a	1.26 ± 0.10a	0.11 ± 0.01a	11.23 ± 1.85	22.21 ± 2.68ab	1.99 ± 0.15a
	Compost + mycorrhizae	5.06 ± 0.21a	3.84 ± 0.05a	1.22 ± 0.17a	0.11 ± 0.01a	11.52 ± 0.60	23.90 ± 3.39a	2.07 ± 0.22a

Mean of three replicates ± SD. Means in the same column followed by the same letter represent significant differences ($P \leq 0.05$) among treatments at the same depth.

manure, compost, and compost + mycorrhizae increased TSN in both depths compared with those after control and mineral fertilizer treatments.

The C:N ratio ranged between 9.32 and 11.52, with an average of 10.50 (Table 4). In the 0- to 0.15-m depth, the C:N ratio is less than 10 in control and mineral fertilizer but more than 10 in organic fertilizer treatments.

Total Soil Organic C and N Pools

The SOC pools in the bulk soils were significantly affected by fertilizer treatments ($P < 0.001$) (Tables 2 and 4). These data indicate that organic fertilizer including mycorrhizal application increased SOC pool in both depths compared with that in control. Soil receiving animal manure had the largest SOC pool (23.1 Mg C ha⁻¹) in the 0- to 0.15-m depth relative to that of the control (17.7 Mg C ha⁻¹), which contained the least. In the 0.15- to 0.30-m depth, compost + mycorrhizae and animal manure treatments contained the largest SOC pool of 23.9 and 23.0 Mg C ha⁻¹, respectively, compared with 18.4 Mg C ha⁻¹ in the control treatment (Table 4).

Fertilizer management treatments also affected the TSN pool, with higher values in both layers of soil receiving mineral fertilizer. In the 0- to 0.15-m depth, TSN pool was 1.83 Mg ha⁻¹ for control, 2.25 Mg ha⁻¹ for the mineral fertilizer, and 1.92 Mg ha⁻¹ for the compost + mycorrhizae treatment.

C and N Sequestration

The effect of fertilizer treatments and management practices on C sequestration (CSQ) was calculated from the data between 1996 and 2010 using data for the year 1996 as the baseline (Table 5). Total CSQ ranged from 0.10 to 5.50 Mg ha⁻¹ for the 0- to 0.15-m depth and 2.73 to 8.20 Mg ha⁻¹ for the 0.15- to 0.30-m depth. The difference in CSQ between control and animal manure treatments was 5.40 Mg C ha⁻¹ for the 0- to 0.15-m depth and 5.42 Mg C ha⁻¹ for the 0.15- to 0.30-m depth. After 14 years of organic fertilizer application, there was a larger CSQ in the 0.15- to 0.30-m depth than in the 0- to 0.15-m depth layer. The average CSQ was 3.33 Mg ha⁻¹ in the 0- to 0.15-m depth and 6.17 Mg ha⁻¹ in the 0.15- to 0.30-m depth.

The calculated value of CSQ was 7 to 393 kg C ha⁻¹ year⁻¹ ($\bar{X}238$) for the 0- to 0.15-m depth compared with 195 to 586 kg C ha⁻¹ year⁻¹ ($\bar{X}441$) for the 0.15- to 0.30-m depth (Table 5). The rate of CSQ was almost double (441 kg C ha⁻¹ year⁻¹) in the 0.15- to 0.30-m depth compared with that (238 kg C ha⁻¹ year⁻¹) of the 0- to 0.15-m depth (Table 5).

Similar to CSQ, N sequestration (NSQ) was also computed using the control treatment as a baseline. Between 1996 and 2010, the NSQ ranged from 0.2 Mg N ha⁻¹ (control) to 0.6 Mg N ha⁻¹ (mineral fertilizer), with an average of 0.3 Mg N ha⁻¹ for the 0- to 0.15-m depth (Table 5). For 0.15- to 0.30-m depth, the NSQ ranged from 0.4 Mg N ha⁻¹ (control) to 0.7 Mg N ha⁻¹ (mineral fertilizer), with an average of 0.6 Mg N ha⁻¹ (Table 5). The annual rate of NSQ ranged from 11.1 to 41.0 kg N ha⁻¹ year⁻¹, with an average of 23.8 kg N ha⁻¹ year⁻¹, for the 0- to 0.15-m depth and 27.2 to 51.0 kg N ha⁻¹ year⁻¹, with an average of 42.5 kg N ha⁻¹ year⁻¹, for 0.15- to 0.30-m depth (Table 5).

A meaningful consideration is the CSQ and NSQ accumulated within the total soil profile. Thus, the total bulk soil CSQ and NSQ for the 0- to 0.30-m depth was calculated by summing the depth intervals. The calculated value of CSQ was 166 to 880 kg C ha⁻¹ year⁻¹ ($\bar{X}640$) for the 0- to 0.30-m depth. The rate of CSQ was 166 kg C ha⁻¹ year⁻¹ in control treatment compared with 880 kg C ha⁻¹ year⁻¹ in manure treatments (Table 5). The NSQ ranged from 38 to 91 kg N ha⁻¹ year⁻¹,

TABLE 5. C and N Sequestration Rates Between 1996 and 2010

Depth	Treatments	ρ_b Mg m ⁻³	SOC	N	C Sequestration			N Sequestration			
					SOC		Rate of CSQ	TSN		Rate of NSQ	
					1996	2010	Mg ha ⁻¹ C	Mg ha ⁻¹ N	1996	2010	kg ha ⁻¹ year ⁻¹
0-0.15 m	Control	1.34	0.88	0.08	17.6	17.7	0.1	1.7	1.8	0.16	11
	Mineral fertilizer				21.0	243	3.4		2.3	0.57	41
	Animal manure				23.1	393	5.5		2.1	0.41	29
	Compost				21.4	272	3.8		2.0	0.28	20
	Compost + mycorrhizae				21.4	273	3.8		1.9	0.25	18
Mean					20.9	238	3.3		2.0	0.33	24
0.15-0.30 m	Control	1.34	0.78	0.07	15.7	18.4	2.7	1.4	1.8	0.38	27
	Mineral fertilizer				21.8	434	6.1		2.2	0.71	51
	Animal manure				23.0	522	7.3		2.1	0.69	49
	Compost				22.2	465	6.5		2.0	0.55	40
	Compost + mycorrhizae				23.9	586	8.2		2.1	0.63	45
Mean					21.9	441	6.2		2.0	0.60	43
C and N Sequestration of 0-0.30 m	Control	1.34	0.83	0.08	33.8	36.2	2.3	3.1	3.7	0.53	38
	Mineral fertilizer				42.8	642	9.0		4.4	1.28	91
	Animal manure				46.1	880	12.3		4.2	1.10	78
	Compost				43.5	690	9.7		3.9	0.82	59
	Compost + mycorrhizae				45.3	822	11.5		4.0	0.87	62
Mean					42.8	640	9.0		4.0	0.9	66

C and N sequestration values were calculated base on data of the year 1996.

TABLE 6. Effect of Different Organic and Inorganic Fertilizers on C and N Concentrations in Different Aggregate Fractions

Parameters	Treatments	8–4.75 mm	4.75–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm
0–0.15 m							
C, %	Control	1.07 ± 0.08c	1.13 ± 0.12c	1.13 ± 0.04b	1.06 ± 0.27b	1.05 ± 0.19b	0.82 ± 0.04c
	Mineral fertilizer	1.34 ± 0.04b	1.26 ± 0.28bc	1.20 ± 0.16b	1.19 ± 0.21b	1.15 ± 0.12b	0.88 ± 0.09bc
	Animal manure	1.61 ± 0.00a	1.66 ± 0.01a	1.71 ± 0.17a	1.71 ± 0.03a	1.57 ± 0.18a	1.05 ± 0.08ab
	Compost	1.50 ± 0.15a	1.51 ± 0.14ab	1.59 ± 0.13a	1.64 ± 0.13a	1.53 ± 0.15a	1.05 ± 0.15a
	Compost + mycorrhizae	1.17 ± 0.10c	1.23 ± 0.06bc	1.25 ± 0.03b	1.22 ± 0.04b	1.19 ± 0.08b	0.88 ± 0.04ac
N, %	Control	0.08 ± 0.00e	0.09 ± 0.00d	0.09 ± 0.00c	0.08 ± 0.01c	0.08 ± 0.00c	0.07 ± 0.01bc
	Mineral fertilizer	0.11 ± 0.01c	0.12 ± 0.02bc	0.11 ± 0.00b	0.11 ± 0.02b	0.10 ± 0.01b	0.07 ± 0.01c
	Animal manure	0.14 ± 0.01a	0.14 ± 0.00a	0.15 ± 0.02a	0.14 ± 0.01a	0.13 ± 0.01a	0.09 ± 0.00a
	Compost	0.13 ± 0.00b	0.13 ± 0.00ab	0.14 ± 0.00a	0.14 ± 0.00a	0.13 ± 0.01a	0.09 ± 0.01ab
	Compost + mycorrhizae	0.09 ± 0.00d	0.10 ± 0.01cd	0.10 ± 0.01cb	0.10 ± 0.01cb	0.10 ± 0.00b	0.07 ± 0.01bc
0.15–0.30 m							
C, %	Control	0.92 ± 0.05c	0.97 ± 0.06c	1.02 ± 0.01d	0.98 ± 0.02c	0.84 ± 0.05b	0.69 ± 0.04c
	Mineral fertilizer	1.14 ± 0.08ab	1.14 ± 0.06ac	1.20 ± 0.07bc	1.18 ± 0.05bc	1.02 ± 0.05b	0.72 ± 0.14bc
	Animal manure	1.30 ± 0.15a	1.37 ± 0.18a	1.41 ± 0.07a	1.40 ± 0.12a	1.32 ± 0.15a	0.94 ± 0.12ab
	Compost	1.22 ± 0.16ab	1.30 ± 0.21ab	1.35 ± 0.19ab	1.36 ± 0.22ab	1.37 ± 0.17a	0.98 ± 0.20a
	Compost + mycorrhizae	1.03 ± 0.03bc	1.07 ± 0.06bc	1.05 ± 0.06cd	1.16 ± 0.06bc	0.99 ± 0.12b	0.82 ± 0.04ab
N, %	Control	0.07 ± 0.00c	0.08 ± 0.01c	0.08 ± 0.00c	0.08 ± 0.01c	0.07 ± 0.00c	0.07 ± 0.01bc
	Mineral fertilizer	0.10 ± 0.02bc	0.10 ± 0.01b	0.10 ± 0.01b	0.10 ± 0.01b	0.10 ± 0.01bc	0.07 ± 0.01c
	Animal manure	0.12 ± 0.01ab	0.13 ± 0.01a	0.13 ± 0.01a	0.12 ± 0.01a	0.11 ± 0.01ab	0.09 ± 0.01b
	Compost	0.13 ± 0.02a	0.12 ± 0.01a	0.13 ± 0.01a	0.13 ± 0.01a	0.13 ± 0.01a	0.10 ± 0.01a
	Compost + mycorrhizae	0.09 ± 0.01c	0.10 ± 0.00b	0.10 ± 0.01b	0.10 ± 0.01b	0.09 ± 0.01c	0.07 ± 0.01c

Mean of three replicates ± SD. Means in the same column followed by the same letter represent significant differences ($P \leq 0.05$) among treatments at the same depth.

with an average of 66 kg N ha⁻¹ year⁻¹, for the 0- to 0.35-m depth. The control treatment had 38 kg N ha⁻¹ year⁻¹ compared with 91 kg N ha⁻¹ year⁻¹ with in mineral fertilizer treatment (Table 5). In general, compared with depth interval data, summation of the soil profile sequestration analysis data shows that differences between control and fertilizer treatment were significantly different.

C and N in Aggregate Size Fractions

In the 0- to 0.15-m depth, the SOC concentration in the control ranged from 1.07% for 4.77 mm to 0.81% for less than 0.25-mm aggregates (Table 6). In the animal manure treatment, however, the SOC concentration ranged from 1.61% for 4.77 mm to 1.50% for the less than 0.25-mm aggregates. A similar trend was observed for the 0.15- to 0.30-m depth. In the control and mineral fertilizer treatments, there was a trend of increase in concentration of SOC between the 4.75-mm and 1-mm aggregates.

Similarly, TSN concentration (in percent) in different aggregate sizes differed among fertilizer treatments. Higher TSN (in percent) was measured in animal manure and compost than in compost + mycorrhizae treatment in both soil layers. In general, TSN (in percent) was highest in the more than 1-mm aggregates and lowest in the less than 0.25-mm aggregates (Table 6). Furthermore, TSN concentration (in percent) decreased with the decrease in aggregate size from the 0.50-mm fraction to the less than 0.25-mm fraction.

Water-Stable Aggregation and the MWD

Size distribution of WSA differed significantly among fertilizer treatments in the 0- to 15-m and 0.15- to 0.30-m depths. In general, a high WSA (in percent) was observed in control, chemical fertilizer, animal manure, and compost treatments. There was also a trend of higher WSA (in percent) in the less than 0.25-mm size aggregates in these treatments. However, WSA (in percent) decreased with the decrease in aggregate size in compost + mycorrhizae-treated soil. Soil receiving compost + mycorrhizae treatment had a greater proportion of WSA in the 5- to 8-mm aggregate size, by 32.48%, and a lower proportion in other aggregate sizes (2–5, 1–2, 0.5–1, 0.25–0.50, and ≤0.25 mm) than those in chemical fertilizer treatments that had the lowest proportion of WSA, by 10.39%, in the 0- to 0.15-m soil depths (Table 7). There was a significant difference among treatments in distribution of macroaggregates (>0.25 mm) and microaggregates (<0.25 mm). High WSA (in percent) was measured in the 0.5-mm size. The WSA (in percent) in the 2- to 4.75-mm size and 1- to 2-mm size did not differ among treatments (Table 7).

The MWD of aggregates was also significantly affected by the fertilizer treatments ($P < 0.005$), ranging from 1.43 to 3.18 mm (Table 7), with a notable increase of 216% in the compost + mycorrhizae treatment compared to that in the chemical fertilizer treatment. The highest MWD of 3.09 mm was found in the compost + mycorrhizae treatment and the lowest of 1.43 mm was found in the chemical fertilizer treatment for the 0- to 0.15-m depth. The MWD was in the order of compost + mycorrhizae > compost > animal manure > control > chemical fertilizer.

DISCUSSION

Relationship Between SOC and Soil Bulk Density and Porosity

Total porosity (f_t), a function of SOM and aggregate stability and size distribution (Baldock and Nelson, 2000), was also significantly ($P < 0.0001$) affected by the treatments. Soil

TABLE 7. Effect of Different Organic and Inorganic Fertilizers on WSA

Depth, m	Treatments	WSA, %							Total WSA, %	MWD, mm
		8–4.75 mm	4.75–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm			
0–0.15	Control	10.54 ± 9.23b	11.62 ± 3.93a	13.58 ± 3.94a	22.46 ± 4.82a	13.63 ± 4.03ab	23.04 ± 10.48a	71.82 ± 9.09b	1.49 ± 0.47b	
	Mineral fertilizer	10.39 ± 2.84b	9.88 ± 3.78a	14.99 ± 0.17a	20.20 ± 2.56ab	18.54 ± 7.31a	21.65 ± 0.36a	74.01 ± 0.61b	1.43 ± 0.19b	
	Animal manure	19.50 ± 3.82ab	11.42 ± 1.58a	13.22 ± 2.25a	17.50 ± 1.08ab	13.15 ± 1.36ab	19.71 ± 3.57a	74.79 ± 4.67b	2.02 ± 0.25b	
	Compost	18.13 ± 4.68b	12.63 ± 1.69a	13.83 ± 2.74a	17.84 ± 3.46ab	14.34 ± 2.07 ab	21.83 ± 2.04a	76.77 ± 5.71ab	1.98 ± 0.26b	
0.15–0.30	Comp. + mycorrhizae	32.48 ± 13.40a	17.77 ± 10.62a	16.35 ± 7.11a	13.20 ± 6.06b	10.30 ± 3.81b	9.39 ± 2.40b	90.10 ± 12.06a	3.09 ± 0.34a	
	Control	14.02 ± 5.15bc	11.71 ± 7.02a	17.16 ± 1.39a	19.70 ± 1.52a	14.24 ± 5.21a	17.38 ± 1.32ab	76.85 ± 1.96c	1.74 ± 0.13c	
	Mineral fertilizer	12.93 ± 7.66c	14.10 ± 3.50a	17.70 ± 1.66a	17.27 ± 0.92ab	13.99 ± 3.07a	19.73 ± 3.41 a	75.98 ± 2.45c	1.75 ± 0.31c	
	Animal manure	21.72 ± 6.78bc	18.41 ± 8.20a	16.43 ± 3.28a	17.08 ± 3.68ab	8.32 ± 1.38ab	13.45 ± 1.65 bc	81.96 ± 2.97b	2.41 ± 0.15b	
	Compost	24.02 ± 3.57b	17.75 ± 1.73a	13.81 ± 5.08a	14.74 ± 2.15ab	9.37 ± 1.32b	13.86 ± 2.46bc	79.70 ± 2.68cb	2.49 ± 0.17b	
	Compost + mycorrhizae	35.64 ± 5.16a	16.09 ± 5.90a	14.88 ± 1.52a	13.52 ± 4.17b	6.88 ± 0.91b	9.96 ± 3.75c	87.00 ± 0.77a	3.18 ± 0.20a	

Mean of three replicates ± SD. Means in the same column followed by the same letter represent significant differences ($P \leq 0.05$) among treatments at the same depth.

porosity, a reverse trend to that of ρ_b , was highest in the compost and lowest in the control and chemical fertilizer treatments. Soils treated with organic fertilizers (compost and compost + mycorrhizae) had the highest f_t . Agbede (2010) observed that application of poultry manure alone and complementary application of NPK fertilizer with poultry manure reduced ρ_b and soil temperature. Similarly, Singh et al. (2009) observed that ρ_b was the highest in the chemical fertilizer compared with the organic treatments. However, applications of organic fertilizers increased the soil water content and f_t , whereas that of the NPK did not improve soil physical properties. Similar results of application of organic fertilizer on ρ_b and f_t were reported by Caravaca et al. (2002) and Celik et al. (2004).

Bearden (2001) observed that AMF-inoculated soil generally has the largest pore size, and mycorrhizal hyphae significantly contributed to stabilize pores.

Effect of Organic and Inorganic Fertilizer on Soil Organic C and N Concentration

The trend of somewhat higher SOC pool in the 0.15- to 0.30-m depth compared with that in the 0- to 0.15-m depth in the control and mineral fertilizer treatments may be caused by incorporation of residues and root biomass and to relatively lesser breakdown of soil aggregates, thus, the lower rate of SOM decomposition in the subsoil (Singh et al., 2009).

In the 0.15- to 0.30-m depth, use of soil mineral fertilizer and animal manure resulted in a larger TSN pool. The fertilizer treatment with high TSN pool can be correlated with high yields producing high crop residues and root biomass, and consequently contributing to the total SOC pool. The high rate of soluble fertilizer used may have influenced the TSN pool. Thus, judicious application of N fertilizer is important to obtain high crop yields and also enhance the SOC pool. Malhi et al. (1997) indicated that long-term annual additions of fertilizer N to bromegrass (*Bromus inermis*) resulted in a marked increase in total C and N concentrations, which were also influenced by the rate and source of N fertilizer.

The increase in the SOC pool was accompanied by an increase in the C:N ratios in all organic treatments compared with those in the control and chemical fertilizers. The high C:N ratio was also related to a high SOC pool. Similar to our data, Hassink (1994) reported that the C:N ratio was usually about 10 in loam and clay soils.

C and N in Different Aggregate Sizes

The SOC concentration tended to decrease in the 0.25- to 1-mm aggregates. Similar results have been reported for some soils in Ohio (Lal and Fausey, 1993; Abid and Lal, 2008). In all treatments receiving biofertilizers (i.e., animal manure, compost, and compost + mycorrhizae), SOC concentration increased with a decrease in aggregate size from 4.75 to 0.25 mm. Similar results were observed in both the 0- to 15-m and 0.15- to 0.30-m layers. Furthermore, the highest SOC concentration in aggregates was observed in organic manure and compost treatments in both depths. Such an increase in concentration of SOC in stable aggregates is crucial to enhancing CSQ and increasing its mean residence time. In general, macroaggregates retain more C than microaggregates (Six et al., 2000; Kong et al., 2005). Singh et al. (2009) also reported that SOC storage was significantly higher in macroaggregates than in mesoaggregates and microaggregates and that in the silt + clay fractions.

The data support the conclusion that higher SOC and TSN concentrations occurred in the aggregate sizes between 1 and

0.50 mm than those in the less than 0.25-mm size (Table 6). For some Alfisols in Central Ohio, Saroa and Lal (2003) also reported the highest SOC concentration (in percent) in the 0.25-mm aggregate size fraction. Furthermore, SOC, MBC, and respiration rate can be the highest for the 1.0- to 2.0-mm aggregates (Jiang et al., 2011). Tisdall and Oades (1982) observed that macroaggregates play an important role in stabilizing SOC and TSN concentrations and that stability of the aggregates protects SOC against mineralization (Holeplass et al., 2004). It is also probable that the wet sieving is not a suitable technique for measuring TSN in aggregate size fractions. The data from the present study show that concentrations of SOC and TSN in bulk soil were more than those in aggregates after sieving in water. Being highly soluble, N is likely to be washed out of the aggregates during the wet sieving procedure.

C and N Sequestration

The higher CSQ in the 0.15- to 0.30-m depth compared with that of the 0- to 0.15-m depth may be attributed to a minimal soil disturbance, which for the plough layer disrupts the dynamic equilibrium of SOM inputs and outputs. Ploughing increases aeration and accentuates oxidation of SOM. Six et al. (2000) observed that soil disturbance from tillage is a major cause of SOM depletion and reduction in the amount and stability of soil aggregates. In addition, plant root in the 0.3-m depth may have relatively contributed more to SOC concentration in subsoil than that in the surface layer. Katterer et al. (2011) indicated that root-derived C was about 2.3 times higher than that contributed by the aboveground plant residues. Liang et al. (2012) also reported that application of FYM is important to soil CSQ and improves soil quality under a wheat/maize system in the North China Plain.

High CSQ in the 0.15- to 0.30-m depth may also be attributed to the climatic effects on SOM decomposition. Under the Mediterranean climate, ambient temperature rises up to 40°C during the summer months. Thus, it may take more time for SOM to accumulate in the surface layer with supraoptimal soil temperatures.

These rates are higher than those reported (Lal, 2002; 2005) for the arid climate. Lou et al. (2011) reported that manure treatment was most effective for sequestering SOC approximately 10.6 Mg ha⁻¹.

Some recommended management practices for CSQ include establishing vegetative cover by deep-rooted perennial vegetation and afforestation, improving soil fertility, and alleviating soil-related constraints caused by physical, chemical, and biological factors through fertilizers and soil amendments such as biosolids, manure, coal combustion by-products, and mulches (Ussiri et al., 2006). The control treatment in the present study, because there is no fertilizer input, is expected to have negative CSQ. On the contrary, the higher SOC pool measured in 2010 than the antecedent level in 1996 may be attributed to plant residue (straw) retention that may have created a positive C budget.

Wu et al. (2008) reported that mycorrhizae enhanced the WSA fraction in 2-mm aggregates more than in 1–2-mm and 0.25 mm aggregates, but reduced the WSA fraction in the 0.25- to 0.5-mm fractions. On the other hand, Lou et al. (2011) reported that application of organic materials increased the proportion of the large WSA (>2 mm) and decreased the proportion of small WSA (<1 mm), resulting in an increase in the MWD of WSA. However, application of chemical fertilizer had little effect. In general, organic amendments increased WSA compared with the chemical fertilizer treatments. In the 0- to 0.15-m depth, WSA ranged from 71.82% in control to 90.10% in compost + mycorrhizae treatment. Such an increase

may be because of retention of plant residues, root biomass, and hyphae and other soil biological factors that increase aggregate stabilization.

Wilson et al. (2009) also reported that AMF abundance was a dominant factor affecting variability in WSA and MWD. Abiven et al. (2007) indicated that fungi enhance resistance to mechanical breakdown and slaking of aggregates. Furthermore, there was a general trend of increase in MWD with increase in the rate of application of organic amendments.

In general, macroaggregates contain higher MBC fraction than microaggregates (Miller and Dick, 1995). Nadian et al. (2009) demonstrated that colonized berseem clover (*Trifolium alexandrinum* L.) improved root length by 20% because of increase in diameter of aggregates. Bedini et al. (2009) reported that MWD was significantly higher in mycorrhizae-treated soil compared with non-mycorrhizae soil.

There is no scientific consensus with regard to the depth distribution of the MWD of aggregates. Fernandez-Ugalde et al. (2009) observed that MWD was higher in the 0.15- to 0.30-m depth than in the 0- to 0.05-m and 0.05- to 0.15-m depths, and Zotarelli et al. (2005) observed no effect of depth on the MWD. The site-specific effects may be related to soil type and clay minerals.

Data from the present study show that the MWD depended more on mycorrhizae application than on SOC concentration. Because MWD was not measured in 1996, it is not possible to assess the evolution of MWD over time under different treatments. Yet, development of soil structure and the dynamics of WSA in many soils are usually closely related to the cycling of SOM and the magnitude of root and mycorrhizal hyphae (Hallett et al., 2009; Rillig et al., 2010).

Bedini et al. (2009) reported that MWD of soil aggregates were positively correlated with the hyphal length and hyphal density of the AMF. Similarly, Caravaca et al. (2006) reported that the combination of *G. intraradices* with organic amendments significantly enhanced structural stability. Abiven

et al. (2007) indicated that aggregate stability was influenced by the length of fungal hyphae. Smith and Read (2008) concluded that the contribution of mycorrhizal root plus hyphae on aggregation is more than those of the hyphae, and that under pasture, the contribution of root and hyphae to WSA increases with the increase in SOC concentration. However, mycorrhizal hyphae and glomalin content were not measured in the present study. Nonetheless, plant root colonization ratio was determined after each cropping cycle. The data showed that colonization and number of spores were greater in compost + mycorrhizae than in other treatments (data not presented). Additional studies on determination of the glomalin and other biochemical properties are needed.

The AMF are key organisms in the soil/plant system because of their positive effects on soil aggregation and stability caused by the combined action of extraradical hyphae and of an insoluble hydrophobic proteinaceous substance named glomalin-related soil protein (Bedini et al., 2009). Holeplant et al. (2004) observed that the dry aggregate size distribution was not significantly affected by fertilizer rates nor were there any apparent trends other than a slight decrease in MWD in the 0- to 0.10-m soil depth and an increase of MWD with increase in fertilizer rates in the 0.10- to 0.25-m soil depth. These trends may be attributed to the effect of soil distribution and long-term management practices. In addition, physical, chemical, and biological properties are different in bulk soil compared with the rhizosphere soil (Marschner, 1995; Ortas, 1997). Most probably, the microstructure is more developed in rhizosphere soil than in the bulk soil through the mycorrhizal hyphae, and C leached from rhizosphere and mycorrhizosphere is present in the soil aggregates.

Intercorrelation Between Soil Aggregates and C and N Concentrations

The data on intercorrelation among soil properties are presented in Table 8. There is a negative and significant correlation between MWD and soil ρ_b ($R^2 = -0.427$, $P < 0.018$)

TABLE 8. The Correlation Matrix of Soil Properties

	TSC, %	ISC, %	OC, %	N, %	ρ_b	f_t	SOC, Mg ha ⁻¹	TSN, Mg ha ⁻¹	MWD, mm	WSA, %
TSC	1.0									
ISC	0.38678	1.0								
	0.0347*									
OC	0.87903	-0.09927	1.0							
	<0.0001*	0.6017								
N	0.75294	-0.01808	0.81985	1.0						
	<0.0001*	0.9244	<0.0001*							
ρ_b	-0.48005	0.44434	-0.75011	-0.63044	1.0					
	0.0073*	0.0139*	<0.0001*	0.0002*						
f_t	0.48278	-0.44079	0.75131	0.63209	-0.99981	1.0				
	0.0069*	0.0148*	<0.0001*	0.0002*	<0.0001*					
SOC	0.87652	0.18737	0.84756	0.67894	-0.29293	0.29495	1.0			
	<0.0001*	0.3215	<0.0001*	<0.0001*	0.1162	0.1136				
TSN	0.54555	0.40028	0.37915	0.65372	0.13679	-0.13506	0.66033	1.0		
	0.0018*	0.0284*	0.0388*	<0.0001*	0.4710	0.4767	<0.0001*			
MWD	0.29218	-0.20399	0.42182	0.18909	-0.42751	0.42865	0.32385	-0.09756	1.0	
	0.1172	0.2796	0.0202*	0.3170	0.0184*	0.0181*	0.0726	0.6080		
WSA	0.12537	-0.03249	0.14847	0.16704	-0.10090	0.09862	0.17392	0.14624	0.67477	1.0
	0.5092	0.8647	0.4336	0.3776	0.5957	0.6041	0.3580	0.4406	<0.0001*	

* $P < 0.05$ significant.

TSC, total soil C; ISC, inorganic soil C; OC, organic C.

and a positive correlation between MWD and f_i ($R^2 = 0.429$, $P < 0.018$) and SOC concentration ($R^2 = 0.421$, $P < 0.02$). The correlation between ρ_b and SOC concentration was significantly negative ($R^2 = -0.750$, $P < 0.001$) (Table 8). These results are in accord with those of Lal and Fausey (1993) who also reported a negative correlation between ρ_b and SOC concentration. Concentration of TSN was positively correlated with those of SOC and TC but not with ρ_b . Concentrations of SOC and TSN in WSA were not correlated among each other (Table 8).

There was a weak correlation between SOC concentration and WSA for either depth. Because the SOC concentrations differ among aggregate fractions, there exists no correlation between SOC and WSA. Abiven et al. (2007) also reported no significant correlation between SOC and WSA. On the contrary, Golchin et al. (1994) reported a strong correlation between SOC concentration and aggregation ($R^2 = 0.69$, $P < 0.001$). Similarly, Jastrow and Miller (1998) and Six et al. (2000) reported that macroaggregates, composed of clusters of microaggregates, were correlated with SOC concentration. The data of the present study support the hypothesis that organic fertilizer increased CSQ, and that more C was encapsulated within macroaggregates than in microaggregates. Thus, soil aggregation plays a key role in CSQ by physically protecting SOM through its encapsulation within stable aggregates. Golchin et al. (1994) and Caravaca et al. (2002) also reported that soil structural stabilization is related to SOM inputs. Six et al. (2000a, 2000b) reported that the SOM pool is stabilized through association with silt and clay particles within macroaggregates and microaggregates. There also exists a positive correlation between SOC concentration and the quantity of macroaggregates (Jiao et al., 2006). Kong et al. (2005) also concluded that CSQ is associated with the proportion of macroaggregation in the soil.

Accurate measurement of changes in SOC and TSN concentrations, in relation to the amount of biomass C and N retained annually, remains to be a major challenge. Generally, measurement of SOC concentration is also affected by the presence of carbonates. There is a strong need for the development of standard methods for credible assessment of SOC in calcareous soils.

CONCLUSIONS

Long-term application of organic fertilizers significantly affected SOC, TSN, WSA, MWD, ρ_b , and f_i relative to the control treatment. These results show that 4 years of organic fertilizer management that changed the SOC pool through the profile and increased SOC storage have an effect on soil physical and chemical properties. The data are also in accord with the proposed hypothesis and support the following conclusions:

1. Application of organic fertilizers decreased ρ_b and increased total f_i because of increase in SOC concentration.
2. Concentrations of SOC and TSN were significantly higher in soils receiving organic fertilizers than those in soils receiving chemical fertilizers and control. Pools of SOC and TSN were also higher in soils receiving organic fertilizers than those in soils treated with inorganic fertilizers.
3. The annual rate of CSQ was greater in soils treated with organic fertilizers than that in soils treated with inorganic fertilizers. However, the rate of N accretion was higher in soils receiving inorganic fertilizers than that in soils receiving organic fertilizers.
4. Concentrations of SOC and TSN in aggregate size fractions were significantly higher in soils receiving organic fertilizers than those in soils receiving chemical fertilizers. Similarly, SOC and TSN pools were also higher in soils

receiving organic fertilizers than those in soils receiving chemical fertilizers and control. Soils treated with organic fertilizer contained more C and N in macroaggregates compared with those contained in microaggregates.

5. Both WSA and their MWD were larger in soils receiving compost + mycorrhizae inoculation treatment than those in soils receiving chemical fertilizer and control. Contribution of compost + mycorrhizae to MWD exceeded that the application of animal manure and compost treatment.
6. Concentration of SOC was positively correlated to MWD.

Application of organic fertilizers increased soil aggregation and enhanced C sequestration. The rate and total amount of sequestration were more in the 0.15- to 0.30-m layer than those in the 0- to 0.15-m layer.

Sustainable management of soil must be viewed in the context of projected climate change. Use of fertilizers and amendments must be done to alleviate nutrient imbalance, enhance SOC and TSN pools, and improve soil quality especially with regard to soil structure and aggregation.

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