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Impacts of biosolids application on soil quality under alternate year no-till corn–soybean rotation

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Abstract Biosolids are a source of recycled organic matter and nutrients. To evaluate the impact of biosolids application (1984–2008) on soil quality, composite soils (Genesee silt loam, fine loamy, mixed, nonacid, and mesic typic udifluvent) were randomly sampled at geo-referenced sites from 0 (control), 2, 5, and 25 years of lime-stabilized anaerobically digested biosolid-applied fields. Results showed that microbial biomass C (C_{mic}), N (N_{mic}), and P (P_{mic}) contents were significantly higher at both depths of the 5 and 25 years of biosolid-applied fields compared to the control. Biosolid application significantly enlarged the biologically labile C (C_{mic} over total organic C, C_{mic}:C_{org}) and N (N_{mic} over total N, N_{mic}:TN) pools with an associated decrease in metabolic C loss (20–53 %) by specific maintenance respiration (qCO_2) relative to the control. The C_{org}, active (AC) and soluble C (SC), TN and reactive N (RN), and reactive P (RP) contents were significantly higher in the long-term biosolid-applied fields than in the control. However, there was an indication of leaching of SC, RN, and RP between depths. Years of biosolid application significantly increased soil moisture content (θ_v at −0.03 MPa) by 20–40 %, macroaggregate stability (MaA) by 2–44 %, and mean weight diameter (MWD) of aggregates by 7–51 %, respectively. Consequently, there was a decrease in soil bulk density (ρ_b) and microaggregate stability (MiA) at both depths. Results confirmed that biosolids application at rates recommended is a viable management option to improve soil quality for crop production. However, long-term and repeated biosolid applications above the recommended agronomic N and P rates may be responsible for accumulation and consequent leaching and runoff of SC, RN, and RP to cause groundwater and surface water pollution with environmental consequences.

Keywords Microbial biomass · Basal respiration · Active carbon · Reactive nitrogen and phosphorus · Bulk density · Aggregate stability

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1 Introduction

Due to increase in population growth and urbanization, municipalities throughout the USA are receiving an increasing volume of wastewater for treatment and recycling (USEPA 2011). Consequently, biosolid production has steadily increased and its disposal has become a major socioeconomic and environmental concern. About 7.2 million tons of biosolid (on a dry-weight basis) are produced annually in the USA, with 55 % of those biosolids applied to land, 15 % are incinerated, and 30 % are landfilled (USEPA 2011). Since biosolids are nutrient-enriched organic matter, recycling biosolid as an agricultural amendment is expected to improve soil quality (Sigua et al. 2005; Hargreaves et al. 2008; Guo et al. 2012).

Soil quality is a composite functional capacity of soil determined by biological, chemical, and physical properties as they respond to management practices (Aziz et al. 2013). As a complex functional state, soil quality cannot be measured directly, but may be inferred from management-induced temporal changes in soil properties (Islam and Weil 2000). Several studies have reported that agronomic management of biosolid as a soil amendment improved soil quality properties through qualitative and quantitative changes in soil organic matter (SOM) and nutrient availability to support crop production (Banerjee et al. 1997; Tsadilas et al. 2005; Lu et al. 2012; Cogger et al. 2013). The labile pool of C and available nutrients in biosolid acts as a source of food and energy for heterotrophic microbes to carry out ecological functions (Banerjee et al. 1997). Although microbial biomass represents a small living and labile pool of SOM, it plays a critical role in plant residue decomposition, nutrient recycling, and soil aggregate formation (Saviozzi et al. 1999; Tarrasón et al. 2010). Microbial biomass, in particular, is a sensitive and early indicator of soil biological quality, which predicts short- and long-term changes in soil ecosystems (Powlson et al. 1987; Sundermeier et al. 2011; Aziz et al. 2013). Soil biological properties are also influenced by long-term organic amendments especially biosolids application (Lu et al. 2012).

It is reported that long-term application of biosolid can result in a significant increase (2.5-folds) in C_{org} content (Parat et al. 2005). Besides increasing C, biosolid application increased N and P availability through partitioning of SOM into different pools (Binder et al. 2002). An advantage of using biosolid to supplement or replace synthetic fertilizers is its chemical nature and composition, which act as a source of slow-release essential nutrients (e.g., N and P) with an additional benefit of SOM accumulation (Singh and Agrawal 2008). While serving as a source of labile C and essential nutrients to support biological activity, biosolids improved soil structure by acting as one of the cementing agents for aggregate formation and stabilization (Oades 1984; Sundermeier et al. 2011). Increased aggregate stability is associated with higher water infiltration, reduced soil compaction, increased porosity and moisture content, and favorable habitat for soil organisms (Hudson 1994; Tsadilas et al. 2005).

While agricultural land application of biosolids can be a viable option for recycling organic matter and essential nutrients to support crop production, it may pose a potential threat by reducing agroecosystem services. Long-term and repeated applications of biosolids for crop production have been debated due to accumulation of soluble and organically bound heavy metals, an excess of micronutrients, and diverse organic contaminants in soil (McGrath et al. 1995; Singh and Agrawal 2008). Higher concentrations of heavy metals and micronutrients can be antagonistic to soil biology and, consequently, affect soil chemical and physical properties (McGrath et al. 1995). However, results from several long-term studies have reported that lime-stabilized biosolid reduce heavy metals solubility and toxicity by rising soil pH (Christie et al. 2001; Luo and Christie 2002; Islam et al. 2013). As more and more biosolids are turned to environmentally viable ways of heavy metals stabilization, more treated biosolids (class A) are expected to be available for using in agricultural crop production (Guo et al. 2012; USEPA 2011; Islam et al. 2013). Lime-stabilized biosolids are expected to serve as an important source of SOM, calcium, and slow-release essential nutrients to support crop production and contribute to reducing the cost of landfilling or incineration (Sigua et al. 2005; Hargreaves et al. 2008; Guo et al. 2012).

Long-term effects of lime-stabilized anaerobically digested biosolids application on soil biological, chemical, and physical properties, as an integrated measure of soil quality, may be synergistic, antagonistic, or neutral. More information is needed regarding the long-term effects of lime-stabilized anaerobically digested biosolids on soil quality for enhanced agroecosystem services. The hypothesis of our study is that due to high lime, organic matter, and essential nutrient contents, application of lime-stabilized biosolid as a soil amendment will cause measureable and consistent positive changes in soil biological, chemical, and physical properties and, consequently, improve soil quality. The objectives of the study were to measure the impact (from 1984 to 2008) of repeated applications of lime-stabilized anaerobically digested urban liquid biosolids on soil microbial biomass and associated biological properties, dynamics of C, N, and P pools in SOM, and soil moisture and aggregate characteristics as soil quality indicators under alternate year no-till corn–soybean rotation, with reference to chemical fertilization.

2 Materials and Methods

2.1 Description of the Site

The study was conducted on a farmer's field (39° 19′ 59″ N and 82° 58′ 57″ W) in the Ross County of Southern Ohio, USA. The soil is a well-drained Genesee silt loam (a fine loamy, mixed, nonacid, mesic typic udifluvent) which was developed from outwash of uplands and terraces underlain by calcareous Wisconsin glacial drift (Soil and Water Conservation Staff 1967). The soil has an average pH of 7.1±0.4 with an electrical conductivity of 240±42 μS cm^{-1} and contains 18, 59, and 23 % of sand, silt, and clay, respectively, at a 0- to 30-cm depth.

2.2 Biosolid Application and Treatments

Lime-stabilized anaerobically digested liquid biosolids generated by the Ross County (Chillicothe) water treatment plant were routinely applied on the farmer's fields under alternate year corn–soybean rotation since 1984 (Islam et al. 2013). Biosolid, on average, had a pH of 7.7 ±0.3 and contained about 6 % solids. Details of the biosolid characteristics and temporal loading on the applied fields are presented in Table 1. While the 2-year biosolid-applied field (~4 ha) received its first application in 2007 with a total loading of 7.2 Mg ha^{-1}, the 5-year field (~9 ha) received its first biosolid application in 2004 and last application in 2008 with a total loading of 21.7 Mg ha^{-1}. The 25-year field (~11 ha) received its first biosolid application in 1984 and last application in 2008 with a total loading of 91.6 Mg ha^{-1}, on a dry-weight basis. Biosolid were surface-applied (based on crop nitrogen requirements) biannually in mid-April followed by no-till planting of corn in the 1st week of May. However, biosolid was not applied to no-till soybeans. Both corn and soybeans were supplemented with P and K fertilization.

Table 1 Lime-stabilized anaerobically digested biosolids characteristics and loading (dry-weight basis) in soil over time (1984–2008)

Biosolids characteristics	Loadings over time (year)		
	2	5	25
Total biosolid applied (mg ha^{-1})	7.2	21.7	91.6
Total organic carbon (mg ha^{-1})	1.7	5.1	21.7
Soluble carbon (kg ha^{-1})	383	1,149	4,857
Total nitrogen (kg ha^{-1})	263	792	3,343
Total carbon: nitrogen	6.5	6.4	6.5
Ammonium-nitrogen (kg ha^{-1})	153	460	1,943
Nitrate-nitrogen (kg ha^{-1})	14	43	183
Soluble carbon: nitrogen	2.3	2.3	2.3
Total phosphorus (kg ha^{-1})	94	283	1,196
Available potassium (kg ha^{-1})	18	55	234
Extractable heavy metals (kg ha^{-1})[a]			
Arsenic	0.07	0.22	0.92
Cadmium	0.04	0.11	0.46
Cobalt	0.15	0.46	1.9
Chromium	0.11	0.33	1.4
Copper	0.24	0.72	3.0
Nickel	0.18	0.54	2.3
Lead	0.79	2.39	10.1
Zinc	2.38	7.16	30.2

[a] Islam et al. (2013)

2.3 Soil Sampling, Processing, and Analysis

Composite soil samples were collected at depths of 0–15 and 15–30 cm from geo-referenced sites on the biosolid-applied fields (Islam et al. 2013). An adjacent field (~14 ha) that received only chemical fertilizers and had a crop rotation similar to the biosolid-amended fields was sampled as a control. Four replicated plots (30 m×30 m) were randomly geo-referenced in all fields, and 25 soil cores (1.98-cm diameter) were collected in sealable plastic bags from each replicated plot. A portion of the field-moist soil was gently sieved through a 2-mm mesh followed by incubation in sealable plastic bags at room temperature (~25 °C) for 7 days to stabilize biological activity prior to analyzing for microbial biomass and associated biological activities. Another portion of the field-moist soil was 4-mm sieved and air-dried at room temperature for 15 days prior to performing soil chemical and physical analyses.

The C_{mic}, N_{mic}, and P_{mic} were measured by the $CHCl_3$ fumigation–extraction method using 0.5 M neutral K_2SO_4 solution (Brookes et al. 1982, 1985; Vance et al. 1987). Basal respiration (BR) was measured by in vitro static incubation of unamended field-moist soil in a temperature-controlled incubator at 25±1 °C for a 15-day period (Islam and Weil 2000). The qCO_2, i.e., the amount of C used for microbial metabolism was calculated as BR per unit of C_{mic} per day (Anderson and Domsch 1990). Potentially mineralizable C (C_{Min}) content of the soil was calculated by dividing the total amount of CO_2 released from the 15 days incubation by the C_{org} content.

The concentration of C_{org} and TN was determined on finely ground (<0.1 mm) air-dried soil by the dry combustion method using Elementar® CN analyzer. The AC content was measured colorimetrically as a 0.02 M neutral $KMnO_4$ oxidizable C pool (Weil et al. 2003). To measure SC, RN, and RP contents, a 10 g sample of field-moist soil was placed in 50 ml screw-top polypropylene tube followed by shaking with 25 ml of 0.5 M K_2SO_4 for 60 min, centrifuged at 2,000 rpm for 5 min, and then filtered to obtain soil-free extracts. The concentration of SC was determined by using Shimadzu® dissolved C and N analyzer. The concentration of RN (NH_4^+ and NO_3^-) and RP (soluble and extractable P) was measured by using Astoria® 310 auto-analyzer. Electrical conductivity (EC_s) was measured with soil to distilled water ratio of 1:1 by a conductivity meter. Soil pH was determined by a glass electrode in 1:2 soil–distilled water suspensions.

The ρ_b was calculated from the relationship of oven-dried equivalent weight of a known volume of soil by using the standard core method. Total porosity (S_t) was calculated from the values of ρ_b and the standard value of particle density (ρ_p) of 2.65 Mg m^{-3}. Soil particle size distribution was determined by the standard hydrometer method after oxidizing the SOM with 5 % H_2O_2 followed by dispersion with 0.5 M Na-hexametaphosphate solution. The θ_v was determined by using the pressure plate apparatus at −0.03 MPa (Klute 1986).

For aggregate size distribution, a 51 g sample of 4 mm sieved air-dried soil aggregates were wetted by capillary rise followed by shaking in distilled water through a stack of 4.0, 2.0, 1.0, 0.5, 0.25, 0.125, and 0.053 mm sieves, respectively, for 15 min (47 oscillation min^{-1}) by using the wet sieving method (Kemper and Rosenau 1986). After the water treatment, the aggregates retained on sieves were collected separately and oven-dried at 105 °C in a forced-air oven until a constant weight was obtained. The MaA was calculated by adding the aggregate fractions retained on the 4.0, 2.0, 1.0, 0.5, and 0.25 mm sieves, respectively, and divided by the total amount of aggregates taken after excluding rock particles (Sundermeier et al. 2011). Those aggregates retained on 0.125 mm sieve were used to calculate the MiA. The MWD of the aggregates was calculated as follows:

$$\mathrm{MWD(mm)} = \sum_{\mathrm{J}=1}^{n} x_j \ w_j$$

where n is the number of aggregate size fractions (mm), w_j is the weight of the aggregates of that size range as a fraction of the total dry-weight of the sample analyzed, and x_j is the mean diameter of any particular size of aggregates separated by wet sieving.

2.4 Statistical Analyses

To evaluate the long-term effects of biosolid application on soil quality properties, the data collected at each depth were organized for statistical analyses by following the completely randomized design. Each treatment combination was replicated four times. The SAS 9.3 (SAS Institute 2010) was used to perform one-way analysis of variance due to lack of significant biosolid × depth interactions on soil quality properties. Significant differences in means among biosolid treatments and between depths were separated by the least significant difference (LSD) test with a value of $p \leq 0.05$ unless otherwise mentioned. All the results were expressed based on oven-dried soil equivalent weight.

3 Results and Discussion

3.1 Soil Biological Properties

Results showed that soil microbial biomass and associated biological properties were significantly influenced by the temporal effects of biosolid application (Table 2). The C_{mic} content at the 0- to 15-cm depth was higher by 1.9- and 3.7-folds in the 5 and 25 years of biosolid-applied fields, respectively, than in the control. Similar responses of C_{mic} to biosolid application at the 15- to 30-cm depth were also observed. While N_{mic} and P_{mic} contents were higher in the 25 years of biosolid-

Table 2 Long-term effects of lime-stabilized anaerobically digested biosolids application on microbial biomass carbon, nitrogen, and phosphorus contents basal and specific maintenance respiration, and potentially mineralizable carbon content at depths of 0–15 and 15–30 cm of soil under alternate year no-till corn–soybean rotation (1984–2008)

Years of biosolids application	C_{mic} (mg kg^{-1})	N_{mic}	P_{mic}	BR (mg CO_2 kg^{-1} day^{-1})	qCO_2 (μg CO_2 g^{-1} C_{mic} day^{-1})	C_{Min} (%)
	0- to 15-cm depth					
0 (Control)	134c[a]	16c	9b	15c	112a	2.3b
2	156c	21bc	10b	20b	116a	2.7b
5	257b	30b	16b	23a	90b	3.3a
25	496a	52a	30a	25a	50c	2.8b
Mean	261	30	15	20	92	2.8
	15- to 30-cm depth					
0 (Control)	84d	11b	8b	10b	119a	2.0a
2	117c	13b	8b	11ab	94b	2.1a
5	152b	14b	11b	14ab	92b	2.5a
25	257a	27a	16a	15a	58c	2.2a
Mean	153	16	11	13	91	2.2
$LSD_{p \leq 0.05}$						
Depth	64	10	4	4	2.6[ns]	0.3

C_{mic} microbial biomass carbon, *N_{mic}* microbial biomass nitrogen, *P_{mic}* microbial biomass phosphorus, *C_{org}* total organic carbon, *BR* basal respiration, *qCO_2* specific maintenance respiration, *C_{Min}* potentially mineralizable carbon, *ns* nonsignificant

[a] Means separated by same lower case letter within a specified depth in each column were not significantly different by the least significant different (LSD) test at $p \leq 0.05$ among the years of biosolids application.

applied fields, they did not vary among the control and short-term biosolid-applied biosolid fields.

Soil biological activity, measured as BR efflux, was 53 to 67 % higher at the 0- to 15-cm depth in the 5 and 25 years of biosolid-applied fields, respectively, over the control. However, the BR efflux at the 15- to 30-cm depth was higher only in the 25 years of biosolid-applied field than in the control. In contrast, the qCO_2 was reduced by 20 to 53 % at the 0- to 15-cm depth in the long-term biosolid-applied fields compared with the control. The qCO_2 at the 15- to 30-cm depth was also decreased in the long-term biosolid-applied fields relative to the control. The C_{Min} at both depths varied consistently in response to years of biosolid application over the control.

The C_{mic}:C_{org}, as a measure of biologically labile C pool, varied significantly by the impacts of biosolid application (Table 3). While the C_{mic}:C_{org} at both depths increased in the 5 to 25 years of biosolid-applied fields over the control, it did not vary significantly between the control and 2-year biosolid-applied field. Similar effects of biosolid application were observed on N_{mic}:TN. The C_{mic}:N_{mic}, C_{mic}:P_{mic}, and N_{mic}:P_{mic} at both depths did not vary consistently between the control and biosolid-applied fields.

Irrespective of the years of biosolid application, the C_{mic}, N_{mic}, and P_{mic} contents and BR efflux were higher by 70, 87, 36, and 54 %, respectively, at the depths of 0–15 cm than at 15–30 cm. The C_{Min} was higher (27 %) in the surface soil than in the subsurface soil. The values of differences of C_{mic}:C_{org}, N_{mic}:TN, C_{mic}:P_{mic}, and N_{mic}:P_{mic} except C_{mic}:N_{mic} were higher at the surface than at the subsurface. In contrast, the C_{mic}:N_{mic} was significantly higher at the subsurface than at the surface.

Since the climatic conditions, soil type, sampling time, and laboratory analyses were identical, significant differences in microbial biomass contents and their associated biological properties among the biosolid treatments are primarily due to a greater availability and utilization of C, N, P and other nutrients by the heterotrophic microbes. In addition, the high pH of the biosolid, due to lime stabilization, may have reduced the solubility of heavy metals to exert any detrimental effects on the size and activity of the soil microbial populations (Bragato et al. 1998; Islam et al. 2013). Our results are inconsistent with the results of other studies

Table 3 Long-term effects of lime-stabilized anaerobically digested biosolids application on microbial biomass carbon and nitrogen contents over total organic carbon and total nitrogen contents and the ratios of microbial biomass carbon, nitrogen, and phosphorus at depths of 0–15 and 15–30 cm of soil under alternate year no-till corn–soybean rotation (1984–2008)

Years of biosolids application	C_{mic}/C_{org}	N_{mic}/ TN	C_{mic}/N_{mic}	C_{mic}/P_{mic}	N_{mic}/P_{mic}
	0- to 15-cm depth				
0 (Control)	1.0c[a]	1.3c	8.4a	14.9b	1.8b
2	1.2c	1.7c	7.4a	15.6ab	2.1a
5	1.8b	2.3b	8.6a	16.0a	1.9ab
25	2.7a	3.1a	9.5a	16.5a	1.7b
Mean	1.7	2.1	8.5	15.8	1.9
	15- to 30-cm depth				
0 (Control)	0.8c	1.1b	7.6b	10.5b	1.4ab
2	1.1c	1.3b	9.0a	14.6a	1.6ab
5	1.4b	1.3b	10.9a	13.8a	1.3b
25	1.9a	2.2a	9.5a	16.1a	1.7a
Mean	1.3	1.5	9.3	13.8	1.5
$LSD_{p \leq 0.05}$					
Depth	0.2	0.3	0.6	1.2	0.3

C_{mic} microbial biomass carbon, *N_{mic}* microbial biomass nitrogen, *P_{mic}* microbial biomass phosphorus, *C_{org}* total organic carbon, *TN* total nitrogen

[a] Means separated by same lower case letter within a specified depth in each column were not significantly different by the least significant different (LSD) test at $p \leq 0.05$ among the years of biosolids application

which reported a significant increase in microbial biomass and labile C contents with long-term biosolid applications (Saviozzi et al. 1999; De Nobili et al. 2001; Tarrasón et al. 2010).

Tarraśon et al. (2010) reported that microbial activities in the biosolid-applied fields were stimulated by C_{org} accumulation especially diverse and labile C contents over the control. However, the significantly higher BR efflux in the recently applied biosolid fields (~2 years) relative to the control is due to stimulated autochthonous microbial respiration by the sudden flush of labile C and available nutrients in soil (De Nobili et al. 2001). In contrast, long-term biosolid application may have stabilized the BR efflux to support a large C_{mic}, N_{mic}, and P_{mic} pools by reducing qCO_2, which may be due to efficient anabolism of C and nutrients for microbial cell growth than respiratory catabolism (Anderson and Domsch 1990). A significantly higher content of C_{mic}, N_{mic}, and P_{mic} suggested that the biologically labile pool of C, N, and P may have enlarged in response to years of biosolid application. The significant linear relationship of C_{org} with C_{mic} (R^2=0.89) and AC (R^2=0.95) justified our results (Fig. 1).

3.2 Soil Chemical Properties

The C_{org} content in the 25 years biosolid-applied field has increased (39 %) significantly at both depths than in the control and recently applied biosolid fields (Table 4). Like C_{org}, the TN content was higher (36 %) in biosolid-applied fields. The AC content was significantly higher by 15 to 98 % at the 0- to 15-cm depth in the 2 to 25 years of biosolid-applied fields than in the control. Similar responses to biosolid on AC content at the 15 to 30 cm were observed. The SC content was higher at both depths in biosolid-applied fields as compared to the control. Likewise, the RN content was 1.4, 2, and 3.8 times higher at the surface in the 2, 5, and 25 years of biosolid-applied fields, respectively, over the control. However, the RN content at the 15- to 30-cm depth was significantly different only between the control and 25 years of biosolid-applied fields. Similar effects of biosolid were observed on RP content.

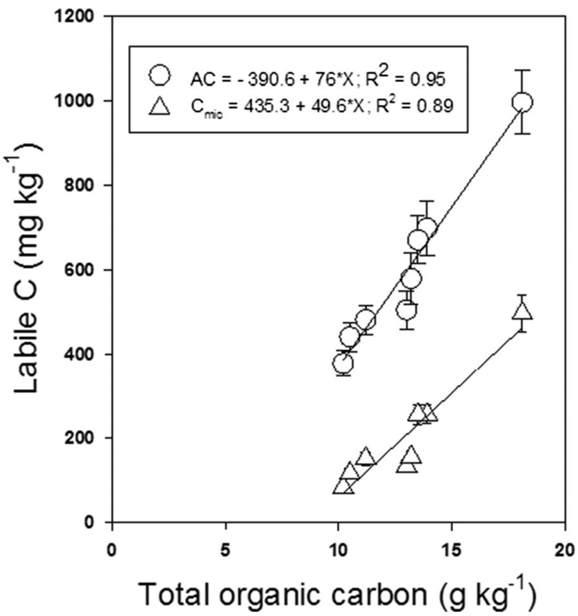

Fig. 1 The relationship of total soil organic carbon with the active carbon (*AC*) and total microbial biomass carbon (*C_{mic}*) as a measure of labile C pool in response to long-term applications (1984–2008) of lime-stabilized anaerobically digested biosolid under alternate year no-till corn–soybean rotation (average values with standard error of mean were presented)

Table 4 Long-term effects of lime-stabilized anaerobically digested biosolids application on total, active and soluble carbon, total and reactive nitrogen, and reactive phosphorus contents at depths of 0–15 and 15–30 cm of soil under alternate year no-till corn–soybean rotation (1984–2008)

Years of biosolids application	C_{org} (g kg^{-1})	TN	CN ratio	AC (mg kg^{-1})	SC	RN	RP
	0- to 15-cm depth						
0 (Control)	13.0b[a]	1.24b	10.5a	504d	29b	12c	10b
2	13.2b	1.24b	10.7a	579c	30b	14c	12b
5	13.9b	1.32b	10.5a	698b	35b	22b	19b
25	18.1a	1.69a	10.7a	996a	44a	35a	31a
Mean	14.6	1.37	10.6	694	35	21	18
	15- to 30-cm depth						
0 (Control)	10.2b	0.99b	10.3a	377d	22b	10b	8b
2	10.5b	1.02b	10.3a	440c	24b	12b	8b
5	11.2b	1.08b	10.4a	481b	26b	15b	13ab
25	13.5a	1.25a	10.8a	670a	36a	24a	20a
Mean	11.4	1.08	10.5	492	27	15	12
$LSD_{p \leq 0.05}$							
Depth	2.1	0.23	ns	112	7	5	6

C_{org} total organic carbon, *TN* total nitrogen, *AC* active carbon, *SC* soluble carbon, *RN* reactive nitrogen (ammonium and nitrate), *RP* reactive phosphorus (soluble and extractable phosphorus)

[a] Means separated by lower case letter within a specified depth in each column were not significantly different by the least significant different (LSD) test at $p \leq 0.05$ among the years of biosolids application.

When comparing the SC, RN, and RP contents, our results showed that the SC:RN and SC:RP decreased in response to long-term biosolid application (Table 4). The SC:RN decreased from 2.4 to 2.1 to 1.3 and the SC:RP decreased from 2.9 to 2.5 to 1.4 at the surface in the 2 and 25 years of biosolid application relative to the control. Similar effects of biosolid application on SC:RN and SC:RP at the 15–30 cm were observed. Averaged across the years of biosolid application, the C_{org} (22 %), TN (21 %), AC (29 %), SC (23 %), RN (29 %), and RP (33 %) contents were significantly higher at the 0- to 15-cm depth than at the 15- to 30-cm depth.

A significant increase in C_{org} and TN contents with years of biosolid application is attributed to the amount and quality of C and N input, biological efficiency, and greater soil physicochemical protection (Angin and Yaganoglu 2011). Gilmour et al. (2003) suggested that a portion of the C and N in biosolid is relatively resistant to microbial decomposition, which eventually accumulates as SOM. Since AC is a small labile pool of C_{org} (Weil et al. 2003; Knight et al. 2013), the increasing amount of C_{org} accumulated from biosolid application justified our results on increased AC content (Table 4; Fig. 1). Tarrasón et al. (2010) reported that long-term biosolid application increased C_{org} especially labile C content. It is expected that a significantly higher SC content is probably associated with a greater input and subsequent accumulation of C_{org} and AC contents in response to years of biosolid application.

An increase in RN and RP content at both depths of long-term biosolid-applied fields as compared with the control is due to an accumulation of N and P at the surface followed by consequent leaching of soluble N and P over time. The results on soluble and organically bound N and P accumulation and movement by the consequences of long-time biosolid applications were reported by other studies (Binder et al. 2002; Gilmour et al. 2003). The relatively narrow SC:RN and SC:RP suggested that long-term biosolid application (e.g., 25 years) may cause leaching and off-site mobility of RN and RP, resulting in environmental pollution.

3.3 Soil Physical Properties

Years of biosolid application significantly improved soil physical properties (Table 5). The θ_v (at −0.03 MPa) increased by 40 % at the 0- to 15-cm depth and 20 % at the 15- to 30-cm depth in the 25 years of biosolid-

Table 5 Long-term effects of lime-stabilized anaerobically digested biosolids application on volumetric moisture content, bulk density, total porosity, macroaggregate, and microaggregate stability, and mean weight diameter of aggregates at depths of 0–15 and 15–30 cm of soil under alternate year no-till corn–soybean rotation (1984–2008)

Years of biosolids application	θ_v (mm cm^{-1})	ρ_b (g cm^{-3})	f_t (%)	MaA (%)	MiA	AR	MWD (mm)
	0- to 15-cm depth						
0 (Control)	1.86c[a]	1.37a	48.3b	53.1c	31.4a	1.7c	0.53c
2	2.15b	1.37a	48.3b	58.3bc	30.1a	1.9c	0.56c
5	2.20b	1.35a	49.1b	61.5b	25.6b	2.4b	0.64b
25	2.68a	1.17b	55.8a	76.4a	20.5c	3.7a	0.80a
Mean	2.22	1.32	50.4	62.3	26.9	2.4	0.63
	15- to 30-cm depth						
0 (Control)	1.75c	1.42a	46.4b	50.3c	35.2a	1.4b	0.49c
2	1.90bc	1.38ab	47.9b	51.7bc	35.6a	1.5b	0.51bc
5	1.93ab	1.36b	48.7b	54.8bc	32.3a	1.7b	0.54bc
25	2.12a	1.28c	51.7a	61.2a	27.4b	2.2a	0.67a
Mean	1.93	1.36	48.7	54.5	32.6	1.7	0.55
LSD$_{p \leq 0.05}$							
Depth	1.8	0.03	3.1	7.1	4.6	0.4	0.06

θ_v volumetric moisture content at −0.03 MPa, ρ_b bulk density, f_t total porosity, *MaA* macroaggregate stability, *MiA* microaggregate stability, *AR* aggregate ratio (MaA/MiA), *MWD* mean weight diameter

[a] Means separated by same lower case letter within a specified depth in each column were not significantly different by the least significant different (LSD) test at $p \leq 0.05$ among the years of biosolids application

applied fields than in the control. Likewise, biosolid application increased f_t with an associated decrease in ρ_b at both depths, compared with the control. The lowest ρ_b of 1.17 g cm^{-3} was measured at the surface in the 25 years of biosolid-applied field. Even at the 15–30 cm, the ρ_b decreased by 10 % in the long-term biosolid-applied fields than in the control.

The MaA was higher by 16 to 44 % at the 0- to 15-cm depth in the 5 and 25 years of biosolid-applied fields relative to the control. Likewise, the MaA was 22 % higher at the 15 to 30 cm in the 25 years biosolid-applied field when compared with the control. In contrast, the MiA decreased at both depths with years of the biosolid application. When the MaA values were divided by the MiA values, a higher aggregate ratio (AR) showed a consistent and cumulative effect of long-term biosolid application on soil aggregation. The MWD of aggregates was increased by 51 % at the surface and 37 % at the subsurface in the 25 years of biosolid-applied field than that in the control. The θ_v, f_t, MaA, AR, and MWD increased and the ρ_b and MiA decreased at the depths of 0 to 15 cm than at the 15 to 30 cm by the impacts of biosolid application.

A significant improvement in soil physical properties by the impacts of biosolid application is probably attributed to greater input of organic matter, improved biological efficiency, and a consequent accumulation of C_{org} and available nutrients (Angin and Yaganoglu 2011). A progressive accumulation of C_{org}, C_{mic}, AC, and TN in the long-term biosolid-applied fields is accounted for the higher θ_v, f_t, MaA, AR, and MWD and reduced ρ_b and MiA as compared with the control and recently applied biosolid fields. Increased θ_v may have resulted from higher water infiltration as influenced by the higher f_t and SOM content (Hudson 1994; Lu et al. 2012). Reduced ρ_b with an associated increase in f_t is obvious due to the beneficial effects of SOM on macroaggregate formation and stabilization (Pagliali and Antisari 1993). Furthermore, the increased f_t with decreased ρ_b is related to an increase in macropore volume created and modified by the low ρ_b (0.3–0.68 g cm^{-3}) of applied biosolid and SOM (Angin and Yaganoglu 2011; Lu et al. 2012).

An increased availability of C and essential nutrients to support microbial anabolism may have produced biochemical cementing agents to bind MiA and primary particles into MaA and, consequently, increased AR and

MWD of aggregates (Oades 1984; Tsadilas et al. 2005, Sundermeier et al. 2011). In one-to-one relationship, the C_{org} significantly and linearly accounted for more than 90 % of the variability in the MaA formation with an associated decrease in the MiA formation (Fig. 2). Similarly, the AC as a small labile pool of C_{org} significantly and linearly accounted for 98 % of the variability in the MaA formation and nonlinearly accounted (R^2=0.96) for significant decrease in the MiA formation (Fig. 3). The significant nonlinear relationship of C_{mic} with the MaA (R^2=0.97) and MiA (R^2=0.93) stability justified biophysical mechanisms in the MaA formation from the MiAs and primary soil particles (Fig. 4). Higher MaA formation with an associated decrease in MiA formation suggested the contributions of accumulated C and available nutrients to support efficient microbial activities in response to years of biosolid application.

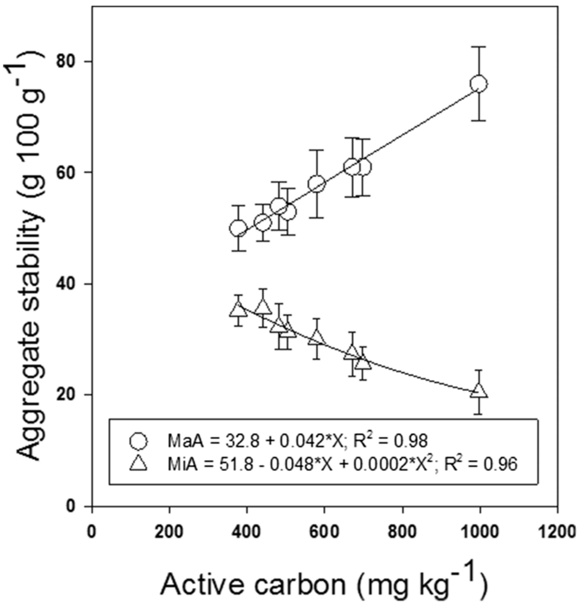

Fig. 3 The relationship of active carbon with the macroaggregate (*MaA*) and microaggregate (*MiA*) stability of soil in response to long-term applications (1984–2008) of lime-stabilized anaerobically digested biosolid under alternate year no-till corn–soybean rotation (average values with standard error of mean were presented)

4 Conclusions

Long-term applications of lime-stabilized anaerobically digested biosolid have consistently improved biological efficiency, increased soil organic matter content, and provided greater physical protection, which together are associated with improved soil quality. Total

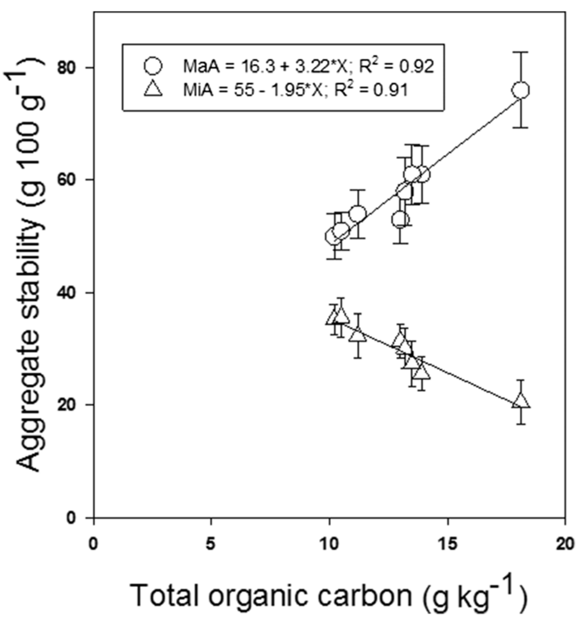

Fig. 2 The relationship of total soil organic carbon with macroaggregate (*MaA*) and microaggregate (*MiA*) stability of soil in response to long-term applications (1984–2008) of lime-stabilized anaerobically digested biosolid under alternate year no-till corn–soybean rotation (average values with standard error of mean were presented)

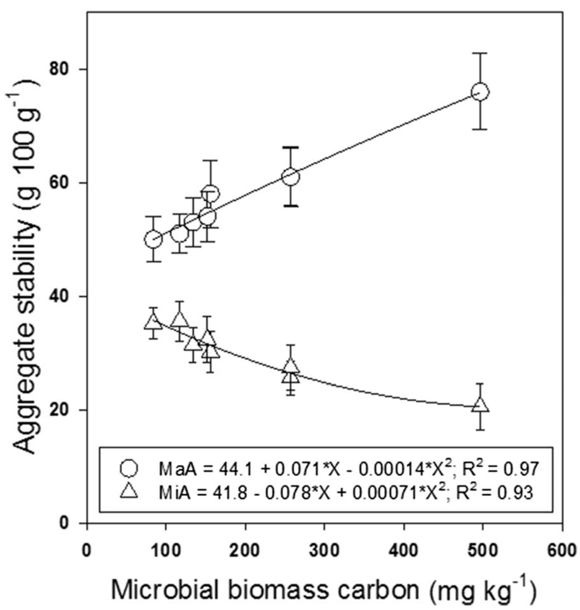

Fig. 4 The relationship of total microbial biomass carbon with the macroaggregate (*MaA*) and microaggregate (*MiA*) stability of soil in response to long-term applications (1984–2008) of lime-stabilized anaerobically digested biosolid under alternate year no-till corn–soybean rotation (average values with standard error of mean were presented)

microbial biomass carbon–nitrogen–phosphorus pools have enlarged with greater metabolic efficiency (low qCO_2) by the impacts of biosolid application. Total organic carbon and total nitrogen contents increased with an accumulation of active and soluble carbon, reactive nitrogen, and reactive phosphorus contents. Increased moisture holding capacity and macroaggregate stability of soil with reduced bulk density is associated with the consequent effects of biological efficiency and labile carbon and essential nutrients accumulation. Likewise, improved soil physical properties provided greater protection for carbon and nutrients accumulation by the impact of biosolid application. Our research supported that biosolids application is one of the components of sustainable agricultural management practices to improve soil quality for crop production. However, a relatively narrow soluble carbon:reactive nitrogen and soluble carbon:reactive phosphorus suggested a greater formation and accumulation at the surface and potential mobility of reactive nitrogen and reactive phosphorus in polluting soil–water ecosystems with long-term biosolid application (e.g., 25 years).

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