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Effect of long term no-till and conventional tillage practices on soil quality

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ABSTRACT

Management systems influence soil quality over time. A randomized block design in 2 (tillage system) × 3 (crop rotation) factorial arrangement was laid-out to evaluate the impact of tillage and crop rotation (2002–2007) on soil quality. Conventional tillage and No-till were factored into continuous corn, corn–soybean, and corn–soybean–wheat–Cowpea systems. Ten soil cores were collected at 0–7.5, 7.5–15, 15–22.5 and 22.5–30 cm depths and analyzed for biological, chemical and physical parameters. The inductive additive approach was used to calculate biological, chemical, physical and composite soil quality indices. A significant impact of no tillage on different physical chemical and biological parameters was observed. The estimated soil quality index was significantly higher in soil under No-till than conventional tillage. Soil biological quality is a sensitive and consistent indicator of soil quality in response to management practices.

1. Introduction

Soil management practices are considered necessary to sustain crop yields to conserve or enhance soil quality (Aziz et al., 2009). A difference in management practices often result in differences in biological, chemical and physical properties of soil which in turn, result in changes in functional quality of soil (Islam and Weil, 2000; Aziz et al., 2009; Derpsch et al., 2010; Wolfarth et al., 2011; Celik et al., 2011; Ding et al., 2011). Inappropriate land uses and management systems lead to soil erosion, depletion of organic matter and other nutrients which results to permanent soil degradation and productivity losses (Ramos et al., 2011).

All internal and interrelated properties of soil (biological, chemical and physical) are significantly affected by reducing soil tillage (Thomas et al., 2007). Soils under No-till have greater storage of diverse plant biomass on undisturbed surface, which results in moist soil and low temperature with efficient microbial activity, better aggregate structure and considerable improvement in soil properties, particularly N content, SOM and SOC content, CEC (Cation exchange capacity) and decrease the C/N ratio (Madejon et al., 2009; Naudin et al., 2010; Derpsch et al., 2010; Moussa-Machraoui et al., 2010; Benitio, 2010; Celik et al., 2011; A'lvaro-Fuentes et al., 2012) compared to CT soils. No-till greatly enhances carbon accumulation within micro aggregates which in return form macro aggregates. This shift of soil organic carbon within micro aggregates is very beneficial for long term carbon storage in soil (Shan et al., 2010; Erkossa, 2011). No-till farming tends to reduce soil bulk density in the upper soil layer (Jina et al., 2011).

Since soil properties are interrelated, the challenge is to pinpoint and quantify core set of properties that can be used to confirm the usefulness of production technology for improvement of SQ. A large change in one property may not significantly affect others and small change in two or more soil properties may be individually insignificant but in concert with each other may have a significant impact on an agro-ecosystem (Reganold and Palmer, 1995).

Soil quality is hard to assess directly due to collective and multiple functional effects but can be evaluated from alterations in soil properties due to management operations. Conventionally, due to availability of easy analysis techniques soil quality studies basically focused on chemical and physical properties of soil (Larson and Pierce, 1994) but in recent years it was found that biological properties of soil act as early and sensitive indicators in response to alteration in management systems (Islam and Weil, 2000; Kennedy and Papendick, 1995). Consequently biological parameters together with soil chemical and physical properties are recognized to be necessary to assess SQ as affected by changes in management operations (Parkin et al., 1996).

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Soil organic matter (SOM) is historically considered as the indicator of soil quality because of its contribution in influencing soil biological, chemical and physical properties and crop yields (Islam and Weil, 2000). Others did not agree with SOM as the single indicator of SQ and suggested a combination of soil properties to be evaluated for assessment of soil quality (Islam and Weil, 2000). The particulate organic matter, active C, total N, microbial biomass, biological activities, enzymes, soil pH, cation exchange capacity, salinity, bulk density, amino sugar and soil aggregation are important indicators of dynamic soil quality because of their quick response to management practices (Islam and Weil, 2000; Wander, 2004; Aziz et al., 2009; Ding et al., 2011). As a dynamic component of SOM, microbial life of soil is often considered as a key indicator of SQ (Islam and Weil, 2000). The best quality soils are biologically more active and have a balanced population of microbes. Microbial biomass consists largely of primary decomposers that mineralize organic materials and release nutrients and energy by enzyme-facilitated metabolic systems. The threads of fungi and actinomycetes, bacterial mucigel and hyphae bind particles of soil together and enhance soil aggregation which result in more absorption of water, reduction in erosion, protects C in macroaggregates and maintain adequate pore spaces in soil (Kennedy and Papendick, 1995).

There are certain characteristics, particularly when considered together, that are good indicators of SQ. Larson and Pierce (1991) suggested that a small data set be used for measuring SQ and uniform methodologies and procedures be followed to measure certain changes in SQ. Monitoring of a select set of soil properties that can serve as indicators of change in SQ is possible and can yield useful information on trends in SQ (Dumanski and Pieri, 2000). Soil quality indicators should be a combination of biological, chemical and physical properties sensitive to management practices (Islam and Weil, 2000; Aparicio and Costa, 2007).

However there is still uncertainty remaining for the understanding of full impact of no-till technology on soil organic carbon (Ogle et al., 2012). This study was planned to evaluate the impact of tillage and crop rotation (2002–2007) on selected biological, chemical and physical properties as a minimum data-set of soil quality indicators and sensitivity of various soil quality indices to determine soil's overall functional capacity in agro-ecosystems.

2. Materials and methods

2.1. Study site

The study was conducted at Vanmeter farm of the Ohio State University South Centers at Piketon (39°02′30″N, 83°02′00″W), South-central Ohio, USA. On average, soil has pH 6.2, electrical conductivity 206.4 μS/cm, total porosity 44.6%, and contains 21, 55, and 24% sand, silt and clay, respectively at 0–30 cm depth

2.2. Field experiment and cultural practices

A field experiment with two (2) types of tillage (conventional tillage, CT and No-till, NT) and three (3) crop rotations (continuous corn, CC; corn–soybean, CS; and corn–soybean–wheat, CSW) in factorial arrangement of randomized complete block (RCB) design was established in 2002. Each treatment was replicated 3 times on 40×100 m^2 plots.

2.3. Soil collection and processing

Prior to establishing the experiment, 18 composite soil samples were randomly collected from the entire field for baseline data using GPS guided systematic sampling in early spring (May) of 2002. Ten soil cores were collected from 30 cm depth in plastic tubes for each composite sample using an environmental soil probe (1.9 cm internal diameter). The soil cores were segmented at 0–7.5, 7.5–15, 15–22.5 and 22.5–30 cm, respectively in the laboratory. The segmented soils at each depth were mixed to get composite samples and gentle sieving was done through a 4-mm mesh to eliminate stones, plants roots and large organic substances. After sieving, the composite field-moist soil was divided into two equal parts and each sub-sample was placed in a separate Ziplock plastic bag. The soil from one sub-sample bag was passed through a 2-mm sieve and homogenized to measure antecedent soil moisture content and incubate for 7 d at room temperature (25 °C) to stabilize microbial activity. After stabilization, the field-moist soil samples were then used to measure microbial biomass and/or incubated for biological properties. Soil from the second bag was spread on a polyethylene sheet and air-dried at room temperature for 72 h and analyzed for selected chemical and physical properties. In early spring (May) of 2007, a total of 18 composite samples were taken (using GPS) from same soil locations and depth, processed and analyzed for evaluation of temporal (2002 vs. 2007) effects of tillage on soil properties.

2.4. Analytical methods

2.4.1. Soil biological properties

The soil microbial biomass (C_{mic}) was determined by following rapid microwave irradiation and extraction procedure of Islam and Weil (1998a, 1998b). The C_{mic} was calculated by using the following formula.

$$C_{mic}\left(\frac{\text{mg C}}{\text{kg soil}}\right) = \left(\frac{MWC_{ext} - UMWC_{ext}}{K_{ext}}\right)$$

The MWC_{ext} is the extractable C in microwaved soil, $UMWC_{ext}$ is the un microwave extractable C, the C_{ext} is extractable C of field-moist soil and K_{ext} is the fraction (0.241) of the C_{mic} extracted by 0.5 M K_2SO_4 (Islam and Weil, 1998a, 1998b).

Basal respiration (BR), as a measure of antecedent biological activity, was determined using 20 d in vitro static incubation of field-moist soil without any amendments (Islam and Weil, 2000). The estimation of BR rate was done by following formula

$$\text{BR rates}\left(\frac{\text{mg } CO_2}{\text{kg soil}}\right) = (CO_2\text{soil} - CO_2\text{air})20\,\text{d}$$

where CO_2 soil is the evolution of CO_2 during 20 d incubation of non-amended homogenized soil and CO_2 air is the ambient air CO_2 in a blank mason jar.

The qCO_2 i.e. catabolism of C per unit C_{mic} per day was calculated by following Anderson and Gray (1991).

$$qCO_2\left(\frac{\mu\text{g } CO_2}{\text{mg } C_{mic}/\text{d}}\right) = \left(\frac{\text{BR rates}}{C_{mic}}\right)$$

2.4.2. Soil chemical properties

The total organic carbon (C_{org}) and nitrogen contents were estimated using finely ground (125 μm sieved) soil with Elementar® CN dry combustion analyzer. Since the pH of the collected soil was <6.5, the total carbon content was considered as C_{org}. Active C (AC) based on $KMnO_4$ oxidation was measured on air-dried soil as described by Weil et al. (2003).

2.4.3. Soil physical properties

Standard core method was used to calculate bulk density (ρb) using mass per unit volume of soil. Particle size analysis was

Table 1
Tillage impacts on soil biological quality indicators at different depths (Averaged across crop rotation).

Tillage Trts.	Depth of soil (cm)	C_{mic} (mg/kg)	BR (mg/kg/d)	qCO_2 (μg/mg/d)	SBQ (%)	ΔSBQ (%/yr)
Initial $_{(2002)}$		103.7Y*	8.1Y	73.0Y	43.8Y	0Y
CT_{2007}		105.1Yb+	8.5Xa	86.0Xa	44.8Yb	0.2Yb
NT_{2007}		163.9Xa	9.1Xa	61.0Zb	56.8Xa	2.6Xa
Tillage and soil depth interaction						
Initial$_{(2002)}$	0–7.5	185.7#	10.7 ns	58.0 ns	58.5 ns	0
	7.5–15	103.8	7.0	68.0	45.8	0
	15–22.5	75.2	5.6	76.0	38.7	0
	22.5–30	50.2	4.2	88.0	32.1	0
CT_{2007}	0–7.5	154.4	11.3	74.0	54.2	−0.8 ns
	7.5–15	109.6	9.0	84.0	46.7	0.2
	15.22.5	85.7	7.5	94.0	40.4	0.3
	22.5–30	71.3	6.2	92.0	38.0	1.2
NT_{2007}	0–7.5	259.5	13.4	53.0	73.7	3.0
	7.5–15	173.7	10.0	62.0	60.1	2.8
	15.22.5	126.0	7.1	61.0	49.1	2.1
	22.5–30	96.5	5.8	66.0	44.5	2.5

Initial = data collected from conventionally tilled (CT) continuous corn (CC) plots in 2002, CT_{2007} = data collected from conventionally tilled plots in 2007, NT_{2007} = data collected from continuous no-till plots in 2007, C_{mic} = microbial biomass carbon, BR = basal respiration rates, qCO_2 = specific maintenance respiration rates, SBQ = soil biological quality, ΔSBQ = rate of change in soil biological quality, and ns = non-significant.
* Means followed by same upper case letter (X to Z) in the column were not significantly different at $p \leq 0.05$ over time (2002 vs. 2007).
+ Means followed by same lower case letter (a to c) in the column were not significantly different at $p \leq 0.05$ between tillage treatments in 2007.
\# Indicates significant tillage and soil depth interaction.

performed by adding 25 ml of 5% hydrogen peroxide to remove organic matter, followed by addition of sodium hexamata phosphate to disperse soil and size of the soil particles were investigated by standard hydrometer techniques. Total porosity (ρt) was calculated from the measured values of bulk density (ρb) and standard soil particle density (ρp) of 2.65 g/cm^3 and was expressed as percent as follows:

$$ft(\%) = \left(1 - \left(\frac{\rho b}{\rho p}\right)\right) \times 100$$

The ρb was calculated by core method of Blake et al. (1986) from the relationship of oven-dried mass of a known volume of soil as:

$$\rho b\left(\frac{\text{g}}{\text{cm}^3}\right) = \frac{W}{(\pi \times r^2 \times L)}$$

where r is the internal radius of a soil core sampler, L is the length of soil core, and w is the total weight (g) of oven dried equivalent (ODE) of soil.

An aggregate stability index (AS) was determined using the method described by (Gardi et al., 2002) wet sieving with vertical oscillation and calculated with following equation:

$$\text{AS}(\%) = \left(\frac{X}{Y}\right) \times 100$$

Where X is the amount of soil aggregates retained on 250 μm sieve after treatment and shaking, and the Y is the total amount of soil aggregates taken for aggregate analysis.

The (particulate organic matter) POM was collected by taking a 10 g oven-dried equivalent (ODE) sample of 2 mm sieved field-moist soil at 80% water-filled porosity in 50 mL screw-top polypropylene tubes. The tubes containing soils used for microwave irradiation (MW) were covered with punctured caps to regulate pressure buildup. After initial MW heating (400 J g^{-1}), the soils in the tube were tapped few times on the bench for thorough mixing followed by an additional MW heating at the same rate. The MW soil samples were allowed to cool down for 30 min at room temperature. The soils were shaken at 250 rpm for one hour with 20 mL of 0.5 M K_2SO_4 (pH 7.0). After shaking, the soil suspensions were centrifuged at 3000 rpm for 5 min and filtered to collect, disperse and floated organic residues on filter paper as particulate organic matter (POM). The POM was then transferred from the filter paper to a 53 μm sieve, washed under running water, and oven-dried at 105 °C for 15 min by using a forced-air oven. A sample of POM was burned at 480 °C for 4 h in a muffle furnace to calculate POM by loss on ignition and the results were expressed as sand-free basis.

A selected number of basic soil properties were also measured. Soil pH was determined by glass electrode method in 1:2 soil-distilled deionized water slurries. The electric conductivity (EC) was determined in 1:1 ratio using a standard conductivity meter.

2.4.4. Calculation of soil quality index

The group of biological, biochemical/chemical and biophysical/physical properties of soil which were selected to use in the study as core indicators of SQ are C_{mic}, BR, qCO_2, TC, AC, TN, *ft*, AS and POM. An integrated measure of soil quality was produced using the inductive additive approach based on normalization, summation, and average of selected core biological, chemical and physical properties into a single integrator of soil quality (Islam, 1997; Stinner and Islam, 2008; Aziz et al., 2009). This approach allowed datum for each individual soil property (X_0) measured or calculated to be transformed on a scale [>0, <1] relative to the maximum value (X_{max}) of that X_0 ($X_i = X_0/X_{max}$) in the data set. Transformations of pi were done to normalize the data sets for reducing heterogeneous variances of the errors and to simplify the relationship between random errors influenced variables. Equal weight were assigned to each X_i such that each X_i is in [>0, <1] scale and the mean summation of the weight for soil quality was [>0, <1].

2.4.5. Statistical analysis

PRC ANOVA techniques of SAS were used for data analysis (SAS, 2008). Means of treatments were separated by using an F-protected LSD test with $p \leq 0.05$. Regression of SBQ, SCQ and SPQ

Table 2
Tillage impacts on soil chemical quality indicators at different depths (Averaged across crop rotation).

Tillage Trts.	Depth of soil (cm)	TC (g/kg)	AC (mg/kg)	TN (g/kg)	SCQ (%)	ΔSCQ (%/yr)
Initial $_{(2002)}$		13.2Y*	622.9Y	1.33Y	50.1Y	0Y
CT_{2007}		11.8Yb+	656.1Yb+	1.23Ya	48.1Yb	−0.4Yb
NT_{2007}		16.9Xa	730.1Xa	1.72Xa	60.7Xa	2.1Xa
Tillage and soil depth interaction						
Initial$_{(2002)}$	0–7.5	17.1 ns	779.6 ns	1.60 ns	53.9 ns	0
	7.5–15	12.9	613.5	1.33	51.6	0
	15–22.5	11.6	563.0	1.25	47.7	0
	22.5–30	11.1	535.4	1.16	47.4	0
CT_{2007}	0–7.5	14.9	783.5	1.52	51.1	−0.6 ns
	7.5–15	12.2	677.8	1.28	50.3	−0.3
	15–22.5	10.3	589.9	1.08	46.1	−0.3
	22.5–30	9.7	573.2	1.04	44.8	−0.5
NT_{2007}	0–7.5	23.9	891.2	2.32	68.4	2.9
	7.5–15	17.8	738.2	1.83	66.9	3.1
	15–22.5	13.3	691.1	1.41	54.4	1.3
	22.5–30	12.5	599.7	1.31	53.1	1.3

Initial = data collected from conventionally tilled (CT) continuous corn (CC) plots in 2002, CT_{2007} = data collected from conventionally tilled plots in 2007, NT_{2007} = data collected from continuous no-till plots in 2007, TC = total carbon, AC = active carbon, TN = total nitrogen SCQ = soil chemical quality, ΔSCQ = rate of change in soil chemical quality and ns = non-significant.
* Means followed by same upper case letter (X to Z) in the column were not significantly different at $p \leq 0.05$ over time (2002 vs. 2007).
\+ Means followed by same lower case letter (a to c) in the column were not significantly different at $p \leq 0.05$ between tillage treatments in 2007.

on SQI, and SQI on C_{index} were fitted to polynomial (linear, quadratic and cubic) functions using Sigma Plot® and the best fit was graphically represented.

3. Results and discussion

3.1. Tillage impact on selected soil quality indicator properties

Tillage had significant impact on microbial biomass (C_{mic}), basal respiration (BR) and specific maintenance (qCO_2) rates at different depths of soil when measured and/or calculated as soil biological quality indicators (Table 1). The difference in C_{mic} concentration (∼56%) was highly significant between CT and NT. The C_{mic} was significantly influenced by tillage. In NT, the BR significantly increased (>30%) over time, however, the BR did not differ (7%) significantly between CT and NT. Regardless of more C_{mic} and greater microganism activity (BR), the qCO_2 was smaller in NT compared to that of initial values measured in 2002. The qCO_2 was significantly decreased by 16% in NT and increased by 18% in CT. The difference (∼34%) in qCO_2 was significantly different between NT and CT. Irrespective of tillage treatments, the C_{mic} and BR decreased and increased with increase in soil depth (Table 1). The C_{mic}, BR and values were normalized and integrate into a soil biological quality index (SBQ). The SBQ was significantly higher (13%) under NT than CT over time. The SBQ under CT did not change significantly over time. The SBQ did increase significantly under NT in five year (Table 1). The SBQ decreased with an increase in soil depth.

Table 3
Tillage impacts on soil physical quality indicators at different depths (Averaged across crop rotation).

Tillage Trts.	Depth of soil (cm)	*ft*	AS	POM (g/kg)	SPQ (%)	ΔSPQ (%/yr)
		(%)				
Initial $_{(2002)}$		44.3X*	35.6Y	8.3Y	58.8Y	0 X
CT_{2007}		44.6Xa+	33.8Yb	8.2Yb	58.2Yb	−0.1Xa
NT_{2007}		44.7Xa	42.6Xa	9.3Xa	63.4Xa	1.5 Xa
Tillage and soil depth interaction						
Initial$_{(2002)}$	0–7.5	51.8 ns	40.7#	12.3#	68.8 ns	0
	7.5–15	44.4	35.8	8.1	58.8	0
	15–22.5	43.3	33.9	7.1	56.0	0
	22.5–30	37.7	32.1	5.8	51.5	0
CT_{2007}	0–7.5	50.7	39.9	10.6	65.5	−0.6 ns
	7.5–15	45.7	35.4	8.6	60.1	0.3
	15–22.5	42.8	31.1	7.3	55.4	−0.1
	22.5–30	39.4	29.1	6.1	51.8	0.1
NT_{2007}	0–7.5	48.8	65.7	14.4	82.0	2.6
	7.5–15	44.9	43.1	9.7	65.3	1.3
	15–22.5	44.7	36.2	7.4	57.4	1.1
	22.5–30	40.3	25.3	5.8	48.9	0.7

Initial = data collected from conventionally tilled (CT) continuous corn (CC) plots in 2002, CT_{2007} = data collected from conventionally tilled plots in 2007, NT_{2007} = data collected from continuous no-till plots in 2007, *ft* = total porosity, AS = aggregate stability, POM = sand free particulate organic matter, SPQ = soil physical quality, ΔSPQ = rate of change in soil physical quality and ns = non-significant.
* Means followed by same upper case letter (X to Z) in the column were not significantly different at $p \leq 0.05$ over time (2002 vs. 2007).
\+ Means followed by same lower case letter (a to c) in the column were not significantly different at $p \leq 0.05$ between tillage treatments in 2007.
\# indicates significant tillage and soil depth interaction.

Table 4
Tillage impacts on soil quality index (Averaged across crop rotation).

Tillage Trts.	Depth of soil (cm)	SQI (%)	ΔSQI (%/yr)
Initial $_{(2002)}$		50.9Y*	0Y
CT_{2007}		50.4Yb+	0.4Yb
NT_{2007}		60.3Xa	2.4Xa
Tillage and soil depth interaction			
Initial$_{(2002)}$	0–7.5	60.4 ns	0
	7.5–15	52.1	0
	15–22.5	47.4	0
	22.5–30	43.7	0
CT_{2007}	0–7.5	56.9	1.3 ns
	7.5–15	52.4	0
	15–22.5	47.3	0
	22.5–30	44.9	0.2
NT_{2007}	0–7.5	74.7	4.9
	7.5–15	64.1	2.4
	15–22.5	53.6	1.2
	22.5–30	48.8	1

Initial = data collected from conventionally tilled (CT) continuous corn (CC) plots in 2002, CT_{2007} = data collected from conventionally tilled plots in 2007, NT_{2007} = data collected from no-till plots in 2007, SQI = soil quality index, ΔSQI = rate of change in soil quality index and ns = non-significant.

* Means followed by same upper case letter (X to Z) in the column were not significantly different at $p \leq 0.05$ over time (2002 vs. 2007).

\+ Means followed by same lower case letter (a to c) in the column were not significantly different at $p \leq 0.05$ between tillage treatments in 2007.

Total carbon (TC), active carbon (AC) and total nitrogen (TN) at different soil depths, measured as soil chemical quality indicators varied significantly in response to tillage (Table 2). The TC concentration under NT was significantly higher (30%) than CT. The TC concentration under CT decreased (11%) over time. Similarly, the AC under NT increased significantly (17%) over time. The AC under CT did not change significantly over time. The net difference in AC (11%) between NT and CT was highly significant. The TN concentration increased significantly by 29% under NT and decreased by 8% under CT over time. Tillage had significant impacts on the soil chemical quality index (SCQ) and the rate of change in ΔSCQ. The difference in SCQ (>10%) between NT and CT was highly significant. The ΔSCQ under NT significantly increased @ 2.1% per year and decreased under CT @ 0.4% per year. Irrespective of tillage treatments TC, AC, TN and SCQ decreased significantly with increase in soil depth (Table 2).

Among the selected soil physical quality indicators AS and POM varied significantly except *ft* (Table 3). The AS increased significantly by 7% under NT while it decreased by 2% under CT over time. The POM under NT increased (12%) significantly over time. In contrast, POM under CT decreased non-significantly over time. The net difference in POM (13%) between NT and CT was significant. The *ft* decreased significantly with increasing soil depth (Table 3). The AS and POM were significantly influenced by tillage and soil depth interaction. Tillage had significant impact on soil physical quality index (SPQ). The SPQ was significantly higher (5%) in NT than CT. Irrespective of tillage treatments SPQ and ΔSPQ decreased with increase in soil depth. The effect was more pronounced in NT than CT over time (Table 4).

Significant change in soil quality indicator properties by tillage at different soil depths over time could be attributed to variable physical disturbance, placement and quality of crop residues, microbial food webs and soil microclimatic parameters (Islam and Weil, 2000; Stinner and Islam, 2008; Derpsch et al., 2010; Moussa-Machraoui et al., 2010; Wolfarth et al., 2011; Ding et al., 2011). The NT leaves most of the crop residues on the surface, thus influencing soil chemical, biological and physical quality properties. Regardless of more C_{mic} and high biological activity (BR), the qCO_2 was smaller under NT compared to CT. A relatively low value means that, for available quantity of organic carbon metabolism, proportionately a smaller amount C would be used in respiration process and larger amount of C would be fixed into C_{mic} cells. A smaller amount also indicates that soil microbes are expecting relatively labile C as a basis for existence and hence can assign more resources to growth so the result in less decomposition and more cycling of nutrients which ultimately improves soil quality (Anderson and Domsch, 1989; Islam and Weil, 2000; Hazarika et al., 2009; Wolfarth et al., 2011). The lower amount may also indicate less stress from soil disturbance for C_{mic} populations under NT. Furthermore, the lower value may show that management practices lead to a fungi dominated microbial community. Several researchers revealed that NT soils have more fungi dominant microbial colonies (Moussa-Machraoui et al., 2010; Celik et al., 2011). NT systems, in which plant materials remain on upper surface instead of mixing into the soil, have fungal dominance as compared to intensively plowed soil where the OM is incorporated (Moussa-Machraoui et al., 2010; Celik et al., 2011). Fungi typically assimilate about 44% of readily decomposable C into biomass, while bacteria typically assimilate only about 32% (Myrold, 1998). So bacteria is expected to be less dominating as more carbon efficient fungi grow in the soil under NT. Carter, 1991 and Celik et al., 2011 reported that an increase in the proportion of C_{mic} in TC indicates a shift in organic C equilibrium toward an aggrading system in which there is a net accumulation of C in soil.

Soil with higher C_{mic} and lower qCO_2 values under NT would be expected to accumulate more labile C over time (Hu et al., 1997; Islam and Weil, 2000). An accumulation of labile C through enhanced microbial assimilation may be one of the most important and early mechanisms by which NT improved soil quality functions (Islam and Weil, 2000; Aziz et al., 2009). This may be attributed to longer retention of C inputs and to differences in the rates of assimilation and decomposition of C under NT (Boehm and Anderson, 1997; Islam and Weil, 2000). The high qCO_2 associated with low values of C_{mic} represent CT soils are under stress and in poor condition (Islam and Weil, 2000). An increased qCO_2 has been reported to be a sensitive indication of soil ecosystem stress from such factors as physical disturbance (Anderson and Domsch, 1990; Wardle and Ghani, 1995).

Several studies have reported that other than bio-efficiency in C utilization, soil C accumulation is achieved through chemical interactions with clay minerals, and physical protection of C within aggregates (Islam and Weil, 2000; Six et al., 2000; Madejon et al., 2009; Naudin et al., 2010). Soils under conservation tillage have greater aggregate stability due to slow microbial decomposition of protected POM (Six et al., 2000). Several reports confirm changes in SOM under long-term management practices and effectiveness of POM as an indicator of sensitivity (Mando et al., 2003). Measures of POM have been positively associated with nutrient recycling and improved physical condition of soil (Wander et al., 1994). Aggregate stability (AS), the resistance of soil structural aggregates to dispersion when wetted, is an important SQ property because it influences many soil functions (Jacobs et al., 2009). Moreover, it reflects many soil functions and interrelationships among biological, chemical and physical soil properties. Greater AS was anticipated because the NT was expected to increase the amount of available labile C for use by microbial communities, which in turn, would produce more organic binding agents and sticky fungal hyphae as a means to stabilize soil macroaggregates (Angers et al., 1992). Soil macroaggregates in turn, may increase the proportion of labile organic C that is physically protected from microbial decomposition (Boehm and Anderson, 1997). A significantly higher content of AC in NT supported our results that maintaining greater

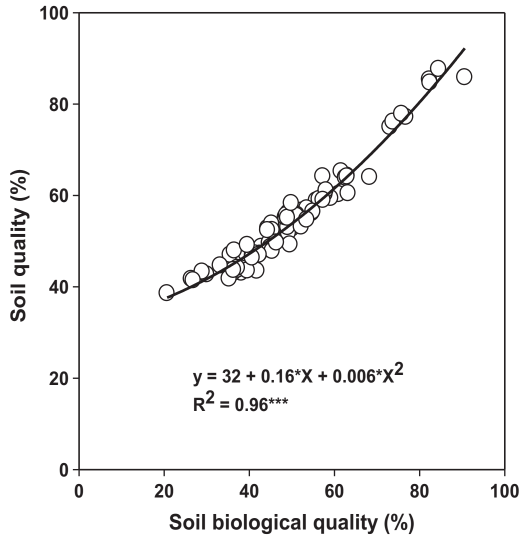

Fig. 1. Relationship between soil biological quality and soil quality at different soil depths (0–30 cm).

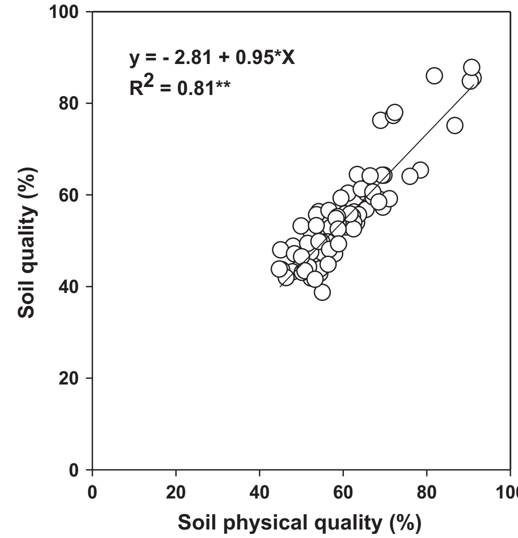

Fig. 3. Relationship between soil physical quality and soil quality at different soil depths (0–30 cm).

proportion of labile C in soil is more important than higher TC content (Benitio, 2010).

Conventional systems especially plowing disturb aggregates of soil and increase soil temperature and soil organic decay which in turn results in a decline in C and N contents of soil (Islam and Weil, 2000; Aziz et al., 2009; Madejon et al., 2009; Naudin et al., 2010; Shan et al., 2010). Tillage practices can modify soil environment, improve porosity, increase disintegration of aggregates and mix plant materials into plow depth which increases crop biomass and soil contact. More porosity by plowing often improves biotic activity and accelerated decomposition of native OM and soil associated crop materials (Morris et al., 2004). Plowing enhances disintegration of aggregates and structure of soil by inverting and mixing and finally, resulting in a rapid breakdown of protected POM in both inter-and intra-aggregate due to exposure of soil microbes (Six et al., 2000; Al-Kaisi and Yin, 2005; Shan et al., 2010). Tillage also increases the rate of decomposition of macro-aggregates by exposing soils to freeze–thaw and wet–dry cycles (Six et al., 2004; Shan et al., 2010). Soil quality improved with increase in AS and residue cover over time (Madejon et al., 2009).

The SQ indicator properties measured, excluding qCO_2 have shown significant improvement in soils which have been converted to NT with continuous inputs of diverse substrates by crop rotations and reduced C loss by NT compared to those of intensive tillage (CT) and continuous mono-cropping (CC). Among tillage treatments, a significantly greater C_{mic} and BR with lower qCO_2, greater TC, AC, and TN and improved physical properties (AS and POM) under NT- over time could be attributed to minimum physical disturbance and quality of substrates (Staben et al., 1997; Thomas et al., 2007; Aziz et al., 2009; Gosai et al., 2009). Significant improvement in soil quality can be achieved by enhancing or conserving soil interrelated properties (biological, chemical and physical) which can ultimately improve overall soil quality (Aziz et al., 2009; Madejon et al., 2009). For example, decline in physical soil properties adversely disturb bio-chemical soil quality parameters and thereby soil quality over time (Islam and Weil, 2000; Dexter, 2004; Madejon et al., 2009; Melero et al., 2009).

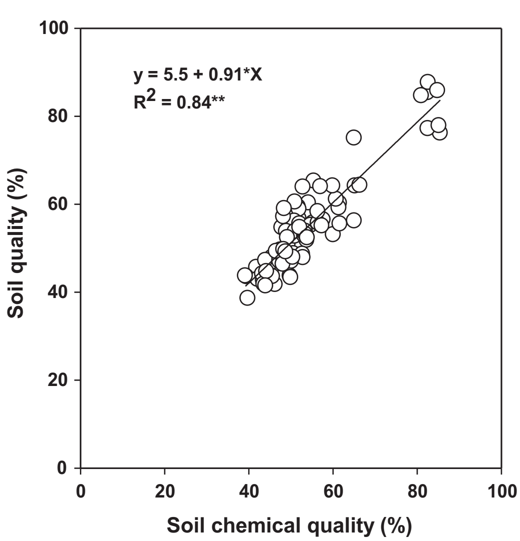

Fig. 2. Relationship between soil chemical quality and soil quality at different soil depths (0–30 cm).

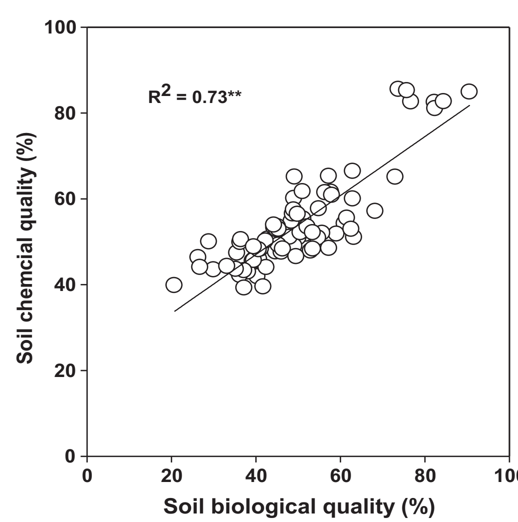

Fig. 4. Correlation between soil biological quality and chemical quality at different soil depths (0–30 cm).

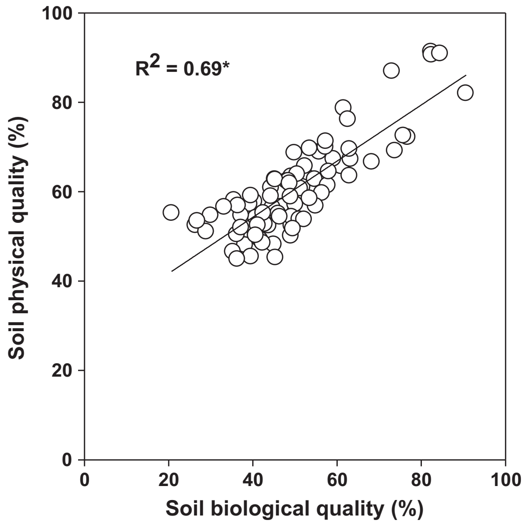

Fig. 5. Correlation between soil biological quality and physical quality at different soil depths (0–30 cm).

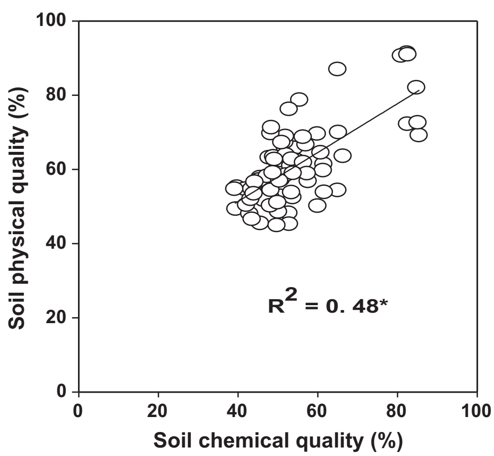

Fig. 6. Correlation between soil chemical quality and physical quality at different soil depths (0–30 cm).

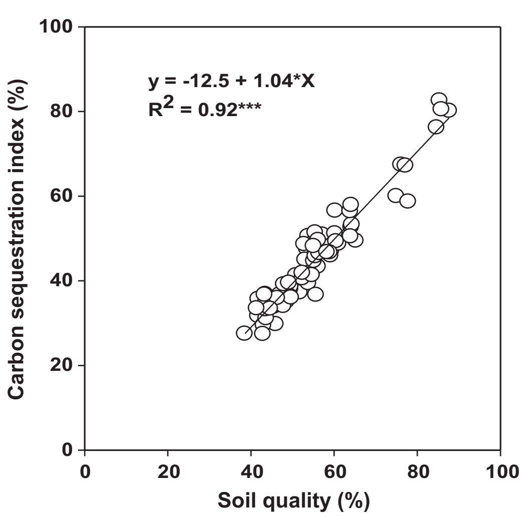

Fig. 7. Relationship between soil quality and carbon sequestration at different soil depths (0–30 cm).

3.2. Relationship among soil quality indices and between soil quality and C sequestration index

The SQI was regressed on SBQ, SCQ and SPQ indices to evaluate their contribution as sensitive and early indicators of SQ (Figs. 1–7). Among the SQ indices, the SBQ contributed more to influence SQ than SCQ and SPQ respectively. When plotted one to one, the SBQ accounted for 96% of the SQI variability in a non-linear manner (Fig. 1). In other words, improving SBQ quadratically improved the SQ. However, both SCQ and SPQ linearly accounted for significant variations in SQI. When plotted one to one the SCQ accounted for 84% of the SQI variability (Fig. 2) whereas the SPQ accounted for 81% of the variability in the SQI (Fig. 3). The SBQ also significantly accounted for 73 and 69% of the variability in SCQ and SPQ respectively (Figs. 4 and 5). However, the SCQ has shown a moderate linear relationship ($r = 0.69^*$) with SPQ (Fig. 6). When plotted, the SQI has shown a highly significant linear relationship with C sequestration index and vice versa (Fig. 7). In other words, increasing SQ significantly influenced soil C sequestration and vice versa.

A highly significant quadratic relationship of SBQ with SQI suggested that among the soil biological, chemical and physical quality indices, the SBQ is a consistent, sensitive, and early indicator of changes in SQ long before the changes are detected in other SQ indicator properties. The SBQ is greatly responsible, among other properties, for decomposition of organic residues, facilitating nutrient cycling, metabolizing labile C, synthesizing humic substances, enhancing macro aggregation and structural stability, and protection of organic matter as POM (Dexter, 2004; Aziz et al., 2009; Melero et al., 2009). Therefore, improvement in soil biological properties relates to improvement in soil chemical and physical properties, and ultimately soil quality. A significant relationship of SBQ with SCQ and SPQ justified the role of soil biology to improve other soil properties. Parkin et al. (1996) reported that changes in biological activities or biochemical processes may be used as indicators of SQ. Furthermore, a significant linear relationship between SQI and C_{index} supported our hypothesis that improved SQ will facilitate soil C sequestration or vice versa. Therefore, a routine evaluation of SBQ can be used as an early and sensitive indicator of both soil quality and C sequestration.

4. Conclusions

Soil quality is an integrated function of biological, chemical and physical properties of soil. Results showed that tillage and crop rotation had significant impact on soil microbial biomass, basal respiration, catabolism of carbon, total carbon, active carbon, total nitrogen, aggregate stability and particulate organic matter except total porosity at different depths of soil when measured and/or calculated as selected soil quality indicators. The No-till significantly increased soil microbial biomass, basal respiration, total carbon, active carbon, total nitrogen, aggregate stability, sand free particulate organic matter and decreased catabolism of carbon over time. In contrast, the conventional tillage decreased soil microbial biomass, total carbon, active carbon, total nitrogen, aggregate stability and sand free particulate organic matter and increased catabolism of carbon. Similarly, soil biological quality, soil chemical quality, soil physical quality and soil quality index improved under No-till and reduced under conventional tillage overtime. Among the tillage and crop rotation combinations, the corn–soybean–wheat under No-till performed best to improve soil quality properties and soil quality over time. A significant relationship between soil quality index and soil biological quality suggests that soil biological quality can be used as a sensitive and indicator of soil quality evaluation including soil carbon sequestration in response to sustainable management practices. Moreover, a routine measurement of soil biological quality can be used as an early indicator of both soil quality and carbon sequestration.

References

Al-Kaisi, M.M., Yin, X., 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations. Journal of Environmental Quality 34, 437–445.

A' lvaro-Fuentes, J., Joaquın Morell, F., Plaza-Bonilla, D., Arrue, J., Cantero-Martinez, C., 2012. Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil and Tillage Research 120, 32–39.

Anderson, T.H., Domsch, K.H., 1989. Ratios of microbial biomass carbon to total organic-C in arable soils. Soil Biology and Biochemistry 21, 471–479.

Anderson, T.H., Domsch, K.H., 1990. Application of eco-physiological quotients (qCO_2 and qD) on microbial biomasses from soils of different cropping histories. Soil Biology and Biochemistry 22, 251–255.

Anderson, T.H., Gray, T., 1991. Soil microbial carbon uptake characteristics in relation to soil-management. FEMS Microbiology Ecology 74, 11–19.

Angers, D.A., Pesant, A., Vigneux, J., 1992. Early cropping-induced changes in soil aggregation, organic matter and microbial biomass. Soil Science Society of America Journal 56, 115–119.

Aparicio, V.C., Costa, J.L., 2007. Soil quality indicators under continuous cropping systems in the Argentinean Pampas. Soil and Tillage Research 96, 155–165.

Aziz, I., Mahmood, T., Raut, Y., Lewis, W., Islam, R., Weil, R.R., 2009. Active organic matter as a simple measure of field soil quality. In: ASA International Meetings, Pittsburg, PA.

Benitio, A., 2010. Carbon accumulation in soil. Ten year study of conservation tillage and crop rotation in a semi-arid areas of Castile-Leon, Spain Aurora Sombrero. Soil and Tillage Research 107, 64–70.

Blake, G.R., Hartge, k.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis Part 1 Physical and Mineralogical Methods. American Society of Agronomy and Soil Science Society of America, Madiso, WI, pp. 363–376.

Boehm, M.M., Anderson, D.W., 1997. A landscape-scale study of soil quality in three prairie farming systems. Soil Science Society of America Journal 61, 1147–1159.

Carter, M.R., 1991. The influence of tillage on the proportion of organic carbon and nitrogen in the microbial biomass of medium-textured soils in a humid climate. Biology and Fertility of Soils 11, 135–139.

Celik, I., Barut, Z.B., Ortas, I., Gok, M., Demirbas, A., Tulun, Y., Akpinar, C., 2011. Impacts of different tillage practices on some soil microbiological properties and crop yield under semi-arid Mediterranean conditions. International Journal of Plant Production 5 (3), 237–254.

Derpsch, R., Friedrich, T., Kassam, K., Hongwen, L., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. International Journal of Agricultural and Biological Engineering 3 (1), 1–25.

Dexter, A., 2004. Soil physical quality part III: unsaturated hydraulic conductivity and general conclusions about S-theory. Geoderma 120, 227–239.

Ding, X., Zhang, B., Zhang, X., Yang, X., Zhang, X., 2011. Effects of tillage and crop rotation on soil microbial residues in a rainfed agroecosystem of northeast China. Soil and Tillage Research 114, 43–49.

Dumanski, J., Pieri, C., 2000. Land quality indicators: research plan. Agriculture, Ecosystems and Environment 81, 93–102.

Erkossa, T., 2011. Tillage effects on physical qualities of a vertisol in the central highlands of Ethiopia. African Journal of Environmental Science and Technology 5 (12), 008–1016.

Gardi, C., Tomaselli, M., Parisi, V., Petraglia, A., Santini, C., 2002. Soil quality indicators and biodiversity in northern Italian permanent grasslands. European Journal of Soil Biology 38, 103–110.

Gosai, K., Ayyanadar, A., Biman, K.D., 2009. Influence of conservation tillage on soil physiochemical properties in a tropical rainfed agricultural system of northeast India. Soil and Tillage Research 105, 63–71.

Hazarika, S., Parkinson, R., Bol, R., Dixon, R., Russell, P., Donovan, S., Allen, D., 2009. Effect of tillage system and straw management on organic matter dynamics. Agronomy for Sustainable Development 29, 525–533.

Hu, S., Grunwald, N.J., Van Bruggen, A.H.C., Gamble, G.R., Drinkwater, L.B., Shennan, C., Demment, M.W., 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrogen availability. Soil Science Society of America Journal 61, 901–911.

Islam, K.R., 1997. Test of active organic carbon as a measure of soil quality. Unpublished Ph.D. dissertation. University of Maryland, College Park.

Islam, K.R., Weil, R.R., 1998a. Microwave irradiation of soil for the routine measurement of microbial biomass C. Biology and Fertility of Soils 27, 408–416.

Islam, K.R., Weil, R.R., 1998b. A rapid microwave digestion method for colorimetric measurement of soil organic C. Communications in Soil Science and Plant Analysis 29, 2269–2284.

Islam, K.R., Weil, R.R., 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. Journal of Soil and Water Conservation 55, 69–78.

Jacobs, A., Rauber, R., Ludwing, B., 2009. Impact of reduced tillage on carbon and nitrogen storage of two Haplic Luvisols after 40 years. Soil and Tillage Research 102, 158–164.

Jina, H., Hongwena, L., Rasaily, R.G., Qingjiea, W., Guohuaa, C., Yanboa, S., Xiaodonga, Q., Lijinc, L., 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain. Soil and Tillage Research 113, 48–54.

Kennedy, A.C., Papendick, R.I., 1995. Microbial characteristics of soil quality. Journal of Soil and Water Conservation 50, 243–248.

Larson, W.E., Pierce, F.J., 1991. Conservation and enhancement of soil quality. In: Wolf, K., et al. (Eds.), Evaluation for Sustainable Land Management Contaminated Soil' 88. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 1495–1503.

Larson, W.E., Pierce, F.J., 1994. The dynamics of soil quality as a measure of sustainable management. In: Doran, J.W., et al. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI, pp. 37–51.

Madejon, E., Murillo, J.M., Moreno, F., Lopez, M.V., Alvaro-Fuentes, J., Cantero, 2009. Effect of long-term conservation tillage on soil biochemical properties in Mediterranean Spanish areas. Soil and Tillage Research 105, 55–62.

Mando, A., Ouattara, B., Se'dogo, M.P., Stroosnijder, L., Ouattara, K., Brussaard, L., Vanlauwe, B., 2003. Long term effects of tillage and organic input on Ferric Lixisol organic matter and crop performance under Sudano-Sahelian conditions. Soil and Tillage Research 80, 95–101.

Melero, S.L., Rosa, G., Jose, M.M., Fe, L.M., 2009. Conservation tillage: short- and long-term effects on soil carbon fractions and enzymatic activities under mediterranean conditions. Soil and Tillage Research 104, 292–298.

Morris, D.R., Gilbert, R.A., Reicosky, D.C., Gesch, R.W., 2004. Oxidation potentials of soil organic matter in histosols under different tillage methods. Soil Science Society of America Journal 68, 817–826.

Moussa-Machraoui, S., Errouissi, F., Ben-Hammouda, M., Nouira, S., 2010. Comparative effects of conventional and no-tillage management on some soil properties under Mediterranean semi-arid conditions in northwestern Tunisia. Soil and Tillage Research 106, 247–253.

Myrold, D., 1998. Transformations of nitrogen. In: Sylvia, D., Furhmann, J., Hartel, P., Zuberer, D. (Eds.), Principles and Applications of Soil Microbiology. Prentice Hall, Upper Saddle River, NJ.

Naudin, K., Goze, E., Balarabe, O., Giller, K.E., Scope, E., 2010. Impact of no tillage and mulching practices on cotton production in North Cameroon: a multi-locational on-farm assessment. Soil and Tillage Research 108, 68–76.

Ogle, S.M., Swana, A., Paustiana, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems and Environment 149, 37–49.

Parkin, T.B., Doran, J.W., Franco-Vizcaino, E., 1996. Field and laboratory tests of soil respiration.Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. SSSA Spec. Publ. 49, Soil Sci. Soc. Am., Madison, WI, pp. 231–246.

Ramos, M.E., Robles, A.B., Sanchez-Navarro, A., Gonzalez-Rebollar, J.L., 2011. Soil responses to different management practices in rainfed orchards in semiarid environments. Soil and Tillage Research 112, 85–91.

Reganold, J.P., Palmer, A.S., 1995. Significance of gravimetric versus volumetric measurements of soil quality under biodynamic, conventional, and continuous grass management. Journal of Soil and Water Conservation 50, 298–305.

Shan, H., Yan-Ni, S., Wen-Yi, R., Wu-Ren, L., Wei-Jian, Z., 2010. Long-term effect of no-tillage on soil organic carbon fractions in a continuous maize cropping system of northeast China. Soil Science Society of China 20 (3), 285–292.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no tillage agriculture. Soil Biology and Biochemistry 32, 2099–2103.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota and soil organic matter dynamics. Soil and Tillage Research 79, 7–31.

Staben, M.L., Bezdicek, D.F., Smith, J.L., Fauci, M.F., 1997. Assessment of soil quality on Conservation Reserve Program and wheat fallow soils. Soil Science Society of America Journal 61, 124–130.

Stinner, D., Islam, K.R., 2008. Organic management systems effect on soil quality. In: Paper Presented at 101st ASA/CSA/SSSA Meetings, Houston, TX.

Thomas, G.A., Dalal, R.C., Standley, J., 2007. No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil and Tillage Research 94, 295–304.

Wander, M.M., 2004. Soil organic matter fractions and their relevance to soil function. In: Magdoff, F., Weil, R. (Eds.), Advances in Agroecology. CRC Press, Boca Raton, FL, pp. 67–102.

Wander, M.M., Traina, S.J., Stinner, B.R., Peters, S.E., 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Science Society of America Journal 58, 1130–1139.

Wardle, D.A., Ghani, A., 1995. A critique of the microbial metabolic quotient (qCO_2) as a bioindicator of disturbance and ecosystem development. Soil Biology and Biochemistry 27, 1601–1610.

Weil, R.W., Islam, K.R., Stine, M., Gruver, J.B., Samson-Liebig, S.E., 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. American Journal of Alternative Agriculture 18, 3–17.

Wolfarth, F., Schrader, S., Oldenburg, E., Weinert, J., Brunotte, J., 2011. Earthworms promote the reduction of Fusariumbiomass and deoxynivalenol content in wheat straw under field conditions. Soil Biology and Biochemistry 43, 1858–1865.