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CHEMICAL FERTILIZATION AND ORGANIC AMENDMENTS IMPACT ON SOIL BIOLOGICAL, CHEMICAL PROPERTIES AND CARBON, NITROGEN LABILITY

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ABSTRACT

Soil organic matter (SOM) management to sustain soil quality requires integrated management practices. The goal of our study was to evaluate the long-term (1996 to 2012) effects of annual chemical fertilization and various organic amendments on soil biological and chemical properties and lability of carbon and nitrogen as indicator of SOM management. Treatments including the control, chemical fertilization, compost, cow manure, and mycorrhizal inoculated compost amendments were established for a corn (*Zea mays* L.) - wheat *(Triticum aestivum L.*) rotation in a randomized complete block design. Composite soils were randomly collected from 0 to 20 cm depth and analyzed for soil biological and chemical properties. Besides, carbon and nitrogen lability as well as management indices were calculated from measured carbon and nitrogen fractions. Results showed that both compost and cow manure amendments significantly increased total microbial biomass (by 1.8 to 2.2 fold), basal respiration (by 1.3 to 1.9 fold), potentially mineralizable carbon (by 1.1 to 1.4 fold), total organic carbon (6 to 11%), oxidizable carbon (28 to 33%), particulate organic cabon (4.2 to 4.5 fold), soluble carbon (1.3 to 1.7 fold), extractable carbon (1.7 to 1.9 fold), total nitrogen (10 to 12%), available nitrogen (2.8 fold), and PON (4.5 to 4.7 fold) with a significant decrease in qCO_2 (20 to 23%), as compared with the control. Moreover, both compost- and cow manure-amended soils had significantly higher values of basal respiration, soluble carbon, extractable carbon, oxidizable carbon, particulate organic cabon, and particulate organic nitrogen than the chemically fertilized soils. The POC and PON lability and management indices consistently accounted and predicted the management-induced qualitative and quantitative changes in TOC and TN, over other C and N fractions.

KEYWORDS:
Compost, mycorrhizae, cow manure, microbial biomass, organic carbon and nitrogen, carbon and nitrogen management indices

INTRODUCTION

Agricultural production systems rely heavily on frequent tillage operations, excessive fertilization, and reactive chemicals used to produce greater amounts of food, feed, biofuel and fiber, but the impacts associated with the current practices are responsible for reduced agroecosystem services [1, 2].

The use of soluble nutrient-enriched chemically reactive fertilizers has increased worldwide due to their economics, widespread availability, flexibility of applications, and use as insurance to support for increased crop productivity [1]. Chemical fertilization, especially nitrogen (N) fertilization, increased grain yield by 43 to 68% and biomass production by 25 to 42% in corn which contributed to increase TOC, TN, available P, and exchangeable K concentration when compared with the control [3]. Several studies have reported that the increase in total organic carbon (TOC) content and soil fertility by chemical fertilizations is attributed to their long-term positive effects on crop growth [4,5,6,7]. In contrast, other studies have reported that long-term and continuous chemical fertilization had marginal or negative effects on soil fertility and TOC contents [8,9,10]. It is reported that continuous and indiscriminate use of chemically reactive N and P fertilizers are not only a waste of valuable resources, but are associated with soil biological inefficiency, ecological degradation, and environmental pollution [1,11].

Agricultural practices that consistently support economic crop production while improving and/or maintaining soil quality are the keys of sustainable production systems. One of the potential sustainability options is to recycle organic waste products alone or with biological agents (such as mycorrhizae) and integrated with chemical fertilization to improve soil quality. Soil organic amendments of various origins have been used as both a waste management alternative and a source of organic matter and bioavailable essential nutrients to improve soil quality for crop production [12,13]. Long-term use of compost, manures, biosolids, and cover crops influence soil biology, increase TOC and total nitrogen (TN) contents, provide essential nutrients to crops, support physical stability, and rejuvenate degraded soils [13, 14].

The TOC is widely considered as a composite indicator of soil quality because of its positive contribution on soil biological, chemical and physical properties, and consequently on crop production [5,15,16,17]. Several long-term field studies have reported that organic amendments either alone or in combination with chemical fertilization are more effective to increase TOC and essential nutrient contents than that of the chemical fertilization alone [7, 10, 18]. While the carbon (C) is stoichiometrically linked to N in SOM, the effects of TOC, including TN on soil quality, are dependent on the type and amount of organic amendments applied, C:N of the applied organic matter, soil and climatic conditions, and management practices [19,20]. However, the effect of short-term management practices (within 1 to 2 years) on the changes in TOC content is inconsistent, as the changes occur very slowly due to the inherent effects of large background levels of passive C in soil [6, 21].

Several C and N fractions, such as total microbial biomass (SMB), particulate organic cabon (POC), oxidizable carbon (OxC), extractable carbon (ExC), soluble carbon (SC), particulate organic nitrogen (PON), and available nitrogen (AN) that have been considered as labile C and N pools due to their sensitivity to management-induced changes than the TOC content over a short period of time [6,7,21]. While the carbon management index (CMI) has been used to determine lability and quantitative changes in TOC content [7,17,22,23,24], similar information on nitrogen management index (NMI) in response to changes in agricultural management practices is lacking. The CMI has been used in different land management uses to evaluate the capacity of a land use to promote soil quality [22,23]. Sainepo et al. [23]. CMI is significantly effectd by soil use mangmenet and they indicated that agriculture soil have high CMI than bedly manged grassland. Moreover, available information regarding the impact of long-term organic amendments and chemical fertilization on soil biological and chemical properties and the sensitivity of labile C and N in SOM associated with soil quality is limited.

Our hypothesis is that long-term effects of organic amendments and chemical fertilization are expected to produce measureable and consistent changes in soil biological and chemical properties, and consequently influence the sensitivity of labile C and N in SOM to influence soil quality. The objectives of the study were to evaluate the long-term (1996 to 2012) effects of compost, cow manure, mycorrhizae inoculated-compost amendments and chemical fertilization on soil microbial biomass and associated biological properties, organic C and N pools, and the suitability of selected C and N fractions as indicators of TOC and TN lability and management under conventionally-tilled corn-wheat-rotation in the semi-arid Mediterranean climates of Turkey.

MATERIALS AND METHODS

Site and experimental design. The field experiment was established in 1996 at the Research Farm of the Çukurova University (37°00′54.31″ N longitude and 35°21′21.56″ E latitude, and 34 m above the mean sea level) in Adana, Turkey. The area is characterized by the Mediterranean semi-arid climate with an average annual rainfall of 670±42 mm that occurs mainly from November to April [25]. The annual mean temperature is 19.1^{0}C with a frost-free period of 2 to 3 days. The soil is a Menzilat clay loam (Typic Xerofluvents) with a pH 7.6±0.7, salt content 50 g kg^{-1}, cation exchange capacity 20.5±2 $Cmol_{+}kg^{-1}$, available P 15±2 mg kg^{-1}, and 319±31, 361±87, and 320±23 g of clay, silt and sand per kg of soil, respectively.

The experiment was laid-out by using a randomized complete block design with three replications. The treatments were: (1) control, (2) chemical fertilizer [N-P-K applied annually at 160 kg N ha^{-1} as $(NH4)_2SO_4$, 83 kg K ha^{-1} as K_2SO_4, and 26 kg P ha^{-1} as $3Ca(H_2PO_4)_2.H_2O$], (3) cow manure (applied at 25 Mg ha^{-1} yr^{-1}) Cow manure was processed (more than one year old).(4) Mix plant residue material made compost (applied at 25 Mg ha^{-1} yr^{-1}) and (5) Mycorrizae inoculated compost (applied at 10 Mg ha^{-1} yr^{-1}), respectively. All plots were ploughed to 15-20 cm depth and the cocktail inoculum (mixture of sand + soil + spores + hyphae) was produced in sorghum (Sorghum bicolor L.) host plants. Mycorrhizal inoculum was mixed with the compost before application. The organic fertilizers (animal manure, compost and mycorrhizae) and NPK mineral fertilizer were uniformly spread on the soil surface (moist basis) just before sowing and incorporated into the surface 10-15 cm layer with a disc harrow**.** While the compost nutrient composition was 19.4% total organic C, 0.87% total N, 0.36% total P, and 0.52% total K, the cow manure nutrient composition was 29.7% total organic C, 0.75% total N, 0.19% total P, and 0.88% total K, respectively. Both compost and cow manure characteristics and their nutrient load in the field over the years were presented in Table 1. The treatments have been

TABLE 1
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhizae-inoculated compost amendments on soil nutrient contents under corn-wheat rotation.

Experimental	Total	C	N	P	K	pH	C:N:P		
Treatment	load (Mg/ha)				(1:2)	C:N	C:P	N:P	
Control	--	--	--	--	--	--	--	--	--
Fertilizer	15.8	--	2.88	0.47	1.49	--	--	--	--
Compost	450	87.2	3.92	1.62	2.34	7.7	22.2	53.8	2.4
Cow manure	450	133.2	3.78	0.86	3.96	7.8	35.2	154.9	4.4
My-compost	180	34.9	1.57	0.65	0.94	7.7	22.2	53.8	2.4

My-compost=Mycorrhizae-inoculated compost, C=Carbon, N=Nitrogen, P=Phosphorus, and K=Potassium.

applied since 1996 in corn-wheat rotation under moldboard plowing after each crop harvest. While corn was irrigated, the wheat was grown under rainfed.

Soil collection, processing, and analysis. Composite soils from each plot at 0 to 20 cm depth were collected by following systematic sampling technique after wheat harvest in 2012. The soil samples were sieved through a 2 mm mesh to remove visible pieces of rocks and organic debris. A portion of the sieved field-moist soil was analyzed for total microbial biomass (SMB) and associated biological properties. Another portion of the field-moist was air-dried at room temperature (~25 ^{0}C) for 15 days prior to chemical and physical analyses.

The SMB concentration was determined by using the rapid microwave irradiation and extraction method [26]. Basal respiration (BR), as a measure of antecedent soil biological activity, was determined by using the static incubation of unamended field-moist soil in a temperature-controlled incubator at 25±1^{0}C for 30 days [16]. Total amount of CO_2 released from the incubated soil was divided by the TOC concentration to calculate the potentially mineralizable carbon (PMC). The specific maintenance respiration (qCO_2) rates, as measures of soil microbial catabolism, were calculated as BR rates over SMB concentration [27].

Total carbon (TC) and TN concentrations were determined on finely-ground (<125 μm) oven-dried soil by using the Elementar® automated CNS dry combustion analyzer. A Scheibler calcimeter was used to measure $CaCO_3$ concentration as inorganic carbon (IC), which was subtracted from the TC to calculate the TOC concentration. The OxC concentration was determined by the chemical oxidation of air-dried soil after reacting with the 0.333 M $KMnO_4$ solution [22]. Samples of field-moist soil were shaken with distilled deionized water and neutral 0.5 M K_2SO_4 solution to extract soluble C (SC), salt extractable C (ExC), and available N (AN), respectively. The SC, ExC, and AN concentrations were determined by using the Shimadzu® automated total dissolved C and N analyzer.

Particulate organic matter (POM) was collected after dispersing the 2 mm sieved air-dried soil with 0.5% $(NaPO_3)_6$ solution [28]. The dispersed soil suspension was passed through a 53 μm sieve to collect sand associated POM followed by washing with running distilled water and oven-drying at 65°C until a constant weight was obtained. A portion of the sand associated POM was burnt in a muffle furnace at 480°C for 2 hr. and the POM concentration was calculated by the loss on ignition method. The residual ash was dissolved in 0.1 M HCl solution, filtered, and analyzed for POP by using the Astoria 300® continuous-flow N and P auto-analyzer. Another sample of the sand associated POM was ground by a ceramic mortar and pestle and analyzed for POC and PON concentration by using the Elementar® automated CNS dry combustion analyzer.

Using all the C data, the CMI and NMI were calculated according to Blair et al. [29] as follows:

CMI = (CPI x CLi)
CPI = (TOC in treatment soil/TOC in control soil)
CLi = (CL in treatment soil/CL in control soil)
CL = (Labile C/Non-labile C)

Where CPI is the C pool index and CLi is the C lability index; CL refers to the lability of C
, which was calculated as:

NMI = (NPI x NLi)
NPI = (TN in treatment soil/TN in control soil)
NLi = (NL in treatment soil/NL in control soil)
NL = (Labile N/Non-labile N)

Where NPI is the N pool index and NLi is the N lability index. NL refers to the lability of In our study, While the labile C pool was considered as the portion of TOC that was measured as SMB, OxC, POC, SC, and ExC, respectively, the labile N pool was considered as the portion of TN that was measured as PON and AN. The non-labile C and N concentration was calculated by subtracting the labile C and N concentration from the TOC and TN concentration.

Statistical analysis. Significant differences in soil biological and chemical properties and C and N lability in response to the effects of various organic amendments and chemical fertilization were analyzed by using one-way analysis of variance procedure of the SAS [30]. While the treatments were considered as a fixed factor, the blocks were considered as a random factor. For all statistical analyses, significant effects of predictor variables on dependent variables were separated by the F-protected least significant difference (LSD) test at $p \leq 0.05$ unless otherwise mentioned. Regression and correlation analyses among TOC, TN, C and N lability, and CMI and NMI were performed by using SigmaPlot® software.

RESULTS AND DISCUSSION

Soil microbial biomass and biological activities. The SMB and biological activities were significantly affected by the long-term effects of chemical fertilization and various organic amendments (Table 2). The SMB concentration increased by 1.6-, 1.8-, and 2.2-fold in mycorrhizae-inoculated compost (My-compost), cow manure and compost amended soils, respectively, as compared with the control. Compost amended soil had also significantly higher SMB concentration by 1.4-fold than that of the chemically fertilized soil. Similarly, compost amendments increased the proportion of TOC as SMB (qR) by 2.1-fold as compared to the control. The qR values were statistically similar among other treatments. The BR rates in the chemically fertilized and My-compost, cow manure and compost amended soils were higher by 1.3- to 1.9-fold than with the control. However, the BR rates were statistically similar between the cow manure- and My-compost amended soils, and between the My-compost amended and chemically fertilized soils. In contrast, the qCO_2 rates were significantly smaller (by 20 to 23%) in the compost amended- and chemically fertilized soils as compared to that of higher qCO_2 rates in the control. While the My-compost and cow manure amended soils had significantly lower qCO_2 rates as compared with the control, the qCO_2 rates in the compost, cow manure and My-compost amended soils were statistically similar. The PMC concentration was significantly higher in the compost amended soil and smaller in the My-compost amended soil, as compared with the control. The PMC concentration increased by 1.1- to 1.4-fold in the cow manure- and compost-amended soils than in the control.

Significant differences in the SMB concentration and biological properties were in response to the variable effects exerted by the long-term organic amendments and chemical fertilization. A higher SMB concentration in the compost- and cow manure amended soils than in the chemically fertilized- and control soils was due to increased availability of labile C and essential nutrients to the heterotrophic microbes, efficient biological anabolism, and improved soil conditions [31,32]. Higher values of qR suggested an enlarging pool of biologically labile C by the impact of compost- and cow manure applications. It is expected that the long-term organic amendments would stabilize the BR rates to support a relatively large size of the SMB pool by reducing the qCO_2 rates, which may be due to efficient anabolism of C and nutrients for cell growth than for respiratory catabolism [27,32]. The significant positive linear relationship of the SMB pool with the BR rates and inverse non-linear relationship of the SMB pool with the qCO_2 rates justified our results related with an improved anabolic efficiency of the SMB (Figure 1).

TABLE 2
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhizae-inoculated compost amendments on soil microbial biomass and associated biological properties under corn-wheat rotation*

Experimental Treatment	SMB (mg/kg)	qR (%)	BR (mg/kg/d)	qCO_2 (µg/mg/d)	PMC (%)
Control	172c§	1.3b	15d	95a	4.2cd
Fertilizer	263bc	2.0ab	19c	73c	4.3bc
Compost	371a	2.7a	28a	76bc	6.1a
Cow manure	308ab	2.1ab	23b	78b	4.7b
My-compost	271b	2.1ab	21bc	80b	3.6d

SMB=Total microbial biomass, qR=Total microbial biomass carbon over total organic carbon, BR=Basal respiration, qCO_2=Specific maintenance respiration, and PMC=Potentially mineralizable carbon.
*Means separated by same lower case letter in each column were not significantly different among the treatments at $p \leq 0.05$.

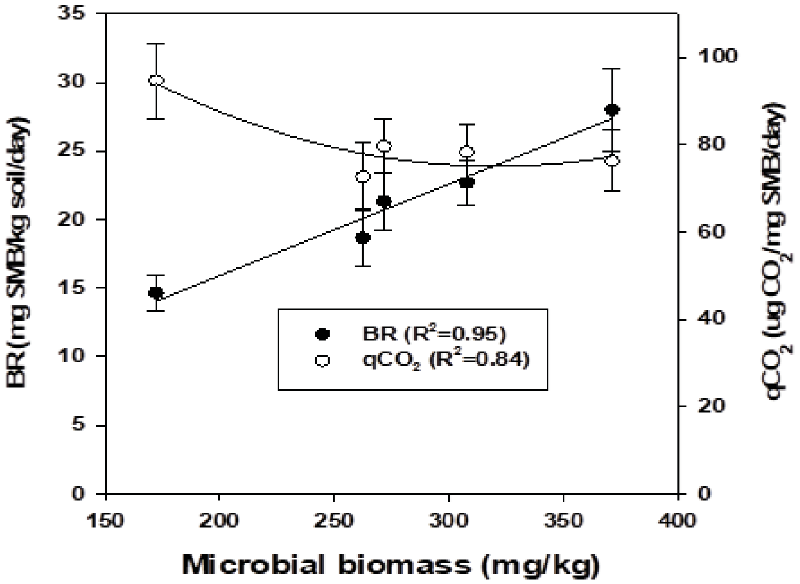

FIGURE 1

Relationship of total microbial biomass (SMB) with basal respiration (BR) and specific maintenance respiration (qCO_2) rates in soils under long-term corn-wheat rotation (1996 to 2012).

Treatment mean values were plotted with standard error.

In contrast, a reduced availability of labile C and nutrients to the heterotrophic microbes was able to support only a relatively smaller size of the SMB pool with higher catabolic activity (qCO_2 rates) in the control than in the cow manure- and compost-amended soils. There were consistent trends to demonstrate that the biological properties were more efficient in the cow manure and compost applied soils as compared with the chemically fertilized and control soils (Figure 1). Our results collaborated with the results of previous studies which reported a significant increase in the SMB pool, biological efficiency, and labile C and N contents with long-term organic amendments [33,34].

Soil carbon and nitrogen contents. Both TC and IC concentration was statistically similar among the treatments except between the cow manure-amended and control soils (Table 3). The TOC concentration was significantly higher by 6 and 13% in the compost- and cow manure amended (11%) soils than in the control. However, the TOC concentration was statistically similar among the chemically fertilized, My-compost amended and control soils. The OxC concentration in both cow manure- and compost amended soils was significantly higher by 28 to 33% than in the control, but the OxC concentration did not vary significantly among the My-compost amended, chemically fertilized and control soils. The SC concentration was higher by 1.3- to 1.7-fold in the My-compost, cow manure- and compost amended soils, respectively than in the control. Both cow manure- and compost amended soils had a significantly higher concentration of ExC (by 1.7- to 1.9-fold), followed by the chemically fertilized- and My-compost amended soils (1.3- to 1.4-fold), as compared with the control. Cow manure amended soil had a significantly higher TN concentration (by 10 to 12%) than in other treatments except the compost amended soil. Similarly, both compost- and cow manure amended soils had a significantly higher AN concentration (by 2.8-fold), followed by the chemically fertilized (2.2-fold) and My-compost amended soils (1.7-fold) than that of the control.

Significantly higher C and N concentration in both compost- and cow manure-applied soils than in the control was possibly due to higher background levels of C and N concentration of the applied organic materials and C and N recycling by crop residue. Previous studies reported a similar result on TOC concentration after 9- and 16-year of cow manure and compost applications, respectively [12,35]. A significant difference in TC concentration (IC plus TOC) between the treated and control soils was possibly due to the increased added effects of TOC on TC concentration in response to long-term organic amendments and chemical fertilization. It is possible that a portion of the C and N in the cow manure and compost is relatively resistant (lignified materials) to microbial decomposition, which may have eventually accumulated as TOC and TN. In contrast, the effects of rapid mineralization of crop residue and native TOC in the control over the years may be responsible for decreased TC and TOC concentration.

A significantly higher concentration of OxC, SC and ExC in the cow manure- and compost-applied soils than in the chemically fertilized- and control soils was probably due to repeated applications of C-enriched compost and cow manures

TABLE 3
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhizae-inoculated compost amendments on soil total, organic, inorganic, oxidizable, soluble, extractable carbon, and total and available nitrogen concentration under corn-wheat rotation*

Experimental Treatment	TC	TOC	IC	OxC	SC	ExC	TN	AN
	(g/kg)			(mg/kg)			(g/kg)	(mg/kg)
Control	51.7b§	12.9c	38.8b	352b	40c	77d	1.43b	6c
Fertilizer	53.7ab	13.4bc	40.3ab	383b	48bc	104c	1.43b	13b
Compost	54.6ab	13.7b	40.9ab	468a	68a	147a	1.5ab	17a
Cow manure	59a	14.8a	44.2a	450a	68a	133ab	1.57a	17a
My-compost	52.6ab	13.1bc	39.5ab	396b	52b	110bc	1.4b	10b

My-compost=Mycorrhizae-inoculated compost, TC=Total carbon, TOC=Total organic carbon, IC=Inorganic carbon, OxC=Oxidizable carbon, SC=Soluble carbon, ExC=Extractable carbon, TN=Total nitrogen, and AN=Available nitrogen.
*Means separated by same lower case letter in each column were not significantly different among the treatments at $p \leq 0.05$.

over the years (Table 1). Similarly, a significantly higher concentration of ExC in the chemically fertilized soil as compared with the control was due to the positive effects of N fertilization on plant growth and rhizosphere excretion and increased return of crop residue [7,10]. Our results are in agreement with Campbell et al. [36], who reported a higher concentration of SC under different cropping systems in response to long-term N fertilization. While the compost and cow manure application rates were the same (25 Mg ha^{-1} yr^{-1}), their effects to cause a significant difference in the TOC concentration were due to the qualitative variation in the C concentration of the applied organic materials (Table 1). Moreover, a significantly lower concentration of TOC, OxC, SC, ExC, and AN in the control than in other treatments was possibly due to reduced C and N inputs to maintain and/or support microbial catabolism and thus, allowed priming of N-rich native SOM over time. It is expected that a significantly higher OxC, SC, ExC, and AN concentration is probably due to TOC and TN accumulation in response to years of organic amendments.

Soil particulate organic carbon, nitrogen and phosphorus contents. The POC concentration was significantly higher by 4.2- to 4.5-fold in the cow manure- and compost-amended soils than in the control (Table 4). The values of POC concentration in the My-compost amended chemically fertilized, and control soils were statistically similar. Likewise, the PON concentration in the cow manure- and compost-amended soils was significantly higher by 4.5-to 4.7-fold than in the control. While the POP concentration was higher in the cow manure- and compost-amended soils than in the chemically fertilized, My-compost-amended and control soils, the POP concentration in both My-compost and control soils was statistically similar. The proportion of TOC as POC (POC: TOC) was significantly higher in both cow manure- and compost-amended soils than in the chemically fertilized, My-compost-amended and control soils (Table 4). As expected, a similar effect of treatments on the proportion of TN as PON (PON: TN) was observed. However, a higher POC: PON was observed in the My-compost amended soil than in the cow manure amended soil. The POC: POP was

TABLE 4
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhiza-inoculated compost amendments on soil particular organic carbon, nitrogen and phosphorus concentration under corn-wheat rotation*

Experimental Treatments	POC (g/kg)	PON	POP	POC: TOC	PON: TN	POC: PON	POC: POP	PON: POP
		(mg/kg)						
Control	1.03b	45b	8b	8b	3b	23ab	156bc	6a
Fertilizer	2.37b	100b	22b	18b	7b	24ab	159bc	7a
Compost	4.62a	210a	39ab	34a	14a	23ab	213b	10a
Cow manure	4.29a	201a	47a	29a	13a	21b	93c	4a
My-compost	2.35b	80b	8b	18b	6b	31a	301a	10a

POC=Particulate organic carbon PON=Particulate organic nitrogen, and POP=Particulate organic phosphorus, TOC=Total organic carbon, TN=Total nitrogen, ,
*Means separated by same lower case letter in each column were not significantly different among the treatments at $p \leq 0.05$.

soil than in other treatments. The PON: POP did not vary significantly among the treatments. A significant positive impact of cow manure and compost amendments on POC, PON and POP concentration over other treatments was expected due to increased organic inputs and consequent accumulation of POM. Whalen et al. [37] reported that the organic matter from manure and composts retained in soil aggregates as POM. While POM is one of the sources of nutrients protected in soil aggregates, the impact of cow manure and compost amendments might have result a consequential increase in POC, PON and POP concentration over time. It is a well-known fact that SOM has more capacity to hold N, and most of the soil N exists in organic form [38]. A greater proportion of both TOC and TN as POC and PON in both cow manure- and compost-applied soils than in the chemically fertilized and control soils, respectively was probably associated with the higher POC and PON accumulation by the impact of organic amendments. Our results showed that the proportion of TOC as POC ranged from 8 to 34%, which were well within the ranges as reported in other studies [39]. While both cow manure and compost are sources of labile C, N, P, and other essential nutrients, it is likely that they have exerted a wide-ranging beneficial impact on soil quality properties than the chemical fertilizer alone [40].

Carbon and nitrogen accumulation, lability and management indices. The CPI, as a measure of TOC sequestration, was significantly higher in the cow manure amended soil (by 14%) followed by the compost amended and chemically fertilized soils (by 6%) than in the control (Figure 2a). However, the CPI values of the compost, My-compost amended and chemically fertilized soils were statistically similar. The CL, a ratio of labile and non-labile C pools of TOC, was ranked from higher values to lower values as POC > OxC > SMB > ExC > SC (Table 5). The CL of POC in the compost-amended soil was significantly higher by 2.3-, 2.4-, and 6-fold than in the My-compost amended, chemically fertilized, and control soils, respectively. While the CL of POC in the cow manure amended soil was 4.8-fold higher than in the control, the CL of OxC in the compost-amended soil was higher by only 12 to 28% than in other treatments, including the control. For SMB, the CL in the compost- amended soil was significantly higher by 1.4- to 2.1-fold, as compared to that in the chemically fertilized- and control soils, respectively. The CL of SC in both compost- and cow manure amended soils was significantly higher by 1.3- to 1.7-fold than that of the My-compost amended, chemically fertilized- and control soils, respectively. Similarly, the CL of ExC was significantly higher in both compost- and cow manure-amended soils than that in other treatments, including the control.

The POC had the highest CLi, followed by SMB, ExC, and SC as compared to that of the lowest CLi values of OxC (Table 6). The CLi of POC in both compost- and cow manure-amended soils was significantly higher by 6.6- and 5-fold, followed by the My-compost amended (3.6-fold) and chemically fertilized (2.6-fold) soils, as compared with the control. In contrast, the CLi of SMB was significantly higher by 2.7- and 2.3-fold in both My-compost- and compost-amended soils as compared with the control. The resulst of Blair et al. [22] showed that N and FYM additi was increased CL and consequently increased CMI. Resualts are in harmony with our foundings. When the SC was used as a measure of labile C, the CLi was significantly higher in both compost- and cow manure applied soils followed by the My-compost-amended and chemically fertilized soils than that in the control soil. The CLi of ExC was significantly higher in the compost-amended soil than in the control. Likewise, the CLi of OxC in the compost-applied soil was significantly higher by 13 to 30% as compared to the soils in other treatments, including the control.

TABLE 5
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhizae-inoculated compost amendments on soluble, extractable, oxidizable, microbial biomass, and particulate organic carbon lability in soil under corn-wheat rotation*

Experimental Treatments	Carbon lability (CL) SC	ExC	OxC	POC	SMB
Control	0.003c	0.006c	0.028b	0.087c	0.013c
Fertilizer	0.004b	0.008bc	0.029b	0.215bc	0.020bc
Compost	0.005a	0.011a	0.036a	0.525a	0.028a
Cow manure	0.005a	0.009b	0.032b	0.415ab	0.021ab
My-compost	0.004b	0.009b	0.031b	0.226bc	0.021a

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C=Soluble carbon, ExC=Extractable carbon, OxC=Oxidizable carbon, POC=Particulate organic carbon, and SMB=Total microbial biomass.
*Means separated by same lower case letter in each column were not significantly different among the treatments at p≤0.05.

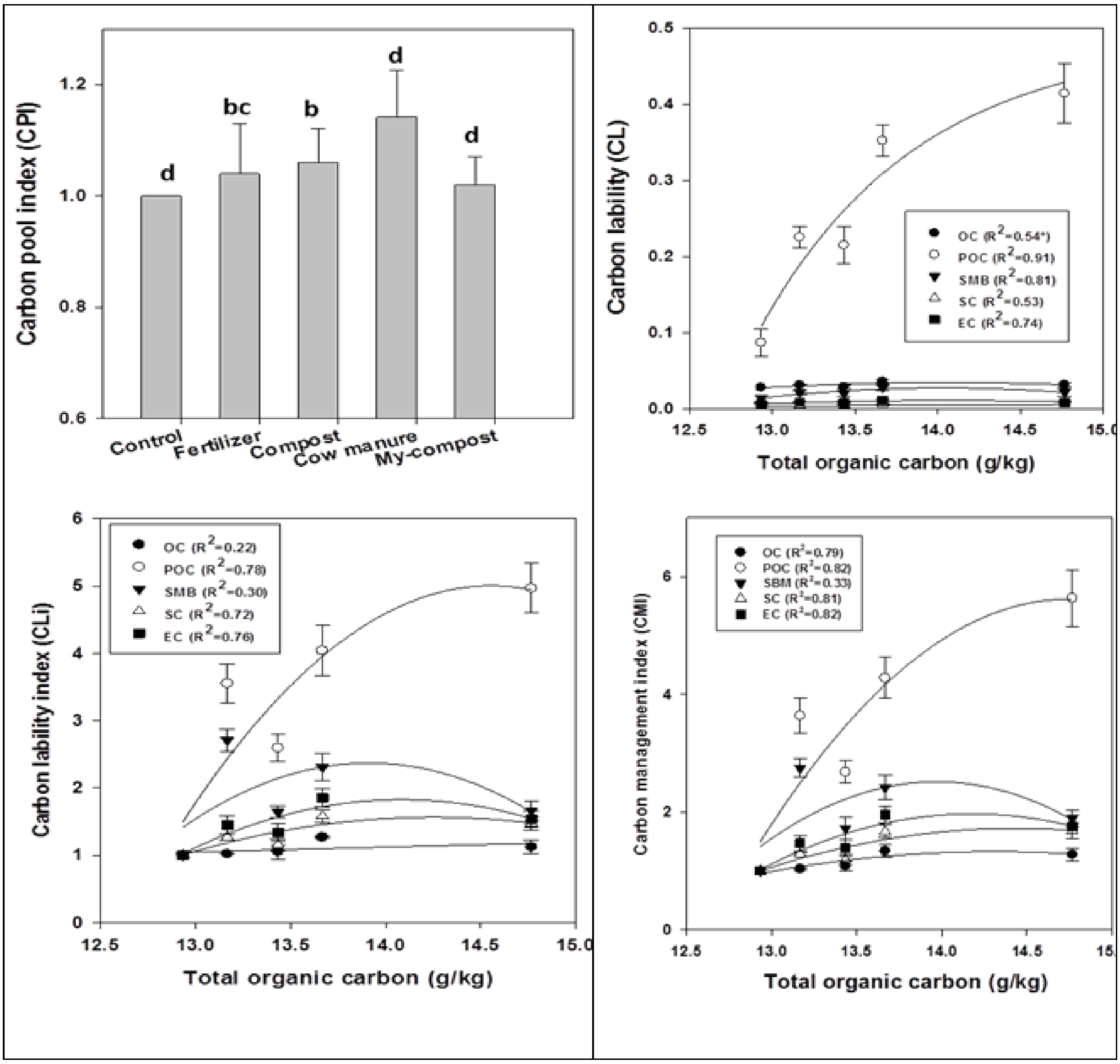

FIGURE 2

Long-term effects (1996 to 2012) of annual chemical fertilization, compost, cow manure, and mycorrhizae-inoculated compost amendments on (a) carbon pool index (CPI), and the relationship between total organic carbon with (b) carbon lability (CL), (c) carbon lability index (CLi), and (d) carbon management index (CMI), calculated based on soluble carbon (SC), extractable carbon (EC), oxidizable carbon (OC), particulate organic carbon (POC), and total microbial biomass (SMB) in soils under corn-wheat rotation. Treatment mean values were plotted with standard error.

TABLE 6

Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and my-corrhiza-inoculated compost amendments on carbon lability index in soil under corn-wheat rotation*

Experimental	Carbon lability index (CLi)				
Treatment	SC	ExC	OxC	POC	SMB
Control	1c	1b	1b	1c	1b
Fertilizer	1.15b	1.33ab	1.05b	2.59b	1.64ab
Compost	1.58a	1.85a	1.27a	6.58a	2.31a
Cow manure	1.47a	1.54ab	1.12b	4.97a	1.66ab
My-compost	1.27b	1.45ab	1.02b	3.55b	2.71a

SC=Soluble carbon, ExC=Extractable carbon, OxC=Oxidizable carbon, POC=Particulate organic carbon and SMB=Total microbial biomass.

*Means separated by same lower case letter in each column were not significantly different among the treatments at $p \leq 0.05$.

TABLE 7
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhizae-inoculated compost amendments on carbon management index in soil under corn-wheat rotation*

Experimental Treatment	Carbon management index (CMI)				
	SC	ExC	OxC	POC	SMB
Control	1c	1c	1b	1b	1b
Fertilizer	1.2b	1.39bc	1.09b	2.68ab	1.72ab
Compost	1.67a	1.95a	1.34a	6.96a	2.42a
Cow manure	1.68a	1.75ab	1.28a	5.64a	1.89ab
My-compost	1.29b	1.49abc	1.04b	3.64ab	2.75a

SC=Soluble carbon, ExC=Extractable carbon, OxC=Oxidizable carbon, POC=Particulate organic carbon, and TMB=Total microbial biomass.
*Means separated by same lower case letter in each column were not significantly different among the treatments at $p \leq 0.05$.

TABLE 8
Long-term effects (1996 to 2012) of annual chemical fertilization and compost, cow manure, and mycorrhizae-inoculated compost amendments on particulate organic and available nitrogen lability and nitrogen management index in soil under corn-wheat rotation*

Experimental Treatment	NL (Based on PON)	NLi	NL (Based on AN)	NLi	NMI (PON)	NMI (AN)
Control	0.033c	1b	0.043c	1c	1b	1c
Fertilizer	0.076bc	2.62ab	0.1ab	2.53ab	2.65ab	2.46ab
Compost	0.166a	5.81a	0.128a	3.04a	5.84a	3.18a
Cow manure	0.147ab	4.74a	0.119a	2.87ab	5.24a	3.1a
My-compost	0.061c	2.23ab	0.076b	1.8b	2.14ab	1.76bc

NL=Lability of nitrogen, Li=Nitrogen lability index, AN=Available nitrogen, PON=Particulate organic nitrogen and NMI=Nitrogen management index.
*Means separated by same lower case letter in each column were not significantly different among the treatments at $p \leq 0.05$.

The CMI, a composite indicator of both TOC sequestration and lability, ranked from highest values to lowest values as POC > SMB > ExC > SC > OxC (Table 7). When the POC was used as measures of CMI, a large range (1 to 6.96) was observed in the CMI values in response to the impact of chemical fertilization and various organic amendments. Significantly higher CMI values of POC in both compost- and cow manure amended soils were observed than in the control. The CMI's of SMB in both compost and My-composted amended soils were significantly higher by 2.7- and 2.4-fold than in the control. The CMI's of OxC in the compost- and cow manure amended soils were also higher than that in other treatments, including the control. While the CMI's of SC were significantly higher by 1.7-, 1.2-, and 1.3-fold in the compost- and cow manure, My-compost amended-, and chemically fertilized soils than in the control, the CMI's of EC in the compost-amended soil were higher by 1.4- and 2-fold than in the chemically fertilized- and control soils.

Unlike CPI, the NPI did not vary significantly by the impact of various organic amendments and chemical fertilization over the control (Figure **3a).** However, the NL, NLi, and NMI were significantly influenced by the impact of both organic amendments and chemical fertilization as compared with the control (Table 8). The NL of PON values in both compost- and cow manure-applied soils were significantly higher by more than 4-fold than in the My-compost-amended and control soils. A similar effect of the compost and cow manure amendments on NL was observed, when AN was used as a measure of labile N. While the NLi of PON was higher by 5.8- and 4.7-fold in the compost-and cow manure applied soils than in the control, the NLi of PON was statistically similar among the My-compost amended, chemically fertilized, and control soils. However, the NLi of AN in the compost-amended soil was statistically similar with the cow manure applied and the chemically fertilized soils, but was significantly higher than the My-compost-amended and control soils. The NMI of PON in both compost- and cow-manure amended soils was significantly higher by 5.8- and 5.2-fold than that in the control, but the NMI values were statistically similar among the My-compost amended, chemically fertilized, and control soils. A similar treatment effect on the NMI of AN was observed.

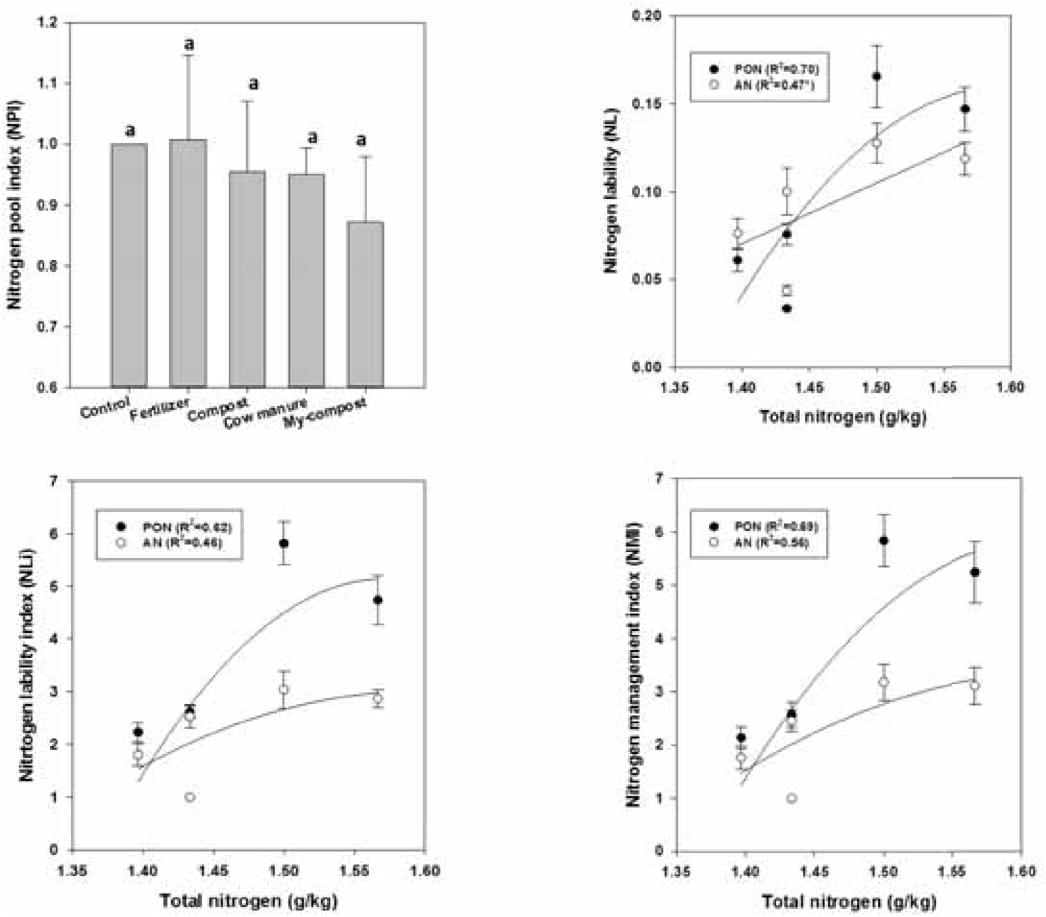

FIGURE 3

Long-term effects (1996 to 2012) of annual chemical fertilization, compost, cow manure, and mycorrhizae-inoculated compost amendments on (a) nitrogen pool index (NPI), and the relationship between total nitrogen (TN) with (b) nitrogen lability (NL), (c) nitrogen lability index (NLi), and (d) nitrogen management index (NMI), calculated based on particulate organic nitrogen (PON) and available nitrogen (AN) in soils under corn-wheat rotation (1996 to 2012). Treatment mean values were plotted with standard error.

Significantly higher values of the CPI and NMI in the cow manure- and compost-applied soils than in the control have indicated a slow restoration in the TOC and TN content by the impact of organic amendments. While the higher values of CL, CLi, NL, and NLi in both cow manure- and compost-amended soils suggested a greater increase in C and N lability, the higher CMI and NMI values were related to both the amount and quality of TOC and TN accumulated over time, thus slowly modifying the size of both labile C and N pools. Our results were similar to other studies which reported that the impact of organic amendments alone and/or with chemical fertilization significantly increased the CMI as compared to the chemical fertilization alone or the control [5,7]. Like CPI and C lability, a similar effect of organic amendments and chemical fertilization observed on the NPI and N lability was due to expected CN stoichiometry in SOM [20]. Any changes in quantitative and qualitative aspects in the TOC content is expected to reflect in the TN content of SOM.

Our results suggested that the POC and PON pools declined as well as restored faster than other C pools, including SMB, SC, ExC, OxC, and AN, and hence are the early, sensitive and consistent indicators of C and N lability associated with the TOC and TN accumulation in SOM for assessing soil quality. Several other studies have suggested that the POC is an early indicator of changes in TOC accumulation or depletion and is more sensitive to changes by soil management practices than the TOC content alone [32, 41]. The OxC did not show significant reliabilities to detect early and sensitive changes in C lability, as shown by its inconsistent differences in the CL, CLi, and CMI's among the treatments. A lack of significant differences in CL, CLi, and CMI calculated based on OxC was possibly due to the effects of unbuffered and higher $KMnO_4$ molarity (0.333 M) used for chemical oxidation of TOC to determine OxC. However, a highly significant difference in OxC concentration (as active C) was reported by other studies when a very dilute buffered solution of $KMnO_4$ (0.02 M at pH 7.2) was used for oxidation of TOC [21, 32].

Relationship of organic C and N contents with C and N lability and management indices. Results showed a variable relationship of the CL, CLi, and CMI calculated based on SC, ExC, POC, OxC, and SMB with the TOC concentration **(**Figure **2b).** The TOC concentration positively and nonlinearly accounted for 91% of the variability in the CL of POC with larger values of regression slopes. Likewise, the TOC concertation positively and nonlinearly accounted for 54, 74, and 81% of the variability in the CL values of OxC, ExC, and SMB, respectively with smaller values of regression slopes. However, the TOC concentration was linearly accounted for only 53% of the variability in the CL of SC. While the TOC concentration significantly and nonlinearly accounted for 72, 76, and 78% in the CLi of SC, ExC, and POC, the TOC did not account for any significant variations in the CLi of SMB and OxC, respectively (Figure **2c**). Moreover, the TOC concentration nonlinearly accounted for significant variations in the CMI of labile C fractions except SMB (Figure 2d). CLI is higher in animal manure and compost treated soils than in control treatments. Ther resulats of Tang et al. [42] indicating that residue combined with conventional tillage was more effective for increasing CMI under rice filed condations. Also it has been indicated that CMI could be used as an indicator for soil degradation or improvement in response to land use [23].

While the TN concentration nonlinearly accounted for 70% of the variability in the NL of PON, the TN concentration linearly accounted for only 47% of the variability in the NL of AN (Figure 3b). The TN concentration significantly and nonlinearly accounted for 46 to 62% of the variability in the NLi of AN and PON concentrations (Figure 3c). Likewise, the TN concentration significantly and nonlinearly accounted for 56 and 69% of the variability in the NMI of AN and PON, respectively (Figure 3d). When the NMI of PON was plotted (Y axis) against the CMI of POC, a significant 1:1 relationship was observed between them (Figure 4). The CMI of POC linearly and significantly accounted for 72% of the variability in the NMI of PON or vice-versa.

A significant relationship of the CL and CLi of POC with the TOC concentration as compared to the CL and CLi of the SC, ExC, SMB and OxC indicated that the POC is a more sensitive and consistent indicator of C lability among the tested labile C pools. Moreover, the significant relationship of the CMI of POC with the TOC concentration as compared to the CMI's of the SC, ExC, SMB and OxC suggested that the POC is a composite and sensitive indicator of both TOC accumulation and

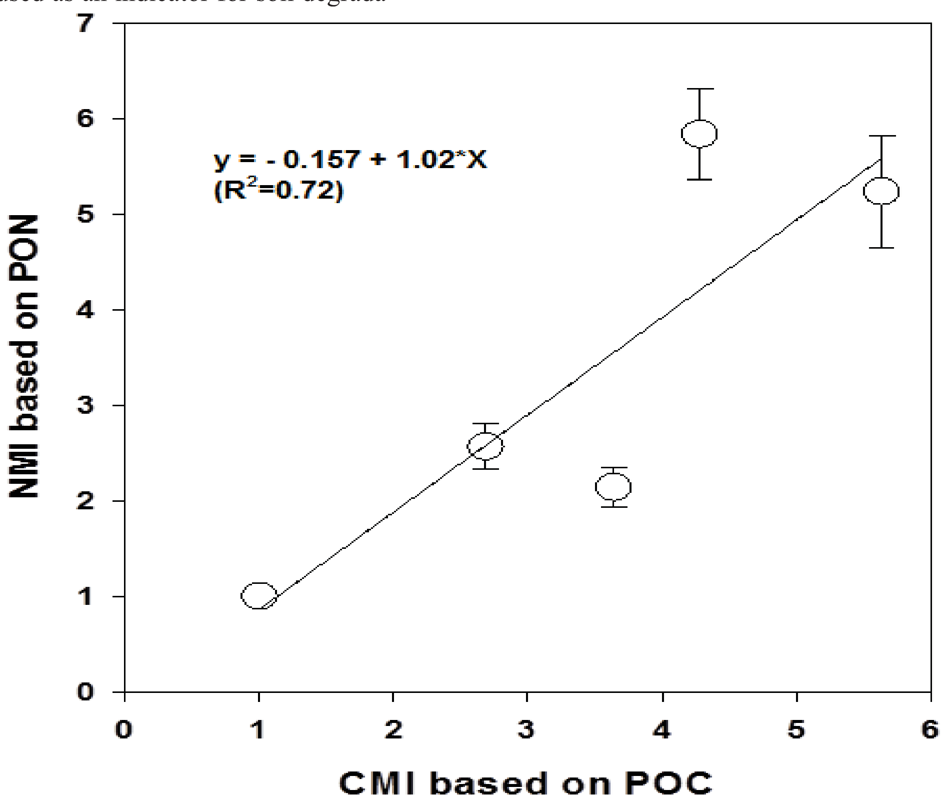

FIGURE 4
Relationship of carbon management index (CMI) calculated based on particulate organic carbon (POC) with nitrogen management index (NMI) calculated based on particulate organic nitrogen (PON) in soils under long-term corn-wheat rotation (1996 to 2012), averaged across chemical fertilization and organic amendments. Treatment mean values were plotted with standard error.

lability by the impact of changes in management practices. Similarly, a close relationship between the NMI of PON with the TN as compared to the NMI of AN suggested that the PON is also an early and sensitive indicator of changes in N accumulation and lability in response to management practices. A strong linear relationship between the CMI of POC and the NMI of PON suggested the POM associated C and N pools were able to detect early and consistent changes in both TOC and TN accumulation and lability to determine soil quality in response to management practices. It sees that all lability and management index are ralted with soil organic carbon content. Previousy Kalisz et al. [43] results showed that carbon management index is determined by total organic carbon.

CONCLUSIONS

Long-term organic amendments especially compost- and cow manure application significantly improved the soil biological and chemical properties over the chemical fertilization and control. As a result, total microbial biomass pool has enlarged with greater biological efficiency (low qCO_2), increased TOC and TN accumulation and lability, and consequently, improved soil quality. The TOC and TN lability and management indices calculated based on microbial biomass C, oxidizable C, soluble and extractable C, particulate organic C and N, and available N concentration were significantly higher in the compost-and cow manure-amended soils than in the chemically fertilized and control soils. The particulate organic C and N pools were more sensitive than any other C and N pools to detect early and consistent changes in soil organic matter accumulation and lability associated with soil quality in response to management practices

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