frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 17 November 2022
DOI 10.3389/fenvs.2022.1058071

OPEN ACCESS

EDITED BY
Guanghui Yu,
Tianjin University, China

REVIEWED BY
Ning Ling,
Nanjing Agricultural University, China
Dan Wan,
Tiangong University, China

*CORRESPONDENCE
Jianning Zhao,
zhaojianning@caas.cn
Dianlin Yang,
yangdianlin@caas.cn

SPECIALTY SECTION
This article was submitted to Soil Processes,
a section of the journal
Frontiers in Environmental Science

RECEIVED 04 October 2022
ACCEPTED 01 November 2022
PUBLISHED 17 November 2022

CITATION
Zhou Z, Zhang S, Jiang N, Xiu W, Zhao J and Yang D (2022), Effects of organic fertilizer incorporation practices on crops yield, soil quality, and soil fauna feeding activity in the wheat-maize rotation system.
Front. Environ. Sci. 10:1058071.
doi: 10.3389/fenvs.2022.1058071

Effects of organic fertilizer incorporation practices on crops yield, soil quality, and soil fauna feeding activity in the wheat-maize rotation system

Zhongkai Zhou[1,2], Siyu Zhang[1], Na Jiang[1], Weiming Xiu[1], Jianning Zhao[1]* and Dianlin Yang[1]*

[1]Agro-Environmental Protection Institute (CAAS), Ministry of Agriculture and Rural Affairs, Tianjin, China, [2]Key Laboratory for Protected Agricultural Engineering in the Middle and Lower Reaches of Yangtze River, Ministry of Agriculture and Rural Affairs, Institute of Facilities and Equipment in Agriculture, Jiangsu Academy of Agricultural Sciences, Nanjing, China

The decline in soil quality is becoming a significant process of soil degradation. Optimizing organic fertilizer incorporation practices in cropland is essential to enhancing crop productivity and soil health. However, that requires a comprehensive understanding of crop yield and soil quality reaction across an application gradient of organic fertilizer. We investigated the effect of organic fertilizer incorporation practices on crop yield, soil quality, and fauna feeding activity from fluvo-aquic soils on wheat (*Triticum aestivum*)-maize (*Zea mays*) rotation field. The six treatments included were unfertilized N control (UC), traditional chemical fertilizer application (TF, 600 N kg ha^{-1} year^{-1}), and recommended chemical fertilization (RF, 400 N kg ha^{-1} year^{-1}) with no organic fertilizer application rate, low-level 15.0 (RFLO), medium-level 30.0 (RFMO), and high-level 45.0 t ha^{-1} year^{-1} (RFHO) application, respectively. The research findings show that the yield with organic fertilizer incorporation treatments increased 26.4%–44.6% for wheat and 12.5%–40.8% for maize compared to RF plots. The long-term organic fertilizer incorporation rate increased organic carbon from 54.7% to 110.6% versus UC plots and 27.9%–74.0% versus chemical fertilizer (TF and RF) treatments, and the total nitrogen content of soil increased from 41.8% to 59.2%, and 24.6%–39.2%. The long-term inorganic fertilizer combined with organic fertilizer incorporation practices significantly enhanced soil sucrose (30.1%–51.9%), urease (28.4%–38.3%), and β-1,4-glucosidase (34.6%–122.4%) activity. Still, nitrite reductase, polyphenol oxidase, and catalase significantly lower 27.3%–49.9%, 8.5%–26.3% and 23.3%–34.3% than single applications of inorganic N fertilizer groups. Meanwhile, the results showed that organic fertilizer incorporation practices improved soil fauna feeding activity by 35.2%–42.5%, and the excessive application of inorganic N fertilizer reduced the activity level of soil fauna.

KEYWORDS

soil organic carbon, soil nutrients, organic fertilizer incorporation, soil enzymes, soil fauna feeding activity, feeding activity

10.3389/fenvs.2022.1058071

Introduction

Organic fertilizers are materials with defined chemical composition and high nutritional value that can provide adequate nutrients for plant growth (Moller and Schultheiss, 2015; Rajan and Anandhan, 2015). Organic fertilizers were mainly made by composting animal manure, human excrement, or plant matter (such as straw and garden waste) under microorganisms fermenting at high temperatures (Chew et al., 2019). Organic fertilizers improve the soil structure, provide a wide range of plant nutrients, and add beneficial microorganisms to the soil. Because of the benefits of organic fertilizers on soil structure and crop yield were widely used in the agricultural system (Brar et al., 2015; Maltas et al., 2018).

Organic fertilization practices can improve crop yields and soil quality, and combining organic and inorganic fertilizers was considered an effective solution to maintain the sustainability of crop ecosystems (Gentile et al., 2008). The application of organic fertilizers can not only improve soil structure and fertility, and increase soil organic carbon and other nutrients (Diacono and Montemurro, 2010; Liu et al., 2010). Many studies have shown that applying organic fertilizers to the soil surface can provide a rich food source for microorganisms and significantly increase microbial community composition and diversity compared to no application (Chang et al., 2007; Diacono and Montemurro, 2010). In addition, applying organic fertilizers significantly changes cation exchange capacity (CEC) and increases soil moisture content, causing changes in soil fauna community structure and composition in acidic soils (Zelles et al., 1992; Abbott and Murphy, 2007). Adding organic fertilizers benefits the formation and stability of earthworm communities due to the more stable nutrients in organic manure after aerobic fermentation (Bertrand et al., 2015). In contrast, others have found that long-term use of chemical fertilizers may reduce soil OM content and change the activity of soil biota, resulting in changes in soil microbial composition, and resulting in decreased soil invertebrates abundance and diversity due to environmental constraints and reductions in soil pH (Fauci and Dick, 1994; Davies et al., 2022). Wahyuningsih et al. (2019) show that the short-term applications of inorganic fertilizers (urea) significantly increased the soil fauna feeding activity after 2 days, compared to before the application. Tao et al. (2016) also show that soil organic matter (empty fruit bunch) plays an important role in soil ecosystem functioning by enhancing soil fauna feeding activity. Therefore, many studies have announced the effects of fertilization practice on soil nutritions, but the effects of inorganic combined with organic fertilizers on soil biota remain unclear.

In the wheat-maize rotation system, long-term fertilization is an essential factor affecting soil physicochemical properties and biota functions (Welbaum et al., 2004; Kaiser et al., 2007; Thomas et al., 2007; Miao et al., 2011; Chen et al., 2015b; Miller et al., 2020; Miner et al., 2020), and its response mechanism is mainly related to local climatic conditions, soil types, and fertilizer types (Lupwayi et al., 2011; Yu et al., 2015). Qaswar et al. (2020) and Gao et al. (2015) studies show that combining organic and inorganic fertilizers is one of the essential techniques to replace part of the inorganic chemical fertilizers and stabilize wheat and maize yield. Many studies have shown that replacing 20%–30% of chemical fertilizers with organic fertilizers can increase wheat-maize yields and improve soil availability and organic matter (Zhang et al., 2016b). Then, the applications of organic fertilizers were a relatively large range of variation, and the fresh weight of compost was generally from 10.0 to 35.0 t ha^{-1} (Hannet et al., 2021), and the application rate of dry matter of compost between 8.8 and 14.0 t ha^{-1}, but liquid manure up to 68.3 t ha^{-1} (Feng et al., 2013). This suggests the need for a better balance of the impact of fertilization with different organic fertilizer incorporation rates on the wheat-maize rotation system. Moreover, few have conducted long-term investigations of inorganic chemical fertilizers combined application of organic fertilizers with different incorporation rates for soil quality and health, including total soil carbon, organic carbon, nutrients, enzyme activities, and soil fauna activities.

The study aimed to determine the influence of inorganic combined with organic fertilizer incorporation practices (high, medium, and low levels) on crop yields, soil quality, and the fauna feeding activity on fluvo-aquic soil in north China.

Methods and materials

Site description

The research treatments were set up starting in 2015 at Tianjin Experimental Farm (TEF), which is located in the suburbs of Tianjin, North China (39°28′N, 117°42′E, Supplementary Figure S1). The region belongs to a temperate monsoon climate, with an annual mean air temperature of 12.9°C and rainfall 586 mm, respectively (2015–2020) (Zhou et al., 2021). Rainfall is concentrated between July and September, with a tremendous annual variation. This soil was classified as fluvo-aquic soil, and the values of TN, OM, TP, and pH in soil (0–20 cm) were 0.82, 12.6, 0.80 and 8.1 g kg^{-1}, respectively.

Experimental design

The research treatments were conducted on a wheat-maize rotation system with the same cultivation and management practice from October 2019 to October 2020. In previous

TABLE 1 Application rates of fertilizers under different fertilization treatments.

Treatment	2019				2020				
	October				April	June			August
	Organic	N	P	K	N	N	P	K	N
	(t·ha^{-1})	(kg·ha^{-1})							
UC	0	0	50	50	0	0	50	50	0
RF	0	120	50	50	80	120	50	50	80
RFLO	15	120	50	50	80	120	50	50	80
RFMO	30	120	50	50	80	120	50	50	80
RFHO	45	120	50	50	80	120	50	50	80
TF	0	180	50	50	120	180	50	50	120

years, all wheat-maize straw was returned to the field following management practices. The six trial treatments of each area being 288 m^2 with three replicates, were established in 2015. The treatments included were unfertilized N control (UC), traditional chemical fertilizer application (TF, 600 N kg·ha^{-1} year^{-1}), and recommended chemical fertilization (RF, 400 N kg·ha^{-1} year^{-1}) with zero organic fertilizer (O) application rate, low-level 15.0 (RFLO), medium-level 30.0 (RFMO), and high-level 45.0 t ha^{-1} year^{-1} (RFHO) application, respectively. The recommended fertilization was based on the local soil characteristics and the crop target yield, combined with precision irrigation conditions (Cai and Qin., 2006; Yang et al., 2015). The recommended inorganic NPK fertilizers were urea (46.4% N), diammonium phosphate (18% N and 20.09% P), and potassium chloride (49.6% K), respectively (Zhou et al., 2021). In this study, inorganic nitrogen fertilizer was the limiting factor; when applying inorganic N fertilizer, simultaneously apply 200 kg ha^{-1} year^{-1} P and K fertilizer as base fertilizer. The organic fertilizer was produced through high-temperature fermentation of garden wastes and agricultural straw, by Xixing Fertilizer Technology Co., Ltd. (Shijiazhuang, China). The values of OM, TN, and TP in organic fertilizer were 86.6 ± 4.9, 6.18 ± 0.10, and 3.39 ± 0.07 g kg^{-1}, respectively (Zhou et al., 2021). The inorganic NPK rate in each wheat and maize season was half the annual application amount in six trial treatments, respectively. The application rates of fertilizers under different fertilization treatments was shown in Table 1. Two-thirds of the inorganic nitrogen fertilizer and the entire quantity diammonium phosphate and muriate potash fertilizer was applied when sowing as basal fertilizer, and one-third of nitrogen fertilizer is mainly used for top-dressing applications of wheat and maize, respectively. The organic fertilizer was applied to the soil surface by scattering before wheat sowing and incorporated into the topsoil by rotary tillage.

Field sampling and processing

The quadrat method determined the winter wheat yield by harvesting three 1 m^2 sampling areas per treatment (Lu et al., 2018). At the summer maize maturity stage, 20 plants were randomly selected from the middle row of each plot and harvested manually to determine the yield (Lu et al., 2018). The remaining crop was harvested mechanically.

Less than 1 week after harvest, three soil samples (each was a composite of five cores that formed one sample, 5.0 cm in diameter) were collected from each treatment at 20 cm depth on 24 October 2019 and 22 October 2020 to determine the chemical properties (Zhou et al., 2021). The chemical properties of soil were determined, including TC, TOC, TN, AN, TP, AP, TK, exchangeable Ca, Mg, K, Na concentrations, and CEC, EC, and soil pH values. The pH value and electric conductivity (EC) of the soil were measured with a glass electrode and extracted in a 1:2.5 soil/water (H_2O) suspension after being allowed to stand for 30 min (Zhang et al., 2016b). The Dumas dry-combustion method analyzed all dry soil samples collected for total soil nitrogen (TC) and soil nitrogen (TN) contents using a PerkinElmer 2400 Series II CHNS/O Analyzer (PerkinElmer Inc., Shelton, CT, United States). Soil total organic carbon (TOC) was determined using $K_2Cr_2O_7$–H_2SO_4 digestion. The alkaline hydrolysis diffusion method determined the available soil nitrogen (AN). The molybdenum blue colorimetrically determined the soil's total phosphorus (TP) content after extraction with a mixed acid solution of H_2SO_4 and $HClO_4$. Available phosphorus (AP) was determined colorimetrically after sodium bicarbonate extraction at pH 8.5. The content of total potassium (TK) in soil was determined by flame photometer detection using H_2SO_4–H_2O_2 digestion (Bao, 2008; Sunnemann et al., 2021). The concentrations of exchangeable Na, Mg, K, and Ca in soil were measured by ICP-OES (Agilent, 710 Series) after extraction with 1.0 mol L^{-1} ammonium acetate (Setia et al., 2013). The cation exchange capacity (CEC) was calculated with colorimetrically after using a hexamminecobalt (III) chloride extraction (ISO, 2018). Air-dried soil samples were sifted through a 2 mm sieve for soil enzyme activity determination. The six soil enzymes activity involved in C and N cycling were studied, including soil catalase, soil nitrite reductase, soil sucrase, soil urease, soil polyphenol oxidase, and soil β-1,4-glucosidase, and was determined spectrophotometrically with the soil enzyme kits provided by Suzhou Comin Biotechnology Company Limited (Suzhou, China) (Liu et al., 2018; Gao et al., 2019).

Soil fauna feeding activity

Törne (1990) set up the bait lamina test for soil fauna feeding activity for soil environmental quality assessment. The bait lamina is made of polyvinyl chloride board (PVC board, gray), and the size by 120 mm × 6.0 mm × 1.0 mm (length × width × thickness) with a set of 16 double tapered holes (inner diameter 1.5 mm, outer diameter 2.0 mm) at the lower 85 mm, with the aperture spacing of 5 mm (Römbke et al., 2006). The standard feed for bait lamina filling usually consists of 70% cellulose (microparticles), 27% bran flakes (<500 mm), and 3% activated carbon (Eisenhauer et al., 2014). After filling double tapered holes with standard feed, insert the bait strip vertically into the soil, and the top hole was just below the soil surface (Supplementary Figure S2). In this study, soil fauna activities were measured from September 15 to 30 in 2019 and September 9 to 24 in 2020, respectively. Five test areas were set up for each treatment, and 5 strips per area were placed about 15–20 cm apart to monitor the feeding activities of soil fauna with 150 bait lamina in total. After 2 weeks of monitoring, the bait strips were taken from the soil and evaluated with filled (0), partly empty (0.5), and empty (1) (Vorobeichik and Bergman, 2021), to calculate the number of perforated bait strips at each study site and evaluate the percentage of perforated bait strips to the number of test holes in the field. In this study, soil temperature was measured using a HOBO U23-003 sensor (Onset Computer Corporation, Pocasset, MA, United States).

Statistical analysis

Statistical analysis used the Statistical Analysis System (SAS 9.2) software package and Origin Pro 2022 software. Analysis of variance and comparisons of means between treatments was determined using Duncan's multiple range test, and correlations between soil chemical properties were determined using Spearman's correlation coefficient analysis. Treatment impacts were reported to be significant at the 5% probability level.

Results

Crop production

The grain yields of wheat and maize according to fertilization management practices are shown in Figure 1. Different fertilization management practices significantly affect wheat and maize yields, and there was no significant difference in the yield of wheat and maize between different years (Table 2). The grain yields ranged from 0.68 to 6.35 t ha^{-1} for wheat and 5.40 to 9.77 t ha^{-1} for maize in 2018–2020. There was no difference in the wheat yields between different organic fertilizer (RFLO, RFMO, RFHO) incorporation and traditional fertilization (TF) treatments in 2018–2019, while the RFHO and TF significantly ($p < 0.05$) increased the maize yield by 34.7%, 36.6% as compared with RF, respectively. In 2019–2020, the medium and high organic fertilizer (RFMO, RFHO) incorporation and TF treatments increased the wheat yield by 36.4%, 50.6%, and 41.5% compared to RF, respectively ($p < 0.05$). There was no difference in wheat yields between RFMO, RFHO, and TF treatments. Similar to the 2018–2019 year, the RFHO and TF plots increased the maize yield by 47.2%, and 42.8% compared to RF, respectively ($p < 0.05$).

Soil physicochemical properties

Table 3 shows the soil chemical variables under each soil fertilizer management practice at 0–20 cm soil depth. Eleven variables were significantly affected by long-term inorganic combined with organic fertilizer incorporation practices compared with inorganic fertilizer plots (Table 3). The soil chemical parameters were significant correlations (Table 4). Organic fertilizer incorporation led to significant changes in total organic carbon (TOC) and total carbon (TC), levels of soil nutrients (Total N and P, Available N and P), and soil chemical properties of RFHO, RFMO, and RFLO plots, as compared to the RF and TF. The long-term organic fertilizer incorporation rate increased total organic carbon (TOC) from 54.7% to 110.6% versus unfertilized soil and 27.9%–74.0% versus chemical fertilizer treatments. TC content showed the same trend as TOC, increasing 19.5%–49.1% compared with UC and 17.2%–46.3% compared with RF. Soil total organic carbon (TC) and total organic carbon (TOC) increased positively under organic fertilizer plots with higher 2.2–6.0 g kg^{-1} for TC, and 2.4–6.4 g kg^{-1} for TOC than RF.

The contents of total soil nitrogen (TN) and available nitrogen (AN) in the organic fertilizer incorporation plots increased significantly by 41.8%–59.2%, 56.1%–82.7% versus

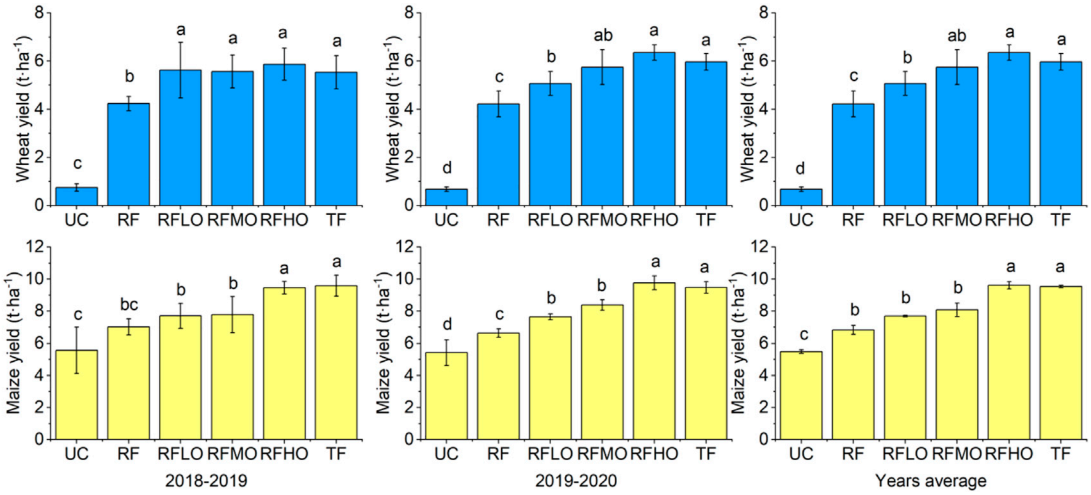

FIGURE 1
Wheat and maize yield (2018–2019, 2019–2020) is according to fertilization management practices. UC, unfertilized control; RF, recommended mineral fertilizer application of 400 kg ha^{-1} N; RFLO, RF plus 15 t ha^{-1} of organic fertilizer; RFMO, RF plus 30 t ha^{-1} of organic fertilizer; RFHO, RF plus 45 t ha^{-1} of organic fertilizer; TF, traditional mineral fertilizer application of 600 kg ha^{-1} N, whole wheat-maize growing season. The same letters are not significantly different at 5% level by Duncan's Multiple Range Test.

TABLE 2 Effects of fertilizer management practices and years on crop yield.

	Wheat			Maize		
	DF	F Value	*p* Value	DF	F Value	*p* Value
Treatment (T)	5	143.0	$p < 0.0001$	5	61.22	$p < 0.0001$
Yearly (Y)	1	0.3167	0.5757	1	0.04022	0.8417
Treatment * yearly	5	1.266	0.2901	5	0.7645	0.5790

unfertilized soil (UC), and 24.6%–39.2%, 25.6%–46.9% compared with the application of recommended mineral fertilizer (RF), with the increase of the amount of organic fertilizer. Still, RFLO, RFMO, and RFHO treatments did not reach a significant level ($p > 0.05$). Compared with the RF treatment, the contents of total phosphorus (TP) and available phosphorus (AP) in the RFHO plots increased by 33.3% and 95.4%, respectively, and RFMO plots increased by 37.0% and 115.8%, and RFLO plots increased by 18.2% and 43.2%, respectively. However, there was no significant difference between RFHO and RFMO treatments ($p > 0.05$). Soil TK concentration remained at the same levels across all plots.

Compared with the UC, the fertilization treatment plots pH decreased by 0.49%–5.68%, while the organic fertilizer (RFLO, RFMO, RFHO) incorporation significantly reduced the pH by 3.40%, 5.44%, and 5.68% ($p < 0.05$), respectively. The content of exchangeable Ca in the organic fertilizer incorporation was significantly lower 10.05%, 7.64%, and 9.82%, than in the TF plots ($p < 0.05$). While no difference in the exchangeable Mg and CEC between different organic fertilizer (RFLO, RFMO, RFHO) incorporation and chemical fertilizer plots. The contents of exchangeable K and Na in the organic fertilizer incorporation plots significantly increased 49.4%–122.2%, and 21.4%–107.4%, compared with inorganic fertilizer. Figure 2 shows PCA for soil characteristics according to fertilization management practices. The PCA results show that the cumulative contribution of the first three principal components reached 84.7% (PC1: 62.9%; PC2: 13.8%; PC3: 8.0%; Supplementary Table S1).

Soil enzyme activity

Organic fertilizer incorporation led to significant changes in the nitrite reductase, catalase, sucrase, urease, β-1,4-

TABLE 3 Soil chemical variables under each soil fertilizer management practice at 0–20 cm soil depth.

Soil chemical index	UC	RF	RFLO	RFMO	RFHO	TF
Total N ($g \cdot kg^{-1}$)	0.98 ± 0.05b	1.12 ± 0.04b	1.39 ± 0.06a	1.48 ± 0.15a	1.56 ± 0.14a	1.11 ± 0.11b
Available N ($mg \cdot kg^{-1}$)	46.3 ± 4.13c	57.6 ± 9.06bc	72.3 ± 5.76ab	81.4 ± 13.21a	84.6 ± 12.63a	52.1 ± 5.26c
Total carbon ($g \cdot kg^{-1}$)	12.7 ± 0.5c	12.9 ± 0.5c	15.1 ± 1.2bc	17.2 ± 1.9ab	18.9 ± 2.5a	13.1 ± 1.2c
Total organic carbon ($g \cdot kg^{-1}$)	7.19 ± 0.57c	8.7 ± 0.57c	11.12 ± 0.66b	14.28 ± 0.94a	15.14 ± 2.54a	7.88 ± 0.61c
Total P ($g \cdot kg^{-1}$)	0.83 ± 0.05bc	0.86 ± 0.12bc	1.02 ± 0.08ab	1.18 ± 0.19a	1.15 ± 0.09a	0.81 ± 0.0c
Available P ($mg \cdot kg^{-1}$)	50.6 ± 10.2cd	55.1 ± 29.9cd	79.0 ± 17.3bc	119 ± 33.3a	107.7 ± 15.4ab	30.2 ± 5.2d
Total K ($g \cdot kg^{-1}$)	18.4 ± 0.69a	18.9 ± 0.89a	19.2 ± 0.35a	19.0 ± 0.57a	19.3 ± 0.86a	18.9 ± 0.52a
Exchangeable Ca ($mg \cdot kg^{-1}$)	5142 ± 236ab	5139 ± 241ab	4833 ± 245b	4963 ± 236b	4846 ± 205b	5374 ± 125a
Exchangeable K ($mg \cdot kg^{-1}$)	337 ± 37c	394 ± 43c	588 ± 51.7b	766 ± 98.8a	843 ± 136.3a	380 ± 28.9c
Exchangeable Mg ($mg \cdot kg^{-1}$)	1015 ± 43.2b	1133 ± 53.6a	1165 ± 43a	1186 ± 36.9a	1155 ± 41.2a	1192 ± 10.9a
Exchangeable Na ($mg \cdot kg^{-1}$)	267 ± 28.5c	253 ± 27.8c	348 ± 96.7bc	465 ± 105.1ab	524 ± 129.7a	287 ± 54.5c
pH	8.25 ± 0.18a	8.12 ± 0.28ab	7.97 ± 0.12ab	7.8 ± 0.29b	7.78 ± 0.19b	8.21 ± 0.25a
Electric conductivity (μs/cm)	309 ± 80c	367 ± 91bc	427 ± 82bc	493 ± 91ab	593 ± 91a	376 ± 64bc
CEC ($cmol \cdot kg^{-1}$)	16.1 ± 0.62b	18.8 ± 0.74a	19.9 ± 0.38a	19.7 ± 0.83a	19.9 ± 0.83a	18.9 ± 0.54a

Values are means ± SD. Means followed by the different lower case letters are significantly different at 5% level by Duncan's multiple range test.

TABLE 4 Spearman's correlation coefficients between soil chemical variables.

Variable	TN	AN	TC	TOC	TP	AP	TK	Ca	K	Mg	Na	pH	EC
TN	1												
AN	0.92***	1											
TC	0.92***	0.84***	1										
TOC	0.91***	0.91***	0.83***	1									
TP	0.82***	0.83***	0.79***	0.84***	1								
AP	0.75***	0.74***	0.74***	0.81***	0.83***	1							
TK	0.24ns	0.37*	0.19ns	0.34*	0.25ns	0.0ns	1						
Ca	−0.46**	−0.30ns	−0.38*	−0.47**	−0.39*	−0.53***	−0.04ns	1					
K	0.93***	0.93***	0.91***	0.93***	0.85***	0.75***	0.35*	−0.32ns	1				
Mg	0.37*	0.46**	0.37*	0.29ns	0.20ns	0.03ns	0.18ns	0.38*	0.44**	1			
Na	0.72***	0.64***	0.75***	0.69***	0.63***	0.69***	0.20ns	−0.43**	0.72***	0.11ns	1		
pH	−0.71***	−0.80***	−0.70***	−0.71***	−0.85***	−0.65***	−0.37*	0.05ns	−0.78***	−0.40*	−0.44**	1	
EC	0.59***	0.42**	0.59***	0.58***	0.50**	0.58***	0.09ns	−0.71***	0.52**	0.04ns	0.65***	−0.27ns	1
CEC	0.75***	0.83***	0.69***	0.69***	0.67***	0.49**	0.32ns	−0.09ns	0.79***	0.66***	0.44**	−0.74***	0.30ns

Significance levels are * 0.05, ** 0.01, *** 0.001, respectively, *ns*, not significant. TN, total N concentration ($g \cdot kg^{-1}$); AN, available nitrogen ($mg \cdot kg^{-1}$); TC, total C concentration ($g \cdot kg^{-1}$); TOC, organic C concentration ($g \cdot kg^{-1}$); TP, total P concentration ($g \cdot kg^{-1}$); AP, available P concentration ($mg \cdot kg^{-1}$); TK, total K concentration ($g \cdot kg^{-1}$); Ca, exchangeable Ca concentration ($mg \cdot kg^{-1}$); K, exchangeable K concentration ($mg \cdot kg^{-1}$); Mg, exchangeable Mg concentration ($mg \cdot kg^{-1}$); Na, exchangeable Na concentration ($mg \cdot kg^{-1}$); EC, electrical conductivity ($\mu s \cdot cm^{-1}$); CEC, cation exchange capacity ($cmol \cdot kg^{-1}$).

glucosidase, and polyphenol oxidase at different plots (Table 5). Compared to RF plots, organic fertilizer incorporation plots significantly increased by 28.4%–38.3%, 34.6%–122.4%, and 30.1%–51.9% of soil urease, β-1,4-glucosidase, and sucrase activity (p < 0.05). The nitrite reductase and catalase activity in the organic fertilizer plots was 3.17–4.59 $\mu mol\ d^{-1}\ g^{-1}$ and 14.9–17.2 $\mu mol\ d^{-1}\ g^{-1}$, significantly lower 27.3%–49.9%, and 23.3%–34.3% than in the RF plots, respectively (p < 0.05). In the TF plots, the activity of nitrite reductase increased 98.7% and 27.6% more than in all organic fertilizer treatments and RF plots (p < 0.05). Compared with organic fertilizer treatments and RF plots, the polyphenol oxidase activity of TF plots increased by 65.5% and 35.3%, respectively. However, the activity of polyphenol oxidase was not significantly different between TF and UC plots (p < 0.05).

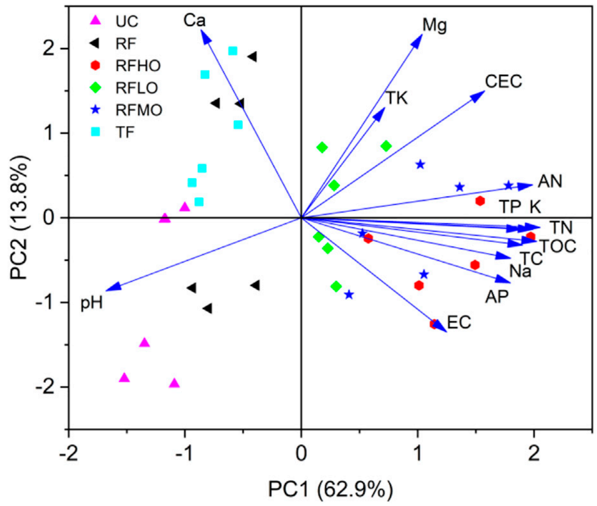

FIGURE 2
Principal component analysis (PCA) for soil chemical characteristics (2019, 2020) is formed by the first principal component (PC1) and the second principal component (PC2) according to fertilization management practices. * Ca, exchangeable Ca concentration ($mg{\cdot}kg^{-1}$); Mg, exchangeable Mg concentration ($mg{\cdot}kg^{-1}$); TK, total K concentration ($g{\cdot}kg^{-1}$); CEC, cation exchange capacity ($cmol{\cdot}kg^{-1}$); AN, available nitrogen ($mg{\cdot}kg^{-1}$); TP, total P concentration ($g{\cdot}kg^{-1}$); K, exchangeable K concentration ($mg{\cdot}kg^{-1}$); TN, total N concentration ($g{\cdot}kg^{-1}$); TOC, organic C concentration ($g{\cdot}kg^{-1}$); TC, total C concentration ($g{\cdot}kg^{-1}$); Na, exchangeable Na concentration ($mg{\cdot}kg^{-1}$); AP, available P concentration ($mg{\cdot}kg^{-1}$); EC, electrical conductivity ($\mu s{\cdot}cm^{-1}$).

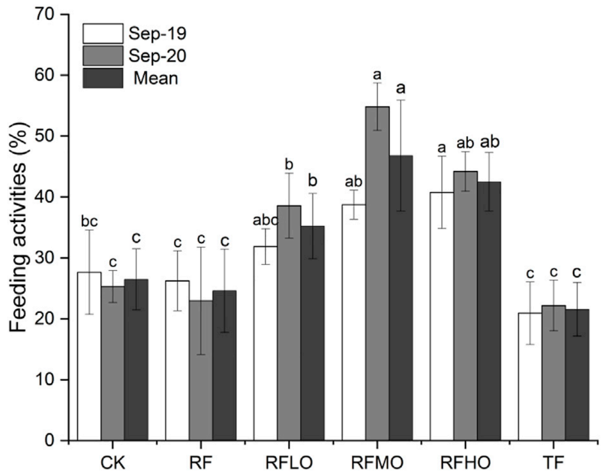

FIGURE 3
Feeding activities (%) in the six fertilization management practices were determined by the bait-lamina test (n = 150 bait laminae) after 15 days of exposure in September 2019, and 2020. The data are median values, and the vertical bars represent SDs. Columns marked by different letters indicate significant differences at p < 0.05.

Soil fauna feeding activity

This study significantly reduced soil fauna feeding activity in inorganic fertilizer plots. The feeding activities of soil fauna in the traditional fertilization (TF) and recommended fertilization (RF) site were lower than in all the other plots, about 24.6% in the RF site and 21.6% in the TF site (Figure 3). We measured the highest average feeding activities in RFLO (35.2%), RFMO (46.8%), and RFHO (42.5%) compared with the other three investigation sites between 2019 and 2020. In RFLO, RFMO, and RFHO, adjoint with increased organic fertilizer incorporation, soil fauna feeding activities were significantly increased compared with RF and TF plots; however, the differences were not statistically significant in RFMO and RFHO plots. Furthermore, RFLO (31.9%) and RFMO (38.8%) in 2019, which had been treated additionally with organic fertilizer, showed higher feeding activities than UC (26.3%), but not significant. Throughout the 0–8 cm soil depth, the UC, RF, and TF treatments showed identical distributions, while RFLO, RFMO, and RFHO had consistent distribution trends (Figure 4). Compared with the organic fertilizer sites, feeding activities in RF and TF treatments showed that they rapidly decreased with increasing soil depth, compared with RFLO, RFMO, and RFHO, and reached a plateau after 4 cm. In the 0–6 cm layer soil depth, the soil fauna feeding activity in organic fertilizer plots was significantly higher compared with the UC and inorganic fertilizer plots (Figure 4).

Discussion

Effect of organic fertilizer incorporation on crop yields

The results showed that compared with the recommended fertilization, the application of organic fertilizer significantly increased the yield of wheat (p < 0.05). Compared with the recommended fertilization (RF), the treatment of medium (RFMO) and low organic fertilizer (RFLO) had no significant influence on maize yield (p > 0.05), and the RFMO and RFLO plots were significantly lower than the high amount of organic fertilizer (RFHO) and the traditional fertilization treatment (TF). Similarly, Yang et al. (2014) reported that combinations of organic and inorganic nitrogen are likely to increase achievable yields and improve soil fertility with the wheat-maize system. This might be due to all organic fertilizers being used as base fertilizers in the wheat season, all chemical fertilizers being used in maize planting, and organic fertilizer incorporation into the soil, which increased soil OM contents, soil water availability, and aeration (Choudhary et al., 2018; Li et al., 2020). Welbaum et al.

TABLE 5 Soil enzyme variables under each soil fertilizer management practice at 0–20 cm soil depth.

Soil enzyme index	UC	RF	RFLO	RFMO	RFHO	TF
S-NiR ($\mu mol \cdot d^{-1} \cdot g^{-1}$)	3.52 ± 0.32de	6.32 ± 0.37b	4.59 ± 0.49cd	4.85 ± 0.70c	3.17 ± 0.19e	8.06 ± 0.58a
S-CAT ($\mu mol \cdot d^{-1} \cdot g^{-1}$)	23.4 ± 0.99a	22.8 ± 0.74a	17.4 ± 0.69b	17.2 ± 0.71b	14.9 ± 0.70c	18.4 ± 0.27b
S-SC ($mg \cdot d^{-1} \cdot g^{-1}$)	1.90 ± 0.40d	2.53 ± 0.16c	3.84 ± 0.31a	3.28 ± 0.13ab	3.39 ± 0.01ab	3.11 ± 0.05bc
S-UE ($\mu g \cdot d^{-1} \cdot g^{-1}$)	624 ± 55c	736 ± 28bc	1017 ± 43a	945 ± 44a	990 ± 21a	827 ± 47b
S-B-GC ($\mu mol \cdot d^{-1} \cdot g^{-1}$)	14.3 ± 0.66bcd	11.2 ± 0.56d	15.0 ± 0.32bc	24.8 ± 2.86a	17.1 ± 0.56b	13.4 ± 0.92cd
S-PPO ($mg \cdot d^{-1} \cdot g^{-1}$)	32.9 ± 1.70ab	27.1 ± 1.44bc	20.0 ± 2.0d	24.8 ± 2.5cd	22.2 ± 4.72cd	36.6 ± 0.98a

S-NiR, nitrite reductase; S-CAT, catalase; S-SC, sucrase; S-UE, urease; S-B-GC, β-1,4-glucosidase; S-PPO, polyphenol oxidase. Values are means ± SD. Means followed by the different lower case letters are significantly different at 5% level by Duncan's multiple range test.

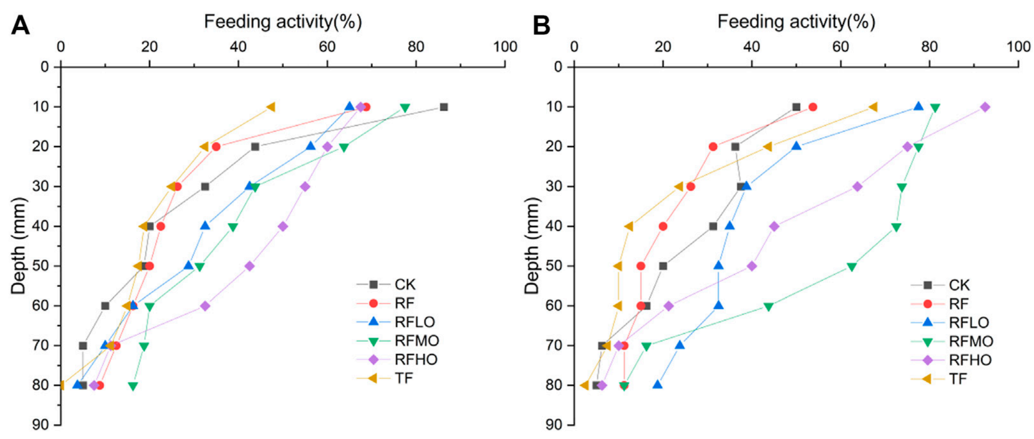

FIGURE 4
Depth profiles of the feeding activities (%) in the six fertilization management practices were determined by the bait-lamina test (n = 150 bait laminae) after 15 days of exposure in September 2019 **(A)**, and 2020 **(B)**.

(2004) and Li et al. (2012) reported that when organic fertilizers incorporation can delay the senescence rate of crop roots and leaves, prolong the photosynthetic time of crops, increase the grain quality of ears by prolonging the grain filling time, and finally increase the yield. Studies have shown that the recommended fertilization amount requires good water and fertilizer management to maximize crop yield (Zhang et al., 2021). The lower wheat yield in the recommended fertilization amount in this study may be caused by flood irrigation resulting in reduced plant availability of nitrogen (Li and Rao, 2003; Shang et al., 2015). The traditional fertilization (TF) could increase crop yields, indicating that inorganic N fertilizer input significantly affects crop yields; the soil organic fertilizers incorporation significantly affects TOC content and yields (Table 2). This result suggests that long-term studies were required to identify the effect of the inorganic combined with organic fertilizers on wheat-maize yield constraints and soil fertility.

Effect of organic fertilizer incorporation on soil chemical properties

The combined application of organic-inorganic fertilizers can provide quick-acting nutrients for crop growth, and effectively increase fertilizer efficiency and ensure the continuous supply of soil nutrients (Diacono and Montemurro, 2010). This study found that organic fertilizer incorporation benefited TC and TOC content, and medium and high levels (>30 t ha^{-1} $year^{-1}$) significantly increased TC, and TOC contents compared to RF and TF treatment. The content of nitrogen (TN, AN) and phosphorus (TP, AP) in the organic-inorganic fertilizers treatment was higher than in the no fertilizer treatment and chemical fertilizer treatment, the same trend as TC and TOC. Liu et al. (2015) and Cai and Qin (2006) research shows that organic fertilizer incorporation can increase TOC capacity by improving agricultural root biomass and exudates. Chen et al. (2015a) studies indicate that soil nutrient content increases after organic fertilizer incorporation and the increase rate is mainly affected by the type and amount of organic fertilizer. Organic fertilizer incorporation increased crop yields, and soil organic matter and nutrient content were improved, consistent with the research of Gao et al. (2015) and Choudhary et al. (2018). The traditional mineral fertilizer (TF) significantly increased wheat and maize yields. Still, it did not have a significant influence on TC and TOC ($p > 0.05$), similar to the findings of Chen et al. (2015a) considered that the balanced application of inorganic fertilizers could keep farmers high, but it has a limited impact on soil carbon sequestration. Moreover, additional C, N, and P releases in the high-rate organic fertilizers could partly explain our findings. In addition, combined application of organic-inorganic fertilizers treatments increased exchangeable K, while the same treatments did not significantly increase the content of soil TK, relative to the UC and RF, consistent with the research of Hannet et al. (2021), indicating that potassium in the soil is not a limiting factor in alkaline soils. In this study, organic fertilizer incorporation significantly decreased soil pH and exchangeable Ca concentration, while exchangeable Na concentration and electrical conductivity increased in these plots compared with inorganic fertilizer. The pH of alkaline soil tends to decrease with the increase of commercial organic fertilizer application years, and the soil pH tends to be neutral, which is beneficial to the better growth of crops (Oyetunji et al., 2022). Demelash et al. (2014) reported increased Ca and Mg content with applying organic-inorganic fertilizers treatments, but it was not observed to increase the levels of other alkaline elements (K, Na). In this study, although the exchangeable Ca decreased, the exchangeable Na and K concentrations increased significantly. Organic fertilizer and soil type may be the main reasons for these differences (Abu Bakar et al., 2011; Manolikaki and Diamadopoulos, 2019; Jain and Kalamdhad, 2020). In this study, the cation exchange capacity (CEC) of soil increased by 4.9%–5.6% due to organic fertilizer incorporation; the same finding by Ouédraogo et al. (2001) and Cooper et al. (2020) studies that the increase in CEC with organic fertilizer application could be attributed to an increase in TOC. Still, it did not significantly affect (CEC) relative to the inorganic fertilizer plots in this study. It shows that based on stabilizing the wheat-maize yield, the soil quality of the wheat-maize planting area can be improved by combining organic and inorganic methods.

Effect of organic fertilizer incorporation on soil enzyme activity

Studies have shown that fertilization management and incorporation of organic matter can affect soil enzyme activity (Zhao et al., 2016; Li et al., 2017). Urease is closely related to soil nitrogen supply, and improving urease activity in the soil can convert organic nitrogen with high stability to available nitrogen (Zhang et al., 2016a). Therefore, the improvement of urease activity indicated that adding organic fertilizer incorporation improved soil nitrogen conversion. Li et al. (2010) and Wang et al. (2021) study found that soil catalase activity increased with more organic nitrogen, while Yang et al. (2018) showed no significant effect with the incorporation of cattle manure and biochar. The fertilization management practices decreased soil catalase, and nitrite reductase activity in this study may be caused by different soil types, organic fertilizer types and sampling time (Li et al., 2017). Soil sucrose and β-1,4-glucosidase reflects soil organic carbon accumulation and are an essential indicator of soil fertility (Zhang et al., 2016b; Ullah et al., 2019). The response of invertase and β-1,4-glucosidase to different fertilization practices was consistent with that of urease. The long-term addition of organic fertilizers significantly increased the activity of soil sucrose and β-1,4-glucosidase, mainly due to the soil organic carbon increase (Table 3). Polyphenol oxidase may suppress the synthesis of humic substances from phenolic intermediates produced during the mineralization of organic C, resulting in the accumulation of phenolic compounds (Wang et al., 2022). Applying organic fertilizers significant reduces the accumulation of phenolic substances and possible poisoning. In the long-term organic fertilizer incorporation plots, the decomposed organic matter provides sufficient energy and carbon source for soil microbial activities, accelerates the reproduction and growth of microorganisms, and improves soil physicochemical properties (Tiemann and Billings, 2011; Ai et al., 2012; Bowles et al., 2014). At the same time, organic fertilizer also contains many enzymes, which are beneficial to improve soil enzyme activity (Li et al., 2017). Therefore, the inorganic fertilizer combined with organic fertilizer incorporation practices can significantly increase the activities of urease (S-UE), sucrose (S-SC), and β-1,4-glucosidase (S-B-GC) in the soil compared with the chemical fertilizer.

Effect of organic fertilizer incorporation on soil fauna feeding activity

This study found that soil fertilizer management influenced the feeding activities of soil fauna, and these responses were closely related to soil nutrition. Organic fertilizer application greatly enhanced soil fauna feeding activity, and then inorganic nitrogen fertilizer reduced the soil fauna feeding activity. The highest feeding activity rates were found in plots RFMO and RFHO with a larger amount of organic fertilizer incorporation practices, and traditional fertilization treatment (TF) had the lowest feeding activities

(Figure 3). However, the feeding activity of soil fauna showed no significant differences between the control UC and inorganic fertilizer (RF and TF) plots. Studies have shown that the experimental time of using the Bait Lamina test is short, usually 3–15 days, and microorganisms cannot decompose and perforate organic matter in a short time, and nematodes, microarthropods such as earthworms, mites, enchytraeids, and collembolans was the main soil fauna causing bait perforation (Gongalsky et al., 2008; Birkhofer et al., 2011). Although some microorganisms are involved in feeding activities, the feeding activities is negligibly small compared to soil fauna (Gestel et al., 2003; Ashford et al., 2013). Applying organic fertilizers increased soil fauna feeding activities, which may be related to the changed soil fauna community's abundance and composition, leading to higher soil fauna feeding activity (Tao et al., 2016). This may explain why the highest feeding activity rates were found in plots RFMO and RFHO with a larger amount of organic fertilizer incorporation practices. The feeding activity of soil fauna in the inorganic fertilizer combined with organic fertilizer polts was high in the 0–6 cm depth range. Many studies show that feeding activities of soil fauna were strongly reduced from 4 to 8 cm soil layer in grassland and forest sites (Larade et al., 2012; Filzek et al., 2004; Gongalsky et al., 2008; Rożen et al., 2010). Other studies showed that soil fauna feeding activities were higher in the bottom of 5–8 cm soil layer than in topsoil layers at ryegrass and soybean fields (Marx et al., 2016; Mousavi et al., 2022). The long-term inorganic fertilizer combined with organic fertilizer incorporation practices significantly increased the soil fauna feeding activity, while the application of RFHO and RFMO did not significantly increase. Soil fertilizer management may affect soil fauna feeding activities by the soil chemical properties; meanwhile, the feeding activities of soil fauna affect the soil physicochemical properties by regulating the decomposition process of soil organic matter (Römbke et al., 2006; Briones and Schmidt, 2017). Geissen and Brummer (1999) research show a strong correlation between soil fauna feeding activities and chemical parameters, and fauna feeding activity increased with higher pH values in acid soil.

In contrast, we found that the soils under organic fertilizer had the higher exchangeable K, Na, EC, nutrients (AN, AP), and TOC of all the management practices; however, the lowest pH and exchangeable Ca in alkaline soil (Table 3). The feeding activity of soil fauna was in organic fertilizer plots significantly higher than inorganic fertilized (RF and TF) plots and unfertilized (UC) plots. Soil water content and soil temperature are the main environmental factors affecting fauna feeding activities. The feeding activity of fauna measured with the bait-laminae showed that the feeding activities increased with temperature (Gongalsky et al., 2008). Drought seriously affects the activities of invertebrates, especially earthworms that like moist soil (Eggleton et al., 2009). Törne (1990) research showed that in cracked clay with low moisture content in Germany, the percentage of bait bar perforation was between 4% and 16%. Precipitation explained the variation in feeding rates observed between 2019 and 2020 (Supplementary Figure S3).

Conclusion

We examined the effects of inorganic fertilizer combined with organic fertilizer incorporation practices on crop yields, soil quality, and fauna feeding activity. We showed that long-term inorganic fertilizer combined with organic fertilizer incorporation practices enhanced soil organic carbon, nutrition, and fauna feeding activity and significantly enhanced soil sucrose, urease, and β-1,4-glucosidase activity. Soil organic carbon, total nitrogen, and fauna activity showed a linear increase of 27.9%–74.0%, 24.6%–39.2%, and 35.2%-42.5%, respectively, but the enzyme activity did not increase with the increase of organic fertilizer incorporation. In our studied area, the treatment of medium levels (30 t ha^{-1} $year^{-1}$) may be recommended from crop yields and soil carbon sequestration. Our study findings have important significance for the application of organic fertilizer to the wheat-maize rotation systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

ZZ: data curation, formal analysis, writing—original draft, and writing—review and editing. SZ: data curation, formal analysis, and writing—review and editing. NJ: formal analysis, investigation. WX: investigation, validation, and writing—review and editing. JZ: conceptualization, funding acquisition, and writing—review and editing. DY: funding acquisition, methodology, writing review and editing, supervision.

Funding

This work was supported by the Central Public-Interest Scientific Institution Basal Research Fund (Agro-Environmental Protection Institute, Ministry of Agriculture and Rural Affairs) and the Cooperative Innovation Project of

Agricultural Science and Technology Innovation Program of CAAS (CAAS-XTCX2016015).

Acknowledgments

We sincerely appreciate the cooperation and assistance of the Tianjin Experimental Farm in the implementation of this field study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1058071/full#supplementary-material

References

Abbott, L. K., and Murphy, D. V. (2007). "What is soil biological fertility?" in *Soil biological fertility: A key to sustainable land use in agriculture*. Editors L. K. Abbott and D. V. Murphy (Dordrecht, Netherlands: Springer), 1–15.

Abu Bakar, R., Darus, S. Z., Kulaseharan, S., and Jamaluddin, N. (2011). Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. *Nutr. Cycl. Agroecosyst.* 89 (3), 341–349. doi:10.1007/s10705-010-9398-9

Ai, C., Liang, G., Sun, J., Wang, X., and Zhou, W. (2012). Responses of extracellular enzyme activities and microbial community in both the rhizosphere and bulk soil to long-term fertilization practices in a fluvo-aquic soil. *Geoderma* 173-174, 330–338. doi:10.1016/j.geoderma.2011.07.020

Ashford, O. S., Foster, W. A., Turner, B. L., Sayer, E. J., Sutcliffe, L., and Tanner, E. V. J. (2013). Litter manipulation and the soil arthropod community in a lowland tropical rainforest. *Soil Biol. Biochem.* 62, 5–12. doi:10.1016/j.soilbio.2013.03.001

Bao, S. D. (2008). *Soil agrochemistry analysis*. Beijing: Chinese Agric Press.

Bertrand, M., Barot, S., Blouin, M., Whalen, J., Oliveira, T., and Roger-Estrade, J. (2015). d.Earthworm services for cropping systems. A review. *Agron. Sustain. Dev.Agronomy Sustain. Dev.* 35 (2), 553–567. doi:10.1007/S13593-014-0269-7

Birkhofer, K., Diekötter, T., Boch, S., Fischer, M., Müller, J., Socher, S., et al. (2011). Soil fauna feeding activity in temperate grassland soils increases with legume and grass species richness. *Soil Biol. Biochem.* 43 (10), 2200–2207. doi:10.1016/j.soilbio.2011.07.008

Bowles, T. M., Acosta-Martínez, V., Calderón, F., and Jackson, L. E. (2014). Soil enzyme activities, microbial communities, and carbon and nitrogen availability in organic agroecosystems across an intensively-managed agricultural landscape. *Soil Biol. Biochem.* 68, 252–262. doi:10.1016/j.soilbio.2013.10.004

Brar, B. S., Singh, J., Singh, G., and Kaur, G. (2015). Effects of long term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize-wheat rotation. *Agron. (Basel).* 5 (2), 220–238. doi:10.3390/agronomy5020220

Briones, M. J. I., and Schmidt, O. (2017). Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. *Glob. Chang. Biol.* 23 (10), 4396–4419. doi:10.1111/GCB.13744

Cai, Z. C., and Qin, S. W. (2006). Dynamics of crop yields and soil organic carbon in a long-term fertilization experiment in the Huang-Huai-Hai Plain of China. *Geoderma* 136 (3-4), 708–715. doi:10.1016/j.geoderma.2006.05.008

Chang, E. H., Chung, R. S., and Tsai, Y. H. (2007). Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population. *Soil Sci. Plant Nutr.* 53 (2), 132–140. doi:10.1111/J.1747-0765.2007.00122.X

Chen, H., Zhao, Y., Feng, H., Li, H., and Sun, B. (2015a). Assessment of climate change impacts on soil organic carbon and crop yield based on long-term fertilization applications in Loess Plateau, China. *Plant Soil* 390 (1), 401–417. doi:10.1007/s11104-014-2332-1

Chen, X., Li, Z., Liu, M., Jiang, C., and Che, Y. (2015b). Microbial community and functional diversity associated with different aggregate fractions of a paddy soil fertilized with organic manure and/or NPK fertilizer for 20 years. *J. Soils Sediments* 15 (2), 292–301. doi:10.1007/s11368-014-0981-6

Chew, K. W., Chia, S. R., Yen, H. W., Nomanbhay, S., Ho, Y. C., and Show, P. L. (2019). Transformation of biomass waste into sustainable organic fertilizers. *Sustainability* 11 (8), 2266. doi:10.3390/su11082266

Choudhary, M., Panday, S. C., Meena, V. S., Singh, S., Yadav, R. P., Mahanta, D., et al. (2018). Long-term effects of organic manure and inorganic fertilization on sustainability and chemical soil quality indicators of soybean-wheat cropping system in the Indian mid-Himalayas. *Agric. Ecosyst. Environ.* 257, 38–46. doi:10.1016/j.agee.2018.01.029

Cooper, J., Greenberg, I., Ludwig, B., Hippich, L., Fischer, D., Glaser, B., et al. (2020). Effect of biochar and compost on soil properties and organic matter in aggregate size fractions under field conditions. *Agric. Ecosyst. Environ.* 295, 106882. doi:10.1016/j.agee.2020.106882

Davies, B., Coulter, J. A., and Pagliari, P. H. (2022). Soil enzyme activity behavior after urea nitrogen application. *Plants (Basel).* 11, 2247. doi:10.3390/plants11172247

Demelash, N., Bayu, W., Tesfaye, S., Ziadat, F., and Sommer, R. (2014). Current and residual effects of compost and inorganic fertilizer on wheat and soil chemical properties. *Nutr. Cycl. Agroecosyst.* 100 (3), 357–367. doi:10.1007/s10705-014-9654-5

Diacono, M., and Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* 30 (2), 401–422. doi:10.1051/AGRO/2009040

Eggleton, P., Inward, K., Smith, J., Jones, D. T., and Sherlock, E. (2009). A six year study of earthworm (Lumbricidae) populations in pasture woodland in southern England shows their responses to soil temperature and soil moisture. *Soil Biol. Biochem.* 41 (9), 1857–1865. doi:10.1016/j.soilbio.2009.06.007

Eisenhauer, N., Wirsch, D., Cesarz, S., Craven, D., Dietrich, P., Friese, J., et al. (2014). Organic textile dye improves the visual assessment of the bait-lamina test. *Appl. Soil Ecol.* 82, 78–81. doi:10.1016/j.apsoil.2014.05.008

Fauci, M. F., and Dick, R. P. (1994). Soil microbial dynamics: Short- and long-term effects of inorganic and organic nitrogen. *soil Sci. Soc. Am. J.* 58 (3), 801–806. doi:10.2136/SSSAJ1994.03615995005800030023X

Feng, W., Xu, M., Fan, M., Malhi, S. S., Schoenau, J. J., Six, M., Xu, J., et al. (2013). Testing for soil carbon saturation behavior in agricultural soils receiving long-term manure amendments. *Canadian J. of Soil Sci.* 94 (3), 281–294. doi:10.4141/cjss2013-012

Filzek, P. D. B., Spurgeon, D. J., Broll, G., Svendsen, C., Hankard, P. K., Parekh, N., et al. (2004). Metal effects on soil invertebrate feeding: Measurements using the bait lamina method. *Ecotoxicology* 13 (8), 807–816. doi:10.1007/s10646-003-4478-0

Gao, G.-F., Li, P.-F., Zhong, J.-X., Shen, Z.-J., Chen, J., Li, Y. T., et al. (2019). Spartina alterniflora invasion alters soil bacterial communities and enhances soil N2O emissions by stimulating soil denitrification in mangrove wetland. *Sci. Total Environ.* 653, 231–240. doi:10.1016/j.scitotenv.2018.10.277

Gao, W., Yang, J., Ren, S.-r., and Hailong, L. (2015). The trend of soil organic carbon, total nitrogen, and wheat and maize productivity under different long-term fertilizations in the upland fluvo-aquic soil of North China. *Nutr. Cycl. Agroecosyst.* 103 (1), 61–73. doi:10.1007/s10705-015-9720-7

Geissen, V., and Brummer, G. W. (1999). Decomposition rates and feeding activities of soil fauna in deciduous forest soils in relation to soil chemical parameters following liming and fertilization. *Biol. Fertil. Soils* 29 (4), 335–342. doi:10.1007/s003740050562

Gentile, R., Vanlauwe, B., Chivenge, P., and Six, J. (2008). Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. *Soil Biol. Biochem.* 40 (9), 2375–2384. doi:10.1016/j.soilbio.2008.05.018

Gestel, C. A. M., Kruidenier, M., and Berg, M. P. (2003). v., Kruidenier, M., & Berg, M. PSuitability of wheat straw decomposition, cotton strip degradation and bait-lamina feeding tests to determine soil invertebrate activity. *Biol. Fertil. Soils* 37 (2), 115–123. doi:10.1007/s00374-002-0575-0

Gongalsky, K. B., Persson, T., and Pokarzhevskii, A. D. (2008). Effects of soil temperature and moisture on the feeding activity of soil animals as determined by the bait-lamina test. *Appl. Soil Ecol.* 39 (1), 84–90. doi:10.1016/j.apsoil.2007.11.007

Hannet, G., Singh, K., Fidelis, C., Farrar, M. B., Muqaddas, B., and Bai, S. H. (2021). Effects of biochar, compost, and biochar-compost on soil total nitrogen and available phosphorus concentrations in a corn field in Papua New Guinea. *Environ. Sci. Pollut. Res.* 28 (21), 27411–27419. doi:10.1007/s11356-021-12477-w

ISO (2018). "ISO 23470:2018," in *Soil quality — determination of effective cation exchange capacity (CEC) and exchangeable cations using a hexamminecobalt(III)chloride solution* (Geneva, Switzerland: International Organization for standardization (ISO)), 22.

Jain, M. S., and Kalamdhad, A. S. (2020). Soil revitalization via waste utilization: Compost effects on soil organic properties, nutritional, sorption and physical properties. *Environ. Technol. Innovation* 18, 100668. doi:10.1016/j.eti.2020.100668

Kaiser, M., Ellerbrock, R. H., and Gerke, H. H. (2007). Long-term effects of crop rotation and fertilization on soil organic matter composition. *Eur. J. Soil Sci.* 58 (6), 1460–1470. doi:10.1111/J.1365-2389.2007.00950.X

LaRade, S. E., Bork, E. W., and Willms, W. D. (2012). Assessment of soil biological activity in Northern Aspen Parkland native and seeded pasture using bait lamina. *J. Agric. Sci.* 4 (5), 83–90. doi:10.5539/jas.v4n5p83

Li, F., Yu, J., Nong, M., Kang, S., and Zhang, J. (2010). Partial root-zone irrigation enhanced soil enzyme activities and water use of maize under different ratios of inorganic to organic nitrogen fertilizers. *Agric. Water Manag.* 97 (2), 231–239. doi:10.1016/j.agwat.2009.09.014

Li, G., Zhang, Z. S., Gao, H. Y., Liu, P., Dong, S. T., Zhang, J. W., et al. (2012). Effects of nitrogen on photosynthetic characteristics of leaves from two different stay-green corn (Zea mays L.) varieties at the grain-filling stage. *Can. J. Plant Sci.* 92 (4), 671–680. doi:10.4141/Cjps2012-039

Li, J., and Rao, M. (2003). Field evaluation of crop yield as affected by nonuniformity of sprinkler-applied water and fertilizers. *Agric. Water Manag.* 59 (1), 1–13. doi:10.1016/S0378-3774(02)00123-3

Li, S., Chen, J., Shi, J. L., Tian, X. H., Li, X. S., Li, Y. B., et al. (2017). Impact of straw return on soil carbon indices, enzyme activity, and grain production. *Soil Sci. Soc. Am. J.* 81 (6), 1475–1485. doi:10.2136/sssaj2016.11.0368

Li, X. G., Liu, X. P., and Liu, X. J. (2020). Long-term fertilization effects on crop yield and desalinized soil properties. *Agron. J.* 112 (5), 4321–4331. doi:10.1002/agj2.20338

Liu, E. K., Yan, C. R., Mei, X. R., He, W. Q., Bing, S. H., Ding, L. P., et al. (2010). Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. *Geoderma* 158 (3-4), 173–180. doi:10.1016/j.geoderma.2010.04.029

Liu, W. X., Wang, Q. L., Wang, B. Z., Wang, X. B., Franks, A. E., Teng, Y., et al. (2015). Changes in the abundance and structure of bacterial communities under long-term fertilization treatments in a peanut monocropping system. *Plant Soil* 395 (1-2), 415–427. doi:10.1007/s11104-015-2569-3

Liu, Y., Zhao, L., Wang, Z., Liu, L., Zhang, P., Sun, J., et al. (2018). Changes in functional gene structure and metabolic potential of the microbial community in biological soil crusts along a revegetation chronosequence in the Tengger Desert. *Soil Biol. Biochem.* 126, 40–48. doi:10.1016/j.soilbio.2018.08.012

Lu, X. L., Lu, X. N., and Liao, Y. C. (2018). Conservation tillage increases carbon sequestration of winter wheat-summer maize farmland on Loess Plateau in China. *PLoS ONE* 13 (9), e0199846. doi:10.1371/journal.pone.0199846()

Lupwayi, N. Z., Clayton, G. W., O'Donovan, J. T., and Grant, C. A. (2011). Soil microbial response to nitrogen rate and placement and barley seeding rate under No till. *Agron. J.* 103 (4), 1064–1071. doi:10.2134/AGRONJ2010.0334

Maltas, A., Kebli, H., Oberholzer, H. R., Weisskopf, P., and Sinaj, S. (2018). The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. *Land Degrad. Dev.* 29 (4), 926–938. doi:10.1002/ldr.2913

Manolikaki, I., and Diamadopoulos, E. (2019). Positive effects of biochar and biochar-compost on maize growth and nutrient availability in two agricultural soils. *Commun. Soil Sci. Plant Analysis* 50 (5), 512–526. doi:10.1080/00103624.2019.1566468

Marx, M. T., Yan, X. M., Wang, X. F., Song, L. H., Wang, K. H., Zhang, B., et al. (2016). Soil fauna abundance, feeding and decomposition in different reclaimed and natural sites in the sanjiang plain wetland, northeast China. *Wetlands* 36 (3), 445–455. doi:10.1007/s13157-016-0753-8

Miao, Y. X., Stewart, B. A., and Zhang, F. S. (2011). Long-term experiments for sustainable nutrient management in China. A review. *Agron. Sustain. Dev.* 31 (2), 397–414. doi:10.1051/agro/2010034

Miller, J. J., Owen, M. L., Yang, X. M., Drury, C. F., Reynolds, W. D., and Chanasyk, D. S. (2020). Long-term cropping and fertilization influences soil organic carbon, soil water repellency, and soil hydrophobicity. *Can. J. Can. J. Soil Sci.* 100 (3), 234–244. doi:10.1139/cjss-2019-0129

Miner, G. L., Delgado, J. A., Ippolito, J. A., and Stewart, C. E. (2020). Soil health management practices and crop productivity. *Agric. Environ. Lett.* 5 (1), 23. doi:10.1002/AEL2.20023

Moller, K., and Schultheiss, U. (2015). Chemical characterization of commercial organic fertilizers. *Archives Agron. Soil Sci.* 61 (7), 989–1012. doi:10.1080/03650340.2014.978763

Mousavi, H., Cottis, T., Hoff, G., and Solberg, S. O. (2022). Nitrogen enriched organic fertilizer (NEO) and its effect on ryegrass yield and soil fauna feeding activity under controlled conditions. *Sustainability* 14 (4), 2005. doi:10.3390/su14042005

Ouédraogo, E., Mando, A., and Zombré, N. P. (2001). Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. *Agric. Ecosyst. Environ.* 84 (3), 259–266. doi:10.1016/S0167-8809(00)00246-2

Oyetunji, O., Bolan, N., and Hancock, G. (2022). A comprehensive review on enhancing nutrient use efficiency and productivity of broadacre (arable) crops with the combined utilization of compost and fertilizers. *J. Environ. Manag.* 317, 115395. doi:10.1016/j.jenvman.2022.115395

Qaswar, M., Jing, H., Ahmed, W., Li, D. C., Liu, S. J., Lu, Z., et al. (2020). Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. *Soil Tillage Res.* 198, 104569–104611. doi:10.1016/j.still.2019.104569

Rajan, J., and Anandhan, S. V. (2015). Survey on nutrient content of different organic fertilisers. *Environ. Monit. Assess.* 187 (6), 385. doi:10.1007/s10661-015-4632-1

Rożen, J., Sobczyk, Ł., Liszka, K., and Weiner, J. (2010). Soil faunal activity as measured by the bait-lamina test in monocultures of 14 tree species in the Siemianice common-garden experiment, Poland. *Applied Soil Ecology* 45 (3), 160–167. doi:10.1016/j.apsoil.2010.03.008

Römbke, J., Hofer, H., Garcia, M. V. B., and Martius, C. (2006). Feeding activities of soil organisms at four different forest sites in Central Amazonia using the bait lamina method. *J. Trop. Ecol.* 22, 313–320. doi:10.1017/S0266467406003166

Setia, R., Rengasamy, P., and Marschner, P. (2013). Effect of exchangeable cation concentration on sorption and desorption of dissolved organic carbon in saline soils. *Sci. Total Environ.* 465, 226–232. doi:10.1016/j.scitotenv.2013.01.010

Shang, F., Ren, S., Yang, P., Li, C., and Ma, N. (2015). Effects of different fertilizer and irrigation water types, and dissolved organic matter on soil C and N mineralization in crop rotation farmland. *Water, Air, Soil Pollut.* 226 (12), 396. doi:10.1007/s11270-015-2667-0

Sunnemann, M., Alt, C., Kostin, J. E., Lochner, A., Reitz, T., Siebert, J., et al. (2021). Low-intensity land-use enhances soil microbial activity, biomass and fungal-to-bacterial ratio in current and future climates. *J. Appl. Ecol.* 58 (11), 2614–2625. doi:10.1111/1365-2664.14004

Tao, H.-H., Slade, E. M., Willis, K. J., Caliman, J.-P., and Snaddon, J. L. (2016). Effects of soil management practices on soil fauna feeding activity in an Indonesian oil palm plantation. *Agric. Ecosyst. Environ.* 218, 133–140. doi:10.1016/j.agee.2015.11.012

Thomas, G. A., Dalal, R. C., and 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 Tillage Res.* 94 (2), 295–304. doi:10.1016/j.still.2006.08.005

Tiemann, L. K., and Billings, S. A. (2011). Indirect effects of nitrogen amendments on organic substrate quality increase enzymatic activity driving decomposition in a mesic grassland. *Ecosystems* 14 (2), 234–247. doi:10.1007/s10021-010-9406-6

Törne, E. (1990). Assessing feeding activities of soil-living animals 1. Bait-Lamina-Tests. *Pedobiologia* 34 (2), 89–101.

Ullah, S., Ai, C., Huang, S., Zhang, J., Jia, L., Ma, J., et al. (2019). The responses of extracellular enzyme activities and microbial community composition under nitrogen addition in an upland soil. *PLoS ONE* 14 (9), e0223026. doi:10.1371/journal.pone.0223026()

Vorobeichik, E. L., and Bergman, I. E. (2021). Bait-lamina test for assessment of polluted soils: Rough vs. Precise scales. *Ecol. Indic.* 122, 107277. doi:10.1016/j.ecolind.2020.107277

Wahyuningsih, R., Marchand, L., Pujianto, S., and Caliman, J. P. (2019). Impact of inorganic fertilizer to soil biological activity in an oil palm plantation. *IOP Conf. Ser. Earth Environ. Sci.* 336 (1), 012017. doi:10.1088/1755-1315/336/1/012017

Wang, C., Ning, P., Li, J. Y., Wei, X. M., Ge, T. D., Cui, Y. X., et al. (2022). Responses of soil microbial community composition and enzyme activities to long-term organic amendments in a continuous tobacco cropping system. *Appl. Soil Ecol.* 169, 104210. doi:10.1016/j.apsoil.2021.104210

Wang, Y., Huang, C., Liu, M., and Yuan, L. (2021). Long-term application of manure reduced nutrient leaching under heavy N deposition. *Nutr. Cycl. Agroecosyst.* 119 (2), 153–162. doi:10.1007/s10705-020-10107-4

Welbaum, G. E., Sturz, A. V., Dong, Z. M., and Nowak, J. (2004). Managing soil microorganisms to improve productivity of agro-ecosystems. *Crit. Rev. Plant Sci.* 23 (2), 175–193. doi:10.1080/07352680490433295

Yang, L., Bian, X. G., Yang, R. P., Zhou, C. L., and Tang, B. P. (2018). Assessment of organic amendments for improving coastal saline soil. *Land Degrad. Dev.* 29 (9), 3204–3211. doi:10.1002/ldr.3027

Yang, X., Sun, B., and Zhang, S. (2014). Trends of yield and soil fertility in a long-term wheat-maize system. *J. Integr. Agric.* 13 (2), 402–414. doi:10.1016/S2095-3119(13)60425-6

Yang, Z., Zhao, N., Huang, F., and Lv, Y. (2015). Long-term effects of different organic and inorganic fertilizer treatments on soil organic carbon sequestration and crop yields on the North China Plain. *Soil Tillage Res.* 146, 47–52. doi:10.1016/j.still.2014.06.011

Yu, C., Hu, X. M., Deng, W., Li, Y., Xiong, C., Ye, C. H., et al. (2015). Changes in soil microbial community structure and functional diversity in the rhizosphere surrounding mulberry subjected to long-term fertilization. *Appl. Soil Ecol.* 86, 30–40. doi:10.1016/j.apsoil.2014.09.013

Zelles, L., Bai, Q. Y., Beck, T., and Beese, F. (1992). Signature fatty acids in phospholipids and lipopolysaccharides as indicators of microbial biomass and community structure in agricultural soils. *Soil Biol. Biochem.* 24 (4), 317–323. doi:10.1016/0038-0717(92)90191-Y

Zhang, P., Chen, X., Wei, T., Yang, Z., Jia, Z., Yang, B., et al. (2016a). Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semiarid region of China. *Soil Tillage Res.* 160, 65–72. doi:10.1016/j.still.2016.02.006

Zhang, X., Xiao, G., Bol, R., Wang, L., Zhuge, Y., Wu, W., et al. (2021). Influences of irrigation and fertilization on soil N cycle and losses from wheat–maize cropping system in northern China. *Environ. Pollut.* 278, 116852. doi:10.1016/j.envpol.2021.116852

Zhang, Y., Li, C., Wang, Y., Hu, Y., Christie, P., Zhang, J., et al. (2016b). Maize yield and soil fertility with combined use of compost and inorganic fertilizers on a calcareous soil on the North China Plain. *Soil Tillage Res.* 155, 85–94. doi:10.1016/j.still.2015.08.006

Zhao, S., Li, K., Zhou, W., Qiu, S., Huang, S., and He, P. (2016). Changes in soil microbial community, enzyme activities and organic matter fractions under long-term straw return in north-central China. *Agric. Ecosyst. Environ.* 216, 82–88. doi:10.1016/j.agee.2015.09.028

Zhou, Z., Yang, D., Zhao, J., Zhang, H., and Wang, L. (2021). Emissions of greenhouse gas and ammonia from an intensive wheat site affected by different fertilization practices. AvaliableAt: https://elibrary.asabe.org/abstract.asp?aid=52457&t=5.