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ARTICLE

Differential Responses of Soil Organic Carbon Fractions and Carbon Turnover Related Enzyme Activities to Wheat Straw Incorporation in Subtropical China

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ABSTRACT

Soil organic carbon (SOC) fractions and C turnover related enzyme activities are essential for nutrient cycling. This is because they are regarded as important indicators of soil fertility and quality. We measured the effects of wheat straw incorporation on SOC fractions and C turnover related enzyme activities in a paddy field in subtropical China. Soil samples were collected from 0–10 cm and 10–20 cm depths after rice harvesting. The total SOC concentrations were higher in the high rate of wheat straw incorporation treatment (NPKS2) than in the not fertilized control (CK) ($P < 0.05$). The concentrations of labile C fractions [i.e., water soluble organic C (WSOC), hot-water soluble organic C (HWSOC), microbial biomass C (MBC), and easily oxidizable C (EOC)], were higher in the moderate NPKS1 and NPKS2 treatments than in CK and the fertilized treatment without straw (NPK) ($P < 0.05$). The geometric means of labile C (GMC) and C pool management index (CPMI) values were highest in NPKS2 ($P < 0.05$). The SOC concentrations correlated positively with the labile C fractions ($P < 0.05$). Soil cellulase activity and the geometric mean of enzyme activities (GMea) were higher in NPKS2 than in CK in all soil layers ($P < 0.05$), and the invertase activity was higher in NPKS2 than in CK in the 0–10 cm layer ($P < 0.05$). Stepwise multiple linear regression indicated that the formation of the SOC, WSOC, HWSOC, MBC, and EOC was mostly enhanced by the cellulase and invertase activities ($P < 0.05$). Therefore, the high rate of wheat straw incorporation may be recommended to increase soil C pool levels and soil fertility in subtropical paddy soils.

KEYWORDS

Wheat straw incorporation; soil organic carbon fractions; soil carbon turnover related enzymes; paddy soil; subtropical China

1 Introduction

Organic carbon (C) content in soil affects soil physical biochemical properties, and is therefore a vital factor responsible for soil fertility and productivity [1]. The maintenance of SOC content is crucial for the sustainability of agricultural ecosystems. SOC dynamic is affected by many agricultural management practices (e.g., fertilizer application, straw incorporation, and tillage) [2–4]. However, SOC content changes are hard to monitor in the short time likely because of the considerable background C content [5–7]. The labile fractions of SOC, e.g., water soluble organic C (WSOC), hot-water soluble organic C (HWSOC), microbial biomass C (MBC), and easily oxidizable C (EOC), are seen as early and sensitive indicators of soil quality changes that result from soil management practices [5,8–10]. The C pool management index (CPMI), which was developed to evaluate the status and rate of SOC changes in agroecosystems based on the total SOC and EOC, is a useful parameter in assessing the influences of management practices on soil quality [5].

The decomposition and accumulation of SOC in agroecosystems can be affected by crop straw, agricultural waste rich in organic C [10]. The direct and indirect straw incorporation into soil can balance the SOC loss resulting from SOC mineralization in agroecosystems [10–11]. Compared with the NPK fertilizers application alone, the SOC change rate was approximately two times higher in straw application treatments in paddy fields [12]. In addition, the WSOC and MBC contents were higher in the top 20 cm soil after a short-term (less than two-years) straw application [13]. Wang et al. [14] revealed that incorporation of straw into soil enhanced the total SOC content in dryland farming, especially with the higher straw incorporation rate. Moreover, the turnover of SOC is mainly associated with soil microbial community functions (e.g., enzyme activities) [15–16]. Several soil enzymes participate in the decomposition of SOC, thus further influencing SOC fractions, and the enzyme activities are also important indicators of soil fertility and quality [16–18]. For example, cellulase, invertase, and β-glucosidase that decompose SOC indicate the metabolic abilities of the soil microbial community and the utilizable C resources [2,19]. Previous studies on soil enzymes related to the SOC turnover mostly paid attention to the grassland and forest ecosystems [15–16,20,21]. Knowledge on crop straw incorporation in agroecosystems is still lacking, especially in the subtropical paddy soils. Organic C may accumulate in the subtropical paddy soils faster than in other soils [22], possibly due to regular and periodic changes between aerobic and anaerobic conditions due to the management [23]. In particular, Tang et al. [24] demonstrated that subtropical paddy soils are markedly responsive to global climate change and management practices (e.g., to crop straw incorporation). This necessitates studying the effects of crop straw incorporation practices on changes in SOC fractions and the corresponding C turnover related enzyme activities in the subtropical paddy soils. Understanding the relationships between SOC fractions and enzymes can reveal the potential mechanisms in SOC turnover and C cycle under straw incorporation practices [13,25,26].

In China, almost 0.80 Pg of straw residue is produced annually, and the rate is currently increasing [27]. More than three tenth of the straw produced is burned directly in open fields [28], which has led to severe environmental pollution (e.g., fine particulate matter) in the past decades [29]. Straw incorporation is regarded as an environment-friendly management practice that can reduce air pollution and supply organic C to soils [10,27]. A full understanding of the effects of wheat straw incorporation on SOC fractions and C turnover related enzyme activities in paddy field is essential to assess the sustainability of straw incorporation practices. Hence, the objectives of this study were to (1) examine the dynamic changes in SOC fractions and C turnover related enzyme activities, and (2) explore the relationships between SOC fractions and the corresponding enzyme activities.

2 Materials and Methods

2.1 Experimental Site

The experimental field (May 2019–November 2019) was in the Modern Agricultural Park of Qingpu, Shanghai, China (121°01′ E, 31°08′ N) (Fig. 1). The study area is characterized by a subtropical monsoon climate, with an average annual precipitation and temperature of 1056 mm and 15.5°C, respectively. The annual daylight hours are 1960.7 h, and the frost-free days are 247 d. The rice-wheat rotation system is the major cropping system in the region. The soil has a clay loam texture, with initial soil properties (0–20 cm) as follows: pH 7.08, bulk density 1.16 g cm^{-3}, SOC 16.59 g kg^{-1}, total N 1.96 g kg^{-1}, available N 140.47 mg kg^{-1}, available P 36.51 mg kg^{-1}, and available K 146 mg kg^{-1}.

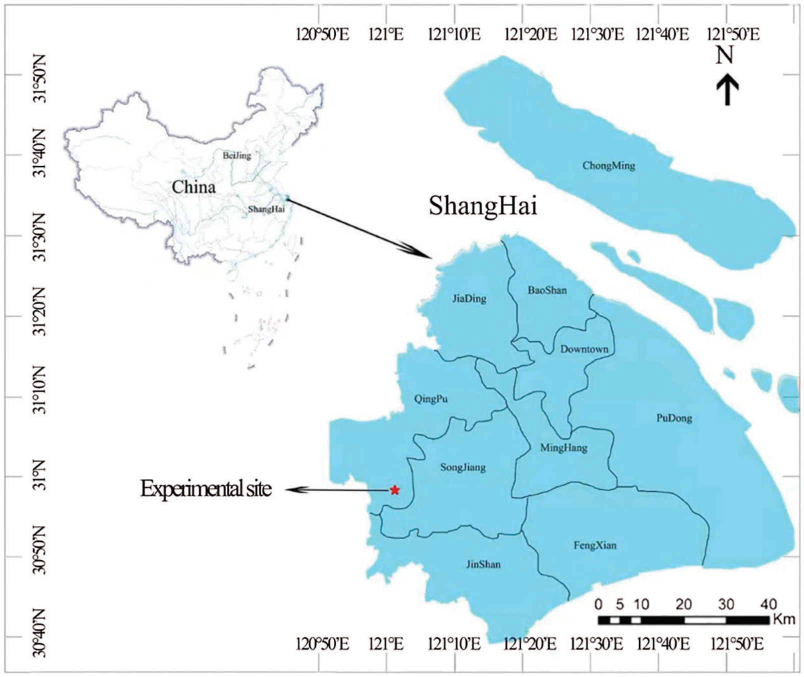

Figure 1: Location of the field experimental site

2.2 Experimental Design and Soil Sampling

Fig. 2 presents the experimental design, which included four treatments: (1) no fertilizer and wheat straw (CK), (2) mineral nitrogen, phosphorus, and potassium fertilizers (NPK), (3) moderate wheat straw (3000 kg ha^{-1}) combined with NPK (NPKS1), and (4) high wheat straw (6000 kg ha^{-1}) combined with NPK (NPKS2). The moderate and high rates were equivalent to about 50% and 100%, respectively, of the harvested wheat straw yield. The treatments were laid out in a randomized block design in triplicate with an 8 × 7 m plot. The wheat straw was chopped and then incorporated into the paddy soil using conventional tillage. Fertilizers were applied as 300 kg ha^{-1} N, 120 kg ha^{-1} P, and 150 kg ha^{-1} K, including urea (46% N), calcium superphosphate (12% P_2O_5), and potassium chloride (60% K_2O). N fertilizer was applied as follows: 40% at the sowing stage, 30% at the tillering stage, and 30% at the panicle stage. Both P and K fertilizers were applied before transplanting the rice. Other field management practices (e.g., the water regime), were in line with the local farmers' practices.

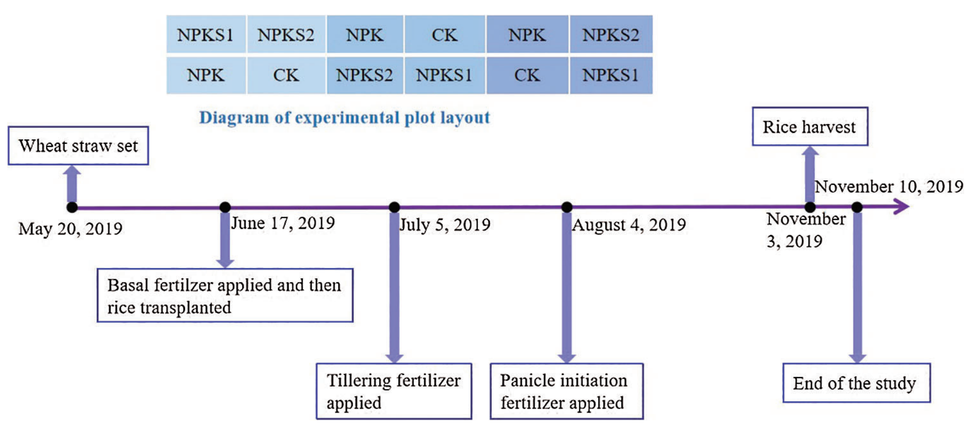

Figure 2: Field experimental design. CK: no fertilizer and wheat straw; NPK: mineral nitrogen, phosphorus, and potassium fertilizers; NPKS1: moderate wheat straw (3000 kg ha^{-1}) combined with NPK; NPKS2: high wheat straw (6000 kg ha^{-1}) combined with NPK

Soil samples were collected from 0–10 cm and 10–20 cm depths after rice harvest at five random points in each plot, and then mixed to form a composite sample. Following the removal of visible stones and plant residues, the samples were homogenized, passed through a 2 mm mesh, and then divided into two subsamples. One subsample was stored at 4°C for the analysis of WSOC and MBC within 10 days, and the other subsample was air-dried for the measurements of SOC, HWSOC, EOC, cellulase, invertase, and β-glucosidase activity.

2.3 Soil Analysis

2.3.1 SOC Fractions Analysis

SOC was determined using an elemental analyzer (Vario EL III, CHNOS Elemental Analyzer, Elementar, Langenselbold, Germany). The WSOC was determined by extracting the fresh soil samples with water at a soil/water ratio of 1:5 and analyzing the C concentrations using the Multi N/C 3100 Analyzer (Analytik Jena, Germany) [30]. The HWSOC was determined on fresh soil samples using the method of Sparling et al. [8] and C concentrations were measured using the Multi N/C 3100 Analyzer (Analytik Jena, Germany). MBC was determined using the chloroform fumigation-extraction method [31] and was calculated as $(C_{fumigated}-C_{non\text{-}fumigated})/0.45$. EOC was determined using the 333 mmol L^{-1} $KMnO_4$ oxidation method and was calculated as the difference between the amount of $KMnO_4$ added and that remaining [5]. The geometric means of labile C (GMC) was calculated based on the method of Yu et al. [32] as follows:

$$GMC = \sqrt[4]{WSOC \times HWSOC \times MBC \times EOC} \quad (1)$$

The CPMI was calculated as follows [5]:

$$CPMI = C\ Pool\ Index\ (CPI) \times Lability\ Index\ (LI) \times 100 \quad (2)$$

The CPI and LI were calculated as follows:

$$CPI = \frac{SOC\ content\ in\ sample\ soil}{SOC\ content\ in\ reference\ soil} \quad (3)$$

$$LI = \frac{L\ in\ sample\ soil}{L\ in\ reference\ soil} \quad (4)$$

The lability of C (L) is defined as the ratio of labile C (EOC) to non-labile C, and non-labile C is calculated as SOC-EOC. In this study, the soil sampled in the control treatment was used as the reference soil.

2.3.2 Soil Enzyme Activity Analysis

The cellulase and invertase activities were analyzed based on the methods described by Guan [33], and carboxymethyl-cellulose and sucrose were used as substrates, respectively. Their activities were expressed as the mass (mg) of glucose in 1 g of soil. The β-glucosidase activity was determined using a substrate of *p*-nitrophenyl-β-*D*-glucopyranoside (PNP) solution and it was expressed as μmol *p*-nitrophenol (PNP) in 1 g of soil [34]. The geometric mean of enzyme activities (GMea) was calculated based on the method of Roberto et al. [35] as follows:

$$GMea = \sqrt[3]{Cellulase \times Invertase \times \beta - glucosidase} \quad (5)$$

2.4 Statistical Analysis

Differences in SOC fractions and C turnover related enzyme activities were tested using the Duncan's Multiple Range Test in SPSS 22.0 (SPSS Inc., Chicago, IL, USA).

Pearson's correlation analysis was used to determine the relationships between SOC fractions and soil C turnover related enzyme activities. The relationships between SOC fractions and C turnover related enzyme activities were examined using the general linear-regression analysis and stepwise regression analysis in SPSS 22.0 (SPSS Inc., Chicago, IL, USA). The data were transformed as necessary to satisfy assumptions of normality and homogeneity of variance, and significant levels were set at the 0.05 level.

3 Results

3.1 SOC Fractions

In the 0–10 cm and 10–20 cm soil layers, the SOC concentrations were higher in NPKS2 than in CK ($P < 0.05$, Fig. 3a), and the WSOC, HWSOC, MBC, and EOC concentrations were higher in NPKS2 than in NPK and CK ($P < 0.05$, Figs. 3b–3e). On average, the WSOC constituted from 0.53% to 0.83%, HWSOC from 2.86% to 4.09%, MBC from 2.22% to 2.70%, and EOC from 17.67% to 32.65% of the total SOC (Tab. 1). The WSOC/SOC, HWSOC/SOC, and MBC/SOC ratios were higher in NPKS2 than in CK in the 0–10 cm soil layer ($P < 0.05$, Tab. 1). The EOC/SOC ratios were higher in NPKS2 than in CK in the two soil layers ($P < 0.05$, Tab. 1). The GMC values in the 0–10 cm and 10–20 cm soil layers were higher in NPKS2 than in the other treatments ($P < 0.05$, Fig. 4).

3.2 Soil CPMI

In the 0–10 cm and 10–20 cm soil layers, the LI, CPI, and CPMI values were highest in the NPKS2 treatment, followed by NPKS1, NPK, and CK (Fig. 5). The LI, CPI, and CPMI values were higher in NPKS2 than in NPK and CK in the two soil layers ($P < 0.05$, Fig. 5).

3.3 Relationships among Different Organic C Fractions

A correlation analysis indicated that the SOC concentrations were positively correlated with the WSOC, HWSOC, MBC, and EOC in the 0–10 cm and 10–20 cm soil layers ($P < 0.05$, Tab. 2). Also, the soil labile organic C fractions were positively correlated with each other ($P < 0.05$, Tab. 2).

3.4 Soil C Turnover Related Enzyme Activities

The soil cellulase activity was higher in NPKS2 than in CK in the 0–10 cm and 10–20 cm soil layers ($P < 0.05$, Fig. 6a), and the invertase activity was higher in NPKS2 than in CK in the 0–10 cm layer ($P < 0.05$, Fig. 6b). However, no difference in β-glucosidase activities were found among the treatments in the two soil layers (Fig. 6c). The GMea values were higher in NPKS2 than in CK in both layers ($P < 0.05$, Fig. 6d).

3.5 Relationships between SOC Fractions and C Turnover Related Enzyme Activities

In the Pearson's correlation analysis (Tab. 3), the cellulase activity in the 0–10 cm soil layer was positively correlated with WSOC, HWSOC, MBC, and EOC. In addition, there were positive relationships between the cellulase and both the HWSOC and EOC in the 10–20 cm soil layer ($P < 0.05$). The invertase activities in the two layers were positively correlated ($P < 0.05$) with most SOC fractions, except for the EOC in the 10–20 cm soil layer. The β-glucosidase activity was positively correlated with MBC and EOC in the 0–10 cm soil layer ($P < 0.05$). In the stepwise multiple regression analysis (Tab. 4), the models explained from 33.60% to 74.50% of the variation in total SOC and its fractions in the 0–10 cm and 10–20 cm soil layers, and both the cellulase and invertase activities were the most significant variables in the models ($P < 0.05$).

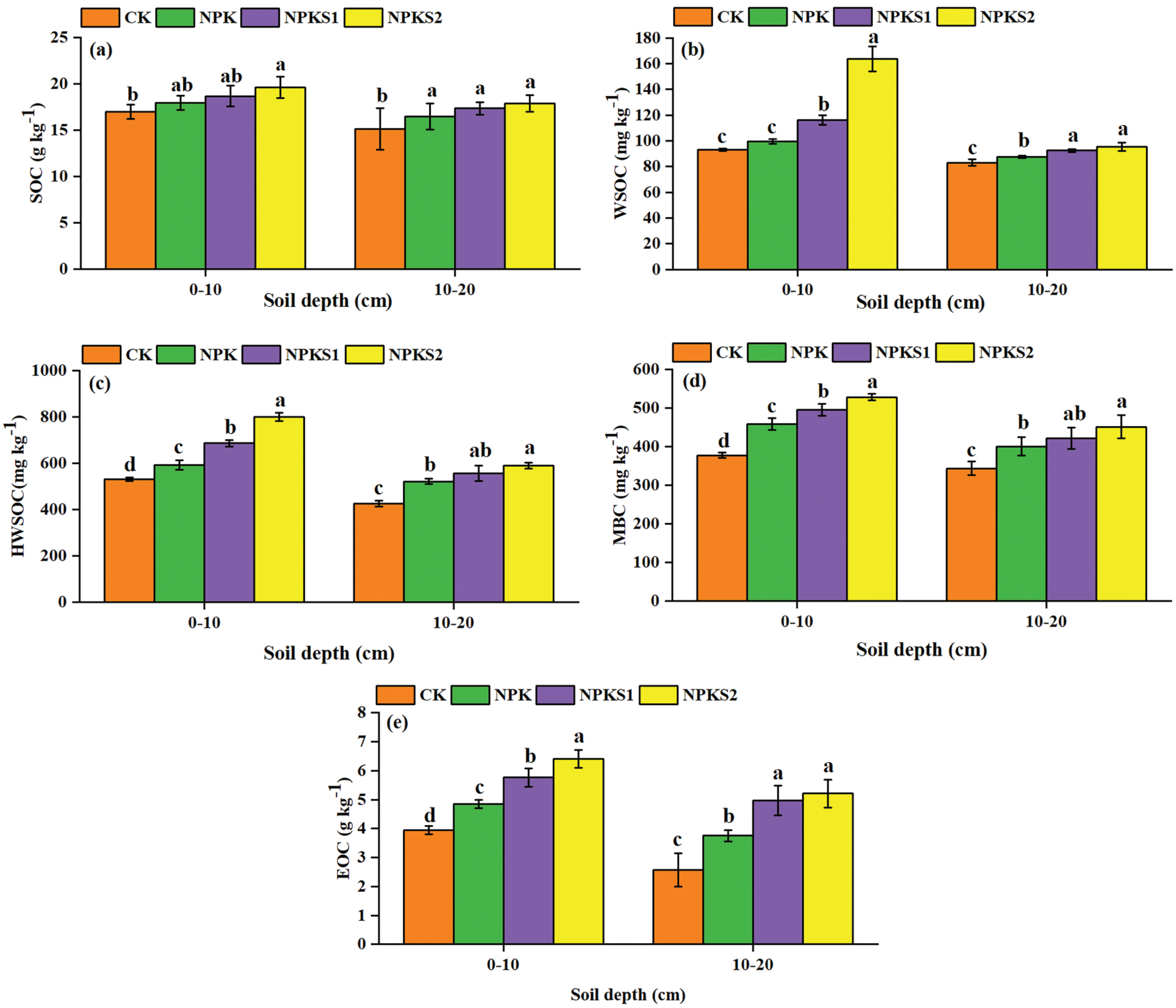

Figure 3: Changes in SOC fractions under different treatments. The values are means ± SD ($n = 3$). Different letters mean statistically significant differences at the 0.05 level. CK: no fertilizer and wheat straw; NPK: mineral nitrogen, phosphorus, and potassium fertilizers; NPKS1: moderate wheat straw (3000 kg ha^{-1}) combined with NPK; NPKS2: high wheat straw (6000 kg ha^{-1}) combined with NPK. SOC: soil organic C; WSOC: water soluble organic C; HWSOC: hot-water soluble organic C; MBC: microbial biomass C; EOC: easily oxidizable C

4 Discussion

Similar to previous studies on crop straw management [14,36,37], our results indicated that a high straw incorporation rate led to higher SOC concentrations compared to not-fertilized treatment (CK). However, the straw incorporation at the moderate (NPKS1) and high (NPKS2) rates did not result in differences in SOC concentrations in comparison to the fertilized treatment (NPK). It is possible that the SOC concentration is generally insensitive to short-term management practices. This is because the changes in SOC content occur slowly and are comparatively small in comparison with the large background SOC content [6].

Table 1: The proportions of labile C fractions under different treatments

Depth (cm)	Treatment	WSOC/SOC (%)	HWSOC/SOC (%)	MBC/SOC (%)	EOC/SOC (%)
0–10	CK	0.55 ± 0.03b	3.11 ± 0.09c	2.22 ± 0.12b	23.11 ± 1.31b
	NPK	0.55 ± 0.03b	3.31 ± 0.25bc	2.56 ± 0.19a	26.95 ± 1.83b
	NPKS1	0.62 ± 0.05b	3.69 ± 0.27ab	2.66 ± 0.24a	30.96 ± 3.39a
	NPKS2	0.83 ± 0.06a	4.09 ± 0.24a	2.70 ± 0.14a	32.65 ± 0.70a
10–20	CK	0.56 ± 0.08a	2.86 ± 0.26a	2.31 ± 0.44a	17.67 ± 6.59b
	NPK	0.53 ± 0.04a	3.19 ± 0.31a	2.44 ± 0.21a	22.89 ± 2.48ab
	NPKS1	0.53 ± 0.03a	3.21 ± 0.25a	2.43 ± 0.21a	28.68 ± 3.68a
	NPKS2	0.53 ± 0.04a	3.14 ± 0.16a	2.52 ± 0.06a	29.20 ± 3.94a

Note: The values are means ± SD (n = 3). Different letters in the same column mean significant differences at the 0.05 level in the Duncan's Multiple Range Test. CK: no fertilizer and wheat straw; NPK: mineral nitrogen, phosphorus, and potassium fertilizers; NPKS1: moderate wheat straw (3000 kg ha^{-1}) combined with NPK; NPKS2: high wheat straw (6000 kg ha^{-1}) combined with NPK. SOC: soil organic C; WSOC: water soluble organic C; HWSOC: hot-water soluble organic C; MBC: microbial biomass C; EOC: easily oxidizable C.

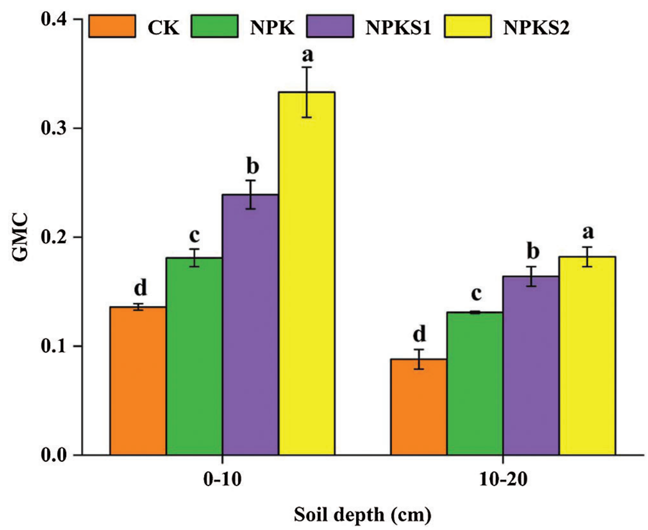

Figure 4: The GMC under different treatments. The values are means ± SD (n = 3). Different letters mean statistically significant differences at the 0.05 level. CK: no fertilizer and wheat straw; NPK: mineral nitrogen, phosphorus, and potassium fertilizers; NPKS1: moderate wheat straw (3000 kg ha^{-1}) combined with NPK; NPKS2: high wheat straw (6000 kg ha^{-1}) combined with NPK. GMC: the geometric means of labile C

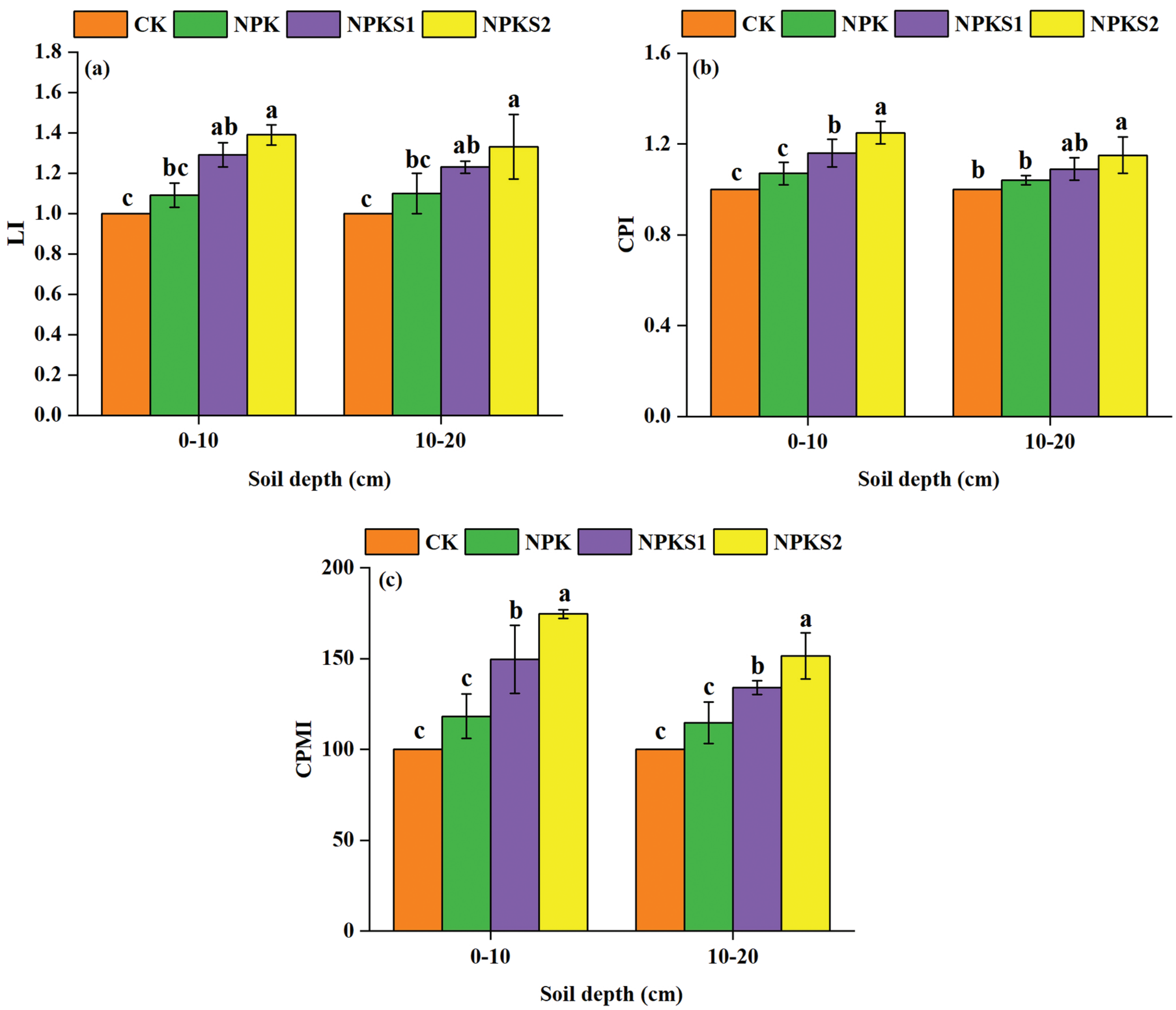

Figure 5: Changes in soil CPMI among different treatments. The values are means ± SD ($n = 3$). Different letters above the columns mean significant differences at the 0.05 level using the Duncan's Multiple Range Test. CK: no fertilizer and wheat straw; NPK: mineral nitrogen, phosphorus, and potassium fertilizers; NPKS1: moderate wheat straw (3000 kg ha^{-1}) combined with NPK; NPKS2: high wheat straw (6000 kg ha^{-1}) combined with NPK. LI: lability index; CPI: C pool index; CPMI: C pool management index

Table 2: The correlation coefficients between SOC and the labile C fractions

	SOC	WSOC	HWSOC	MBC	EOC
0–10 cm					
SOC	1				
WSOC	0.708**	1			
HWSOC	0.741**	0.951**	1		
MBC	0.696*	0.818**	0.923**	1	
EOC	0.750**	0.880**	0.959**	0.975**	1
10–20 cm					
SOC	1				
WSOC	0.628*	1			
HWSOC	0.621*	0.907**	1		
MBC	0.617*	0.789**	0.912**	1	
EOC	0.457*	0.890**	0.852**	0.724**	1

Note: $^{**}P < 0.01$; $^{*}P < 0.05$. SOC: soil organic C; WSOC: water soluble organic C; HWSOC: hot-water soluble organic C; MBC: microbial biomass C; EOC: easily oxidizable C.

The WSOC, HWSOC, MBC, and EOC concentrations respond to management practices more rapidly than the total SOC, making short-term changes easier to detect on them [38–39]. These fractions are considered as important indicators of changes in soil quality [2,39]. Generally, straw incorporation increased soil labile C fractions in the short time [9,13,36,40]. In this study, the concentrations of the labile C fractions (i.e., WSOC, HWSOC, MBC, and EOC concentrations) were higher in the NPKS2 treatment than in the NPK and CK treatments. This might be because crop straw contains large portions of labile C and is an important source of C and energy for microorganisms that convert crop straw C into labile organic C [10,41]. The WSOC to SOC ratio was lower than the ratios of other C fractions to SOC, but it played a key role in nutrient turnover and in the development of microbial populations. The ratios of HWSOC, MBC, and EOC to SOC were similar to those in previous studies [36,42–44]. In agreement with Xu et al. [9] and Li et al. [13], the straw incorporation increased the WSOC concentrations in the two soil layers. As with WSOC, we found that straw incorporation resulted in higher EOC concentrations in both layers, which is consistent with results reported in other studies [9,36]. For the HWSOC and MBC, the concentrations increased in the 10–20 cm soil layer only with the higher straw incorporation rate. Taken together, the response of WSOC and EOC was rapid and sensitive to soil management even in the short-term.

The geometric means of labile C (GMC) value integrates the responses of WSOC, HWSOC, MBC, and EOC into a single value that may be used as a sensitive indicator of the changes in SOC quantity or quality. Both the total SOC and the labile C fractions contribute to the C pool management index (CPMI) that is a sensitive indicator of the response of SOC to changes in soil management [5,9]. CPMI can detect small changes in the quantity and quality of SOC, and thereby it can be used to assess the efficacy of soil management practices [4,9,39]. In our study, the treatments were clearly different according to both the GMC and CPMI values, with highest values in the NPKS2 treatment. The results indicated that soil labile C was more sensitive to the NPKS2 than to the other treatments, and that the SOC was more stable in the NPKS2 treatment. The results suggested that the NPKS2 application had a positive influence on the accumulation of the soil C pool.

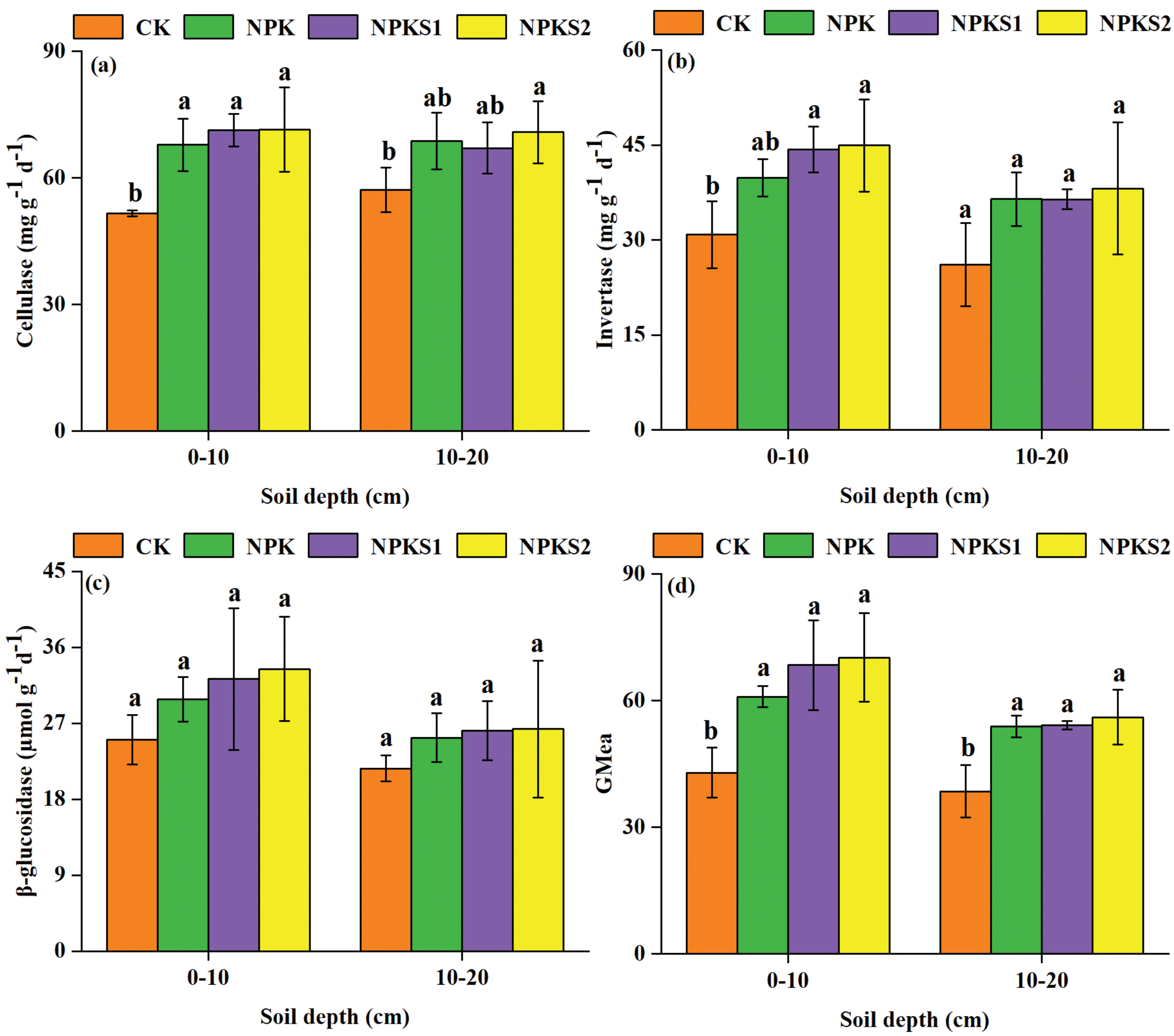

Figure 6: Soil C turnover related enzyme activities in response to different treatments. The values are means ± SD ($n = 3$). Different letters mean statistically significant differences at the 0.05 level. CK: no fertilizer and wheat straw; NPK: mineral nitrogen, phosphorus, and potassium fertilizers; NPKS1: moderate wheat straw (3000 kg ha^{-1}) combined with NPK; NPKS2: high wheat straw (6000 kg ha^{-1}) combined with NPK. GMea: the geometric mean of enzyme activities

Table 3: Pearson's correlation analysis between soil C turnover related enzyme activities and SOC fractions

Depth (cm)	Index	SOC	WSOC	HWSOC	MBC	EOC
0–10	Cellulase	0.575	0.577*	0.712**	0.863**	0.829**
	Invertase	0.746**	0.607*	0.706*	0.841**	0.834**
	β-glucosidase	0.250	0.411	0.483	0.605*	0.620*
10–20	Cellulase	0.339	0.412	0.607*	0.569	0.624*
	Invertase	0.580*	0.388*	0.591*	0.642*	0.412
	β-glucosidase	0.335	0.477	0.366	0.130	0.429

Note: **$P < 0.01$; *$P < 0.05$. SOC: soil organic C; WSOC: water soluble organic C; HWSOC: hot-water soluble organic C; MBC: microbial biomass C; EOC: easily oxidizable C.

Table 4: Stepwise multiple regression analysis of the relationships between SOC fractions and soil C turnover related enzymes

Depth (cm)	SOC fractions	Regression equation	R^2	P
0–10	SOC	$Y = 13.009 + 0.133\ X_2$	0.557	0.005
	WSOC	$Y = 20.911 + 2.434\ X_2$	0.369	0.036
	HWSOC	$Y = 156.400 + 7.578\ X_1$	0.508	0.009
	MBC	$Y = 129.118 + 5.125\ X_1$	0.745	0.000
	EOC	$Y = 0.673 + 0.114\ X_2$	0.696	0.001
10–20	SOC	$Y = 12.345 + 0.128\ X_2$	0.336	0.048
	WSOC	$Y = 74.256 + 0.470\ X_2$	0.345	0.045
	HWSOC	$Y = 179.101 + 5.227\ X_1$	0.368	0.036
	MBC	$Y = 267.432 + 3.997\ X_2$	0.412	0.024
	EOC	$Y = -2.090 + 0.094\ X_1$	0.390	0.030

Note: SOC: soil organic C; WSOC: water soluble organic C; HWSOC: hot-water soluble organic C; EOC: easily oxidizable C; MBC: microbial biomass C. Y, SOC fractions. X_1: cellulase; X_2: invertase.

Consistent with previous studies [2,45,46], the labile fractions correlated positively with the SOC concentration. This highlighted that SOC was a pivotal determinant of the labile C fractions. In addition, the labile fractions correlated positively with each other, showing that they were closely interrelated [45].

The activities of the soil enzymes are related to the soil nutrient cycling and serve as good indicators of soil quality [47]. Similar to earlier studies [48–50], the enzyme activities were higher in the NPKS2 treatment. Possibly crop straw addition led to higher amounts of endoenzymes in the viable microbial populations, and therefore more enzymes accumulated in the soils [50]. Consistent with Guo et al. [51], the soil cellulase activity was higher in NPKS2 than in CK, and the invertase activity was higher in NPKS2 than in CK in the top 10 cm soil. This may be attributable to higher SOC concentrations that enhanced the activity of soil microorganisms. The results indicated that the NPKS2 treatment improved soil quality by increasing the nutrient cycling and turnover in the soil. The geometric mean of enzyme activities (GMea) value can provide effective information on soil enzymes as indicators of soil quality [52]. In this study, the GMea values in the two soil layers were highest in NPKS2 and lowest in CK, suggesting that high amounts of straw residues could stimulate microbial growth.

Each C turnover related enzyme has its own substrate and ability to catalyze specific chemical and biological reactions [13,53]. Similar to Li et al. [13], the cellulase and invertase activities in the top 10 cm soil correlated positively with the labile fractions. These C turnover related enzymes degrade cellulose into labile organic C [54–55]. The correlations of cellulase and invertase were higher with MBC than with other fractions in the 0–10 cm soil layer, suggesting that these enzymes were mainly from soil microorganisms. Hence, high biomass turnover could increase microbial biomass and enzyme activities [13,56]. Assessing the roles of C turnover related enzymes in SOC turnover under straw incorporation using stepwise multiple linear regression demonstrated that the labile organic C formation was mostly enhanced by cellulase and invertase (Tab. 4), indicating that cellulase and invertase might increase the loss of SOC [13].

5 Conclusion

In this study, the total SOC concentrations were higher in the high rate of wheat straw incorporation treatment than in the not fertilized control, and the concentrations of labile C fractions were higher with wheat straw incorporation than without wheat straw. The treatments were clearly different according to both the GMC and CPMI values, with highest values in the high rate of wheat straw incorporation treatment. The concentrations of SOC and labile C fractions correlated positively. Soil cellulase activity and GMea were higher in the high rate of wheat straw incorporation treatment than in the not fertilized control. Soil cellulase and invertase activities enhanced the formation of SOC fractions. In conclusion, the high rate of wheat straw incorporation may be recommended to further increase SOC levels and soil fertility for sustainable agricultural development in the subtropical paddy fields.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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