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耕作方式和有机肥对土壤有机碳及作物产量的影响

杨杰 赵霖 由福英 王培烨 周静 谢颖 王萌瑶 张鑫 王贵彦*
(河北农业大学农学院/华北作物改良与调控国家重点实验室/农业农村部华北节水农业重点实验室,
河北保定 071033)

摘要 为探讨不同耕作方式和施用有机肥对土壤有机碳、活性碳组分和作物产量的影响,于2022—2023年开展田间试验,采用裂区设计,设深翻(D)、深翻施用有机肥(DM)、旋耕(R)和旋耕施用有机肥(RM)4个处理,以旋耕(R)为对照处理,探究了耕作方式与施有机肥对土壤有机碳(Soil organic carbon, SOC)及其活性碳组分、碳相关酶活性、土壤碳库管理指数(Carbon pool management index, CPMI)和作物产量的影响。结果表明:1)耕作方式与施有机肥对土壤有机碳库具有显著影响,深翻比旋耕显著提高了SOC及其活性碳组分含量,施有机肥比不施有机肥显著提高了SOC及其活性碳组分含量($P<0.05$);深翻施用有机肥处理SOC含量显著高于其他处理,与对照相比显著提高10.18%($P<0.05$)。2)耕作方式和施有机肥对土壤碳相关酶活性有显著影响,深翻比旋耕显著提高了土壤碳相关酶活性,施有机肥比不施有机肥显著提高了土壤碳相关酶活性($P<0.05$);深翻施用有机肥处理过氧化氢酶(Soil catalase, S-CAT)活性(>20—40 cm土层)显著高于其他处理,较对照显著提高了15.40%($P<0.05$)。3)耕作方式与施有机肥对小麦-玉米两熟周年产量及CPMI有显著影响,均是深翻施用有机肥显著高于其他处理($P<0.05$);深翻施用有机肥周年产量较对照处理显著提高了9.40%,深翻施用有机肥CPMI较对照处理显著提高了28.50%($P<0.05$)。4)SOC及其活性碳组分、碳相关酶活性和CPMI均与小麦-玉米两熟周年产量呈显著正相关($P<0.05$),碳相关酶活性与SOC及其活性碳组分均呈极显著正相关($P<0.01$),CPMI与碳相关酶活性、SOC及其活性碳组分均呈极显著正相关($P<0.01$)。综上,深翻施用有机肥可激发土壤碳相关酶活性,促进土壤活性碳与有机碳增加,提高了碳库管理指数,达到增碳增产的目的。

关键词 耕作方式; 有机肥; 土壤有机碳; 产量; 碳库管理指数

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Effects of tillage practices and organic manure on soil organic carbon and crop yield

YANG Jie, ZHAO Mai, YOU Fuying, WANG Peiye, ZHOU Jing, XIE Ying,
WANG Mengyao, ZHANG Xin, WANG Guiyan*

(College of Agronomy/State Key Laboratory of North China Crop Improvement and Regulation/Key Laboratory of Water-Saving Agriculture in North China of Ministry of Agriculture and Rural Affairs, Hebei Agricultural University,
Baoding 071033, China)

Abstract To investigate the effects of different tillage practices and organic fertilizer application on soil organic carbon, active carbon components, and crop yield, a field experiment was conducted from 2022 to 2023. Split-plot design was adopted. Four treatments deep tillage (D), deep tillage with organic fertilizer (DM), rotary tillage

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第一作者: 杨杰(ORCID:0009-0008-2199-1647), 硕士研究生, E-mail: yjie3452@gmail.com

通讯作者: 王贵彦(ORCID:0009-0007-8037-2646), 教授, 主要从事生态高效种植制度研究, E-mail: wanggy@hebau.edu.cn

(R), and rotary tillage with organic fertilizer (RM) were set by taking rotary tillage (R) as the control. The impacts of tillage practices and organic fertilizer application on soil organic carbon (SOC), its active components, carbon-related enzyme activities, soil carbon pool management index (CPMI), and crop yield were examined. The results showed that: 1) Tillage practices and organic fertilizer application significantly influenced the soil organic carbon pool. Deep tillage significantly increased the SOC and active carbon components compared with rotary tillage, while organic fertilizer application significantly enhanced the SOC and active carbon fraction contents compared with non-application ($P < 0.05$). The SOC content under the deep tillage with organic fertilizer treatment was significantly higher than that under other treatments, which was significantly increased by 10.18% compared with the control ($P < 0.05$). 2) Tillage practices and organic fertilizer application significantly affected soil carbon-related enzyme activities. Deep tillage significantly increased soil carbon-related enzyme activities compared with rotary tillage, and organic fertilizer application significantly enhanced these activities compared with non-application ($P < 0.05$). The soil catalase (S-CAT) activity in the >20 -40 cm soil layer under the deep tillage with organic fertilizer treatment was significantly higher than that under other treatments, significantly increased by 15.40% compared with the control ($P < 0.05$). 3) Tillage practices and organic fertilizer application significantly influenced the annual yield of the wheat-maize double-cropping system and CPMI ($P < 0.05$). The deep tillage with organic fertilizer treatment exhibited significantly higher values in both parameters compared with other treatments. The annual yield under deep tillage with organic fertilizer increased by 9.40% compared with the control, while the CPMI increased by 28.50% ($P < 0.05$). 4) SOC and its active fractions, carbon-related enzyme activities, and CPMI were significantly positively correlated with the annual yield of the wheat-maize double-cropping system ($P < 0.05$). Carbon-related enzyme activities showed highly significant positive correlations with SOC and its active fractions ($P < 0.01$), and CPMI was highly significantly positively correlated with carbon-related enzyme activities, SOC and its active fractions ($P < 0.01$). In conclusion, deep tillage combined with organic fertilizer application can stimulate soil carbon-related enzyme activities, promote the accumulation of soil-active carbon and organic carbon, and enhance the carbon pool management index, thereby achieving the dual goals of increasing carbon sequestration and crop yields.

Keywords tillage practices; organic manure; soil organic carbon; yield; carbon pool management index

华北麦玉两熟区是我国重要的粮食产区和农业生产基地,在国民经济中占据重要地位^[1]。近年来,作物产量的持续提高是农业生产的主要目标,该区域集约化程度和作物产量较高,导致土壤有机质流失严重^[2],而提高农田土壤固碳能力和维持土壤碳库平衡,是有效维持土壤健康和持续高产的重要途径^[3]。

土壤有机碳在培肥土壤、提高土地生产力等方面发挥着重要作用,是评价土壤质量的关键指标^[4],活性有机碳周转速率快,能有效激活土壤微生物,活化土壤养分^[5]。耕作方式是影响土壤有机碳转化的田间措施之一,不同耕作深度与强度对土壤碳库矿化速率的作用各异^[6]。华北平原小麦-玉米长期浅旋耕导致耕层浅薄化、肥力衰退等问题制约了沃土提质与持续高产^[7]。研究表明,深翻(20~40 cm)可改善土壤物理性质,促进作物根系生长^[8],提高土壤微生物总量,从而增加碳输入^[9],秸秆还田配合旋耕^[10]或深翻^[11]显著提高了土壤有机碳及活性碳组分含量。有

机肥具有增加土壤有机质含量、培肥地力、改良土壤、增强土壤保水保肥能力的特性^[12],可向土壤提供有机碳来源,提高土壤微生物活性,促进有机碳与营养物质之间的转换,从而增加土壤有机碳积累量^[13]。因此,施用有机肥也是增强农田土壤有机碳的重要技术途径^[14]。牛粪与无机肥混施显著提高了冬小麦-夏玉米两熟农田土壤微生物生物量碳(Microbial biomass carbon, MBC)、土壤易氧化有机碳(Easily oxidizable organic carbon, EOC)以及土壤可溶性有机碳(Dissolved organic carbon, DOC)等活性有机碳组分含量,增强了土壤固碳能力^[15]。施用有机肥比无机肥显著提高了耕作层中 EOC 和 MBC 含量^[16-17]。

因此,本研究以小麦-玉米两熟粮田为研究对象,于2022—2023年开展田间不同耕作方式下施用有机肥试验,探究不同耕作方式下施用有机肥对土壤有机碳、活性碳组分、土壤碳库变化及作物产量的影响,旨在为华北麦玉两熟区土壤增碳保碳和提高粮食产量提供科学理论依据。

1 材料与方法

1.1 试验地概况

试验于2022年10月—2023年10月在河北省保定市高阳县硕丰农场(115°38′ E, 38°30′ N)进行,该地区属于温带大陆性季风气候,降雨集中在7—9月,月平均气温14.44℃,无霜期205 d,试验期间年降水量494.57 mm。试验地0—20 cm土层基础养分有机质20.29 g/kg、全氮0.92 g/kg、速效磷13.81 mg/kg、速效钾150.23 mg/kg。

1.2 试验设计

采用双因素裂区设计,不同耕作方式为主区,设深翻(D)和旋耕(R)2个处理;副区为不施用有机肥和施用有机肥2个处理(M)。试验处理分别为:深翻(D)、深翻施用有机肥(DM)、旋耕(R)和旋耕施用有机肥(RM),以R处理为对照,小区面积50 m²(长10 m,宽5 m),3次重复。

小麦于2022年10月24日播种,2023年6月13日收获,品种为‘济麦22’,基本苗600万/hm²。播种前将有机肥和基施氮肥撒施地表后进行旋耕(15 cm)或深翻(25~30 cm),耕后耙耱进行播种。行距15 cm,滴灌水肥一体化管理模式,滴灌带间距60 cm。玉米于2023年6月20日播种,10月2日收获,品种为‘秋乐368’,种植密度6.0万株/hm²。小麦和玉米总施化肥纯氮量均为210 kg/hm²,小麦基施纯氮90 kg/hm²,拔节期追施氮肥72 kg/hm²,开花期追施氮肥48 kg/hm²、磷肥(P₂O₅)135 kg/hm²和钾肥(K₂O)105 kg/hm²;玉米基施纯氮42 kg/hm²,大喇叭口期追氮105 kg/hm²,开花期追施氮肥63 kg/hm²、玉米磷肥(P₂O₅)120 kg/hm²和钾肥(K₂O)150 kg/hm²。有机肥(有机质含量≥45%,有效菌≥5亿/g, NPK含量4.5 g/kg)1 800 kg/hm²和磷钾肥基施。小麦和玉米收获后秸秆粉碎还田,其他田间管理根据当地高产田管理措施进行。

1.3 测定指标及方法

分别于小麦和玉米成熟期,各小区取0—40 cm土层的土壤,20 cm为一层,去除杂质后分为2份,一份土样自然风干,测定有机碳;另一份保存于4℃冰箱中,用于土壤微生物生物量碳及碳相关酶活性测定。

1.3.1 土壤有机碳和碳组分含量的测定

土壤有机碳(Soil organic carbon, SOC)含量采

用重铬酸钾-浓硫酸外加热法测定^[18];MBC含量采用氯仿熏蒸浸提法测定^[19];EOC含量采用高锰酸钾氧化法测定^[20];难氧化有机碳(Hardly oxidizable carbon, HOC)含量=SOC含量-EOC含量;颗粒有机碳(Particulate organic carbon, POC)含量采用六偏磷酸钠分散法测定^[21]。

1.3.2 土壤碳相关酶活性的测定

过氧化氢酶(Soil catalase, S-CAT)活性采用0.1 mol/L高锰酸钾滴定法测定^[22];蔗糖酶(Soil sucrase, S-SC)活性采用3, 5-二硝基水杨酸比色法测定^[22]。

1.3.3 作物产量的测定

小麦成熟期按小区收获,风干后脱粒测定产量。取样面积为1 m²,按13%含水量统一折算籽粒产量,以平均值作为单位面积产量。玉米成熟后按小区收获,风干脱粒测产。取样面积为5 m²,按14%含水量统一折算,以平均值作为单位面积籽粒产量。

1.3.4 土壤碳库管理指数

参考O' rourke等^[23]的方法计算碳库活度(Activity, A)、碳库指数(Carbon pool index, CPI)、碳库活度指数(Activity index, AI)和碳库管理指数(Carbon pool management index, CPMI),以EOC作为活性有机碳表征,HOC为稳态有机碳表征,对照处理(R)为参照土壤,计算公式如下:

$$A = \text{EOC} / \text{HOC} \quad (1)$$

$$\text{CPI} = \text{SOC} / \text{SOC}_{\text{CK}} \quad (2)$$

$$\text{AI} = A / A_{\text{CK}} \quad (3)$$

$$\text{CPMI} = \text{CPI} \times \text{AI} \times 100 / \% \quad (4)$$

式中:SOC为样品总有机碳含量,g/kg;SOC_{CK}为对照总有机碳含量,g/kg;A_{CK}为对照土壤碳库活度。

1.4 统计分析

数据处理采用Microsoft Excel 2021软件,用SPSS 17.0软件进行多因素方差分析和相关性分析,采用Duncan法进行差异显著性检验,采用Origin 2024软件作图。

2 结果与分析

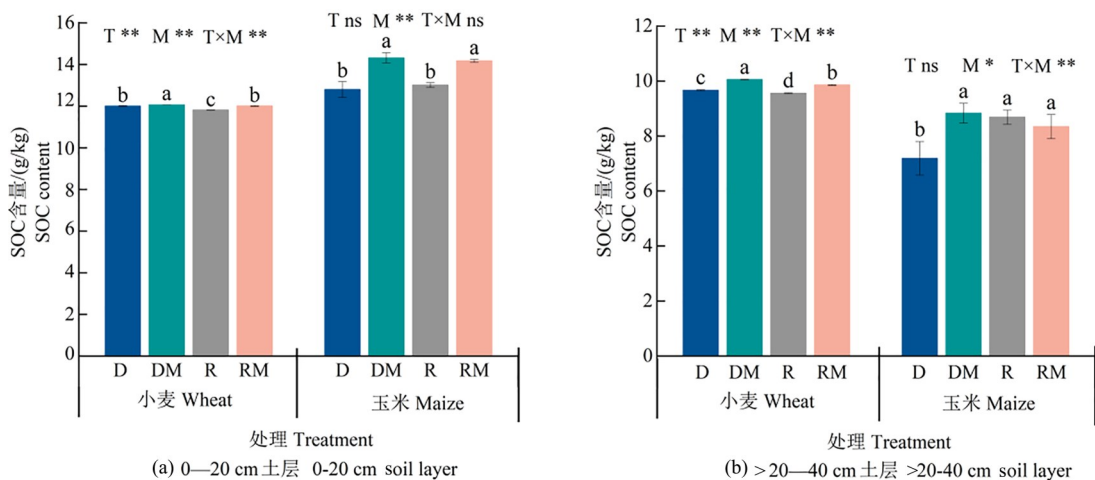
2.1 耕作方式和有机肥对土壤SOC及其组分含量的影响

2.1.1 土壤SOC含量

小麦和玉米成熟期不同处理土壤SOC含量如图1所示。0—20 cm土层,互作分析表明小麦季耕

作方式、施用有机肥及其交互作用均对 SOC 含量具有显著($P<0.05$)或极显著($P<0.01$)影响,深翻处理下 SOC 含量显著高于旋耕($P<0.05$),施用有机肥 SOC 含量显著高于不施用有机肥($P<0.05$);玉米季,互作分析表明施用有机肥极显著影响 SOC 含量($P<0.01$),深翻和旋耕处理下施用有机肥 SOC

含量较不施用有机肥分别显著增加了 18.5% 和 8.9% ($P<0.05$)。>20—40 cm 土层,互作分析表明玉米季施用有机肥及其交互作用均对 SOC 含量具有显著($P<0.05$)或极显著($P<0.01$)影响,深翻处理下施用有机肥较不施用有机肥 SOC 含量显著增加 22.9% ($P<0.05$)。



D:深翻;DM:深翻施用有机肥;R:旋耕;RM:旋耕施用有机肥。不同小写字母表示不同处理间具有显著差异($P<0.05$)。*和**分别表示差异显著($P<0.05$)和差异极显著($P<0.01$),ns表示差异不显著。T:耕作方式;M:施用有机肥;T×M:耕作方式与施肥交互作用。下同。
D: deep tillage; DM: deep tillage with organic manure; R: rotary tillage; RM: rotary tillage with organic manure. Different lowercase letters indicate significant differences between different treatments ($P<0.05$). * and ** denote significant ($P<0.05$) and highly significant ($P<0.01$) differences, respectively, and ns indicates no significant difference. T: tillage practices; M: organic manure; T×M: interaction between tillage practices and fertilization. The same below.

图 1 不同处理下作物成熟期土壤有机碳(SOC)含量

Fig. 1 Soil organic carbon content at crop maturity under different treatment

2.1.2 土壤活性碳组分含量

如表 1 所示,小麦和玉米成熟期不同处理互作

分析表明,0—20 和>20—40 cm 土层施用有机肥均对 MBC、POC 和 EOC 含量具有显著($P<0.05$)

表 1 耕作方式和有机肥对土壤活性碳组分的互作分析

Table 1 Interaction analysis of the tillage practices and organic manure on soil active carbon components					
土层/cm Soil layer	作物 Crop	处理 Treatment	MBC 含量 MBC content	POC 含量 POC content	EOC 含量 EOC content
0—20	小麦 Wheat	T	ns	ns	**
		M	**	*	**
		T×M	ns	ns	ns
	玉米 Maize	T	ns	*	ns
		M	*	**	**
		T×M	ns	ns	ns
>20—40	小麦 Wheat	T	ns	ns	*
		M	**	*	**
		T×M	ns	ns	ns
	玉米 Maize	T	**	ns	**
		M	**	**	**
		T×M	ns	ns	ns

或极显著($P<0.01$)影响。由表2可知,不同耕作方式和有机肥处理下MBC、POC和EOC含量随土层加深而降低。0—40 cm土层,小麦和玉米在DM处理下MBC、POC和EOC含量显著高于其他处理($P<0.05$),较对照组R分别提高了23.15%、15.31%和10.12%。此外,施有机肥较不施有机肥MBC、POC和EOC含量分别显著提高了28.21%、7.92%和11.31%($P<0.05$)。

表2 不同耕作方式和有机肥处理下活性碳组分
Table 2 Active carbon components under different tillage practices and organic manure treatments

土层/cm Soil layer	作物 Crop	处理 Treatment	MBC 含量/(mg/kg) MBC content	POC 含量/(g/kg) POC content	EOC 含量/(g/kg) EOC content
0—20	小麦 Wheat	D	242.62±10.45 b	3.34±0.02 a	1.89±0.05 b
		DM	352.07±19.71 a	3.56±0.03 a	2.02±0.03 a
		R	252.56±37.23 b	2.50±0.20 c	1.81±0.03 c
		RM	361.81±9.36 a	2.97±0.15 b	1.97±0.03 a
	玉米 Maize	D	252.7±5.12 ab	2.49±0.04 b	1.59±0.05 a
		DM	267.13±6.28 a	2.72±0.10 a	1.66±0.03 a
		R	233.95±16.27 b	2.50±0.08 b	1.48±0.03 b
		RM	265.9±23.32 a	2.68±0.06 a	1.61±0.08 a
>20—40	小麦 Wheat	D	61.5±5.44 c	4.32±0.36 ab	2.84±0.01 b
		DM	95.64±2.13 a	4.73±0.11 a	3.14±0.05 a
		R	57.91±0.94 c	3.95±0.41 b	2.65±0.03 c
		RM	80.5±3.04 b	4.43±0.28 ab	2.89±0.05 b
	玉米 Maize	D	55.15±22.69 bc	4.41±0.16 b	2.67±0.06 bc
		DM	95.62±4.19 a	5.12±0.10 a	2.82±0.03 a
		R	31.97±6.01 c	4.16±0.09 b	2.65±0.03 c
		RM	62.85±7.91 b	4.89±0.25 a	2.75±0.06 ab

注:同列数据不同字母表示差异显著($P<0.05$),相同字母表示差异不显著($P>0.05$)。下同。
Note: Within the same column, different letters represent significant differences ($P<0.05$), while the same letters represent no significant differences ($P>0.05$). The same below.

2.2 耕作方式和有机肥对土壤碳相关酶活性的影响

2.2.1 土壤S-CAT活性

小麦和玉米成熟期不同处理下不同土层S-CAT活性如图2所示。互作分析表明施有机肥极显著影响0—40 cm土层S-CAT活性($P<0.01$)。0—20 cm土层,小麦季和玉米季S-CAT活性施有机肥均显著高于不施用有机肥($P<0.05$),玉米季S-CAT活性旋耕显著高于深翻($P<0.05$)。>20—40 cm土层,玉米季S-CAT活性深翻显著高于旋耕($P<0.05$),小麦季和玉米季S-CAT活性施有机肥均显著高于不施用有机肥($P<0.05$)。此外,小麦季和玉米季DM均显著高于其他处理($P<0.05$),较对照组R分别提高13.25%和14.35%。

2.2.2 土壤S-SC活性

小麦和玉米成熟期不同处理下不同土层S-SC活性如图3所示。互作分析表明施有机肥极显著影响0—20 cm土层S-SC活性($P<0.01$)。0—20 cm土层,小麦季和玉米季S-SC活性施有机肥均显著高于不施用有机肥($P<0.05$),玉米季S-SC活性旋耕显著高于深翻($P<0.05$);其中小麦季和玉米季RM较对照组R分别显著提高98.7%和75.8%($P<0.05$)。>20—40 cm土层,小麦季S-SC活性DM显著高于其他处理($P<0.05$),较对照组R提高了47.82%。

2.3 耕作方式和有机肥处理对土壤CPMI的影响

由表3可知,耕作方式和施有机肥及其交互作用对小麦季和玉米季CPI、AI和CPMI均具有显著($P<0.05$)或极显著($P<0.01$)影响。如表4所示,

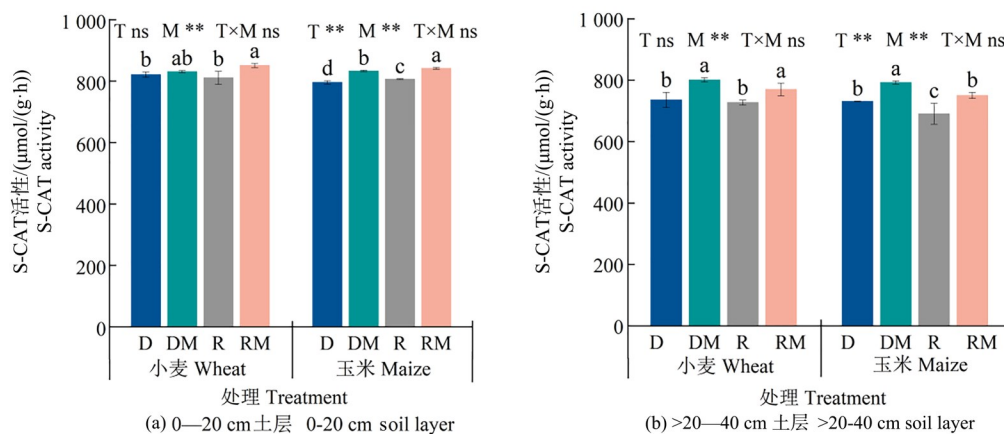


图 2 不同处理下作物成熟期土壤过氧化氢酶(S-CAT)活性

Fig. 2 S-CAT activity at crop maturity under different treatment

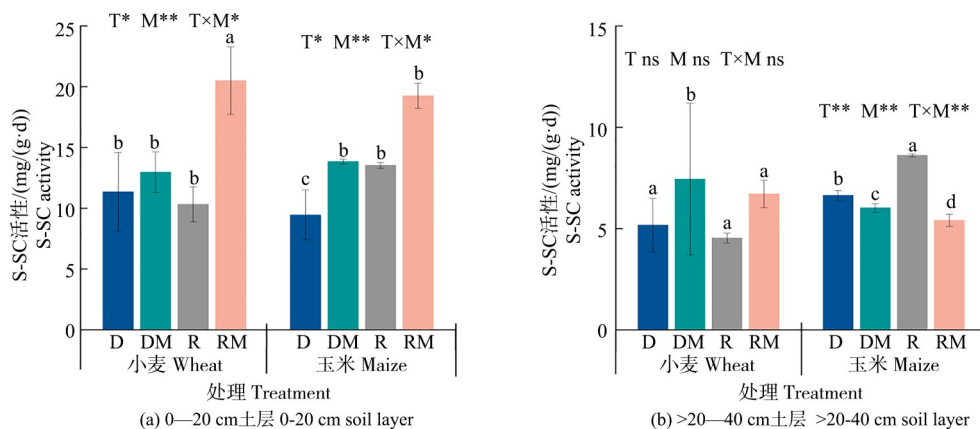


图 3 不同处理下作物成熟期土壤蔗糖酶(S-SC)活性

Fig. 3 S-SC activity at crop maturity under different treatment

小麦季和玉米季DM均显著高于其他各处理($P < 0.05$),各处理CPMI由高到低依次为DM>RM>D>R。CPMI小麦季和玉米季DM相比R处理分别显著提高了25.8%和32.7%($P < 0.05$)。此外,

施有机肥小麦季和玉米季CPI、AI和CPMI均显著高于未施有机肥($P < 0.05$),DM相比D处理小麦季和玉米季分别提高20.6%和20.9%,RM相比R处理小麦季和玉米季分别提高了16.5%和24.4%。

表 3 耕作方式和有机肥对土壤CPMI的互作分析

Table 3 Interactive analysis of tillage practices and organic manure on CPMI

作物 Crop	处理 Treatment	碳库指数 CPI	碳库活度指数 AI	碳库管理指数 CPMI
小麦 Wheat	T	**	**	**
	M	**	**	**
	T×M	*	**	*
玉米 Maize	T	**	**	**
	M	**	**	**
	T×M	*	*	*

表4 不同耕作方式和有机肥处理下土壤CPMI
Table 4 Soil CPMI under different tillage practices and organic manure treatments

作物 Crop	处理 Treatment	碳库指数 CPI	碳库活度指数 AI	碳库管理指数 CPMI
小麦 Wheat	D	1.05±0.05 c	0.94±0.02 c	92.23±3.58 c
	DM	1.42±0.10 a	1.35±0.08 a	116.30±6.22 a
	R	0.82±0.01 d	0.75±0.06 d	86.41±2.35 d
	RM	1.23±0.07 b	1.18±0.03 b	103.22±2.47 b
玉米 Maize	D	1.04±0.03 c	0.83±0.05 c	87.10±5.14 c
	DM	1.34±0.09 a	1.28±0.07 a	110.18±6.21 a
	R	0.76±0.01 d	0.62±0.03 d	74.20±6.28 d
	RM	1.18±0.06 b	1.07±0.01 b	98.27±4.01 b

2.4 耕作方式和有机肥处理对作物产量的影响

由表5可知,耕作方式、施用有机肥及其交互作用均显著($P<0.05$)或极显著($P<0.01$)影响小麦和玉米产量及周年产量。如表6所示,DM处理小麦和玉米产量及周年产量均为最高,且显著高于其他处理($P<0.05$)。深翻处理显著提高了作物产量

($P<0.05$),D相比R处理,小麦和玉米产量及周年产量分别显著提高2.6%、3.1%和2.9% ($P<0.05$)。施用有机肥可显著提高作物产量($P<0.05$),小麦和玉米产量及周年产量DM相比D处理分别增产6.2%、7.1%和6.7%,RM相比R处理分别增产2.3%、8.5%和5.5%。

表5 耕作方式和有机肥对小麦和玉米产量及周年产量的互作分析
Table 5 Interaction analysis of the tillage practices and organic manure on wheat and maize yield and annual yield

处理 Treatment	小麦产量 Wheat yield	玉米产量 Maize yield	周年产量 Annual yield
T	**	**	**
M	**	**	**
T×M	**	*	*

表6 不同耕作方式和有机肥处理下小麦和玉米的产量及周年产量
Table 6 Wheat and maize yield and annual yield under different tillage practices and organic manure treatments

处理 Treatment	小麦产量 Wheat yield	玉米产量 Maize yield	周年产量 Annual yield
D	9 037.32±64.93 b	9 035.73±73.68 c	18 073.05±138.61 c
DM	9 639.75±104.88 a	9 724.19±1.30 a	19 363.94±106.18 a
R	8 804.17±24.17 c	8 751.53±19.30 d	17 555.70±43.47 d
RM	9 007.00±21.68 b	9 566.17±0.99 b	18 573.17±22.67 b

2.5 耕作方式和有机肥处理土壤SOC及其活性碳组分、碳相关酶、CPMI与周年产量的相关性分析

由表7可知,周年产量与土壤SOC及其活性组分含量、碳相关酶活性和CPMI均呈显著正相关($P<0.05$),土壤SOC含量与活性碳组分含量和碳相关酶活性均呈极显著正相关($P<0.01$),CPMI与土壤SOC及其组分含量和碳相关酶活性均呈极显著正相关($P<0.01$)。

表 7 不同耕作方式和有机肥处理 SOC 及其活性碳组分、碳相关酶、CPMI 与周年产量的相关性分析

Table 7 Correlation analysis of SOC and its active carbon components, carbon-related enzymes, CPMI, and annual yield with different tillage practices and organic manure treatments

指标 Index	周年产量 Annual yield	SOC	MBC	EOC	POC	S-CAT	S-SC	CPMI
周年产量 Annual yield	1.000							
SOC	0.859**	1.000						
MBC	0.946**	0.982**	1.000					
EOC	0.856**	0.646*	0.633*	1.000				
POC	0.984**	0.980**	0.975**	0.792**	1.000			
S-CAT	0.968**	0.826**	0.965**	0.834**	0.989**	1.000		
S-SC	0.698*	0.895**	0.885**	0.885**	0.932**	0.911**	1.000	
CPMI	0.985**	0.949**	0.974**	0.804**	0.985**	0.998**	0.955**	1.000

3 讨 论

3.1 耕作方式和有机肥对土壤有机碳及其碳组分含量的影响

深翻能有效促进耕层有机碳和活性有机碳含量显著增加^[24],且 0—40 cm 土层变化尤为显著^[25]。本研究结果表明,深翻施用有机肥 0—20 cm 土层土壤有机碳及活性碳组分显著高于旋耕施用有机肥,原因可能与旋耕能促进作物残余均匀融入土层,扩大了秸秆与土壤的交互界面,比深翻更能促进微生物分解^[26],但由于秸秆分解缓慢,秸秆中的碳分解与固存也较为迟缓^[27],所以表层土壤中深翻处理的 SOC 高于旋耕处理^[28]。深翻增加了>20—40 cm 土层土壤有机碳及其活性有机碳含量,由于深翻能减小土壤紧实度,降低深层土壤容重和增强深层保水能力,可将根系分泌物翻入深层土壤提供有机基质,从而提高微生物活性,加速根茬残留物分解和活性有机碳组分转化。此外,深翻将 0—35 cm 耕层土壤进行置换,可有效提升深层土壤肥力,从而提高活性有机碳组分及有机碳含量^[29]。施用有机肥可显著增加土壤有机碳及微生物生物量碳含量^[30],有机和无机肥配施也会增加有机碳组分含量,从而影响土壤有机碳的转化和固定^[31]。本研究中施用有机肥处理土壤有机碳及其活性碳组分显著高于未施用有机肥处理,由于施用有机肥料可为土壤微生物群落提供充裕的碳源和能源基质,促进微生物生长与繁衍,提升其生物活性水平,释放出更多活性有机碳,提高了活性碳组分 DOC 和 MBC 含量^[32-33]。

3.2 耕作方式和有机肥对土壤碳相关酶活性的影响

深翻后土壤结构疏松,土壤真菌多样性上升,增强了土壤酶活性^[34],促进腐殖质分解,深层微生物能够接触到更多的氧气和有机质,从而分泌更多土壤酶加速土壤养分循环^[35]。本研究中,深翻施用有机肥>20—40 cm 土层蔗糖酶和过氧化氢酶活性高于其他处理,由于深翻能为作物根系向深层土壤延伸及根系分泌物释放创造有利条件,进而增强土壤微生物活性,对提高土壤酶活性有积极作用^[36]。施用有机肥能够改变土壤物理和化学特性及微生物群落,可能刺激土壤碳相关酶活性增强^[37]。本研究结果表明,施用有机肥显著提升土壤碳相关酶活性,这与邓婵娟^[38]的研究结果一致,相较于化肥,有机肥为土壤微生物提供了关键碳源,进而提高了土壤碳相关酶活性。此外,有机肥通过增加土壤碳源储备,促进根系分泌物增多,提升了微生物活性,这些均有利于土壤碳相关酶活性的提升^[39]。张欢^[40]进一步证明了施用有机肥能够改变土壤物理和化学特性及微生物群落,从而刺激土壤碳相关酶活性增强。然而,本研究中玉米季>20—40 cm 土层,蔗糖酶活性并未达到未施有机肥的水平,这可能由于有机肥能够在土壤中存在较长时间,从而使土壤中能够耐受有机肥的微生物物种增多,而耐受能力低的敏感物种尤其是与蔗糖酶相关的特定微生物减少,导致蔗糖酶活性降低^[41]。

3.3 耕作方式和有机肥对小麦和玉米产量及土壤碳库管理指数的影响

耕作制度、施肥方式、土壤状况和气候条件等

均影响产量形成^[42]。本研究中深翻施用有机肥小麦玉米产量均显著高于旋耕施用有机肥处理。这是因为深翻打破犁底层,有助于作物根系向深处生长,能从土壤深层获取更多养分,确保生长发育所需的养分供给,显著提高干物质累积量,进而提升作物产量^[43-44]。本研究结果表明,土壤活性碳组分含量与小麦和玉米周年产量有强相关关系,作物产量与土壤易氧有机碳化和颗粒有机碳显著正相关,说明土壤有机碳含量提高,有利于作物产量的增加^[45]。本研究中,施用有机肥处理小麦和玉米产量均显著高于未施用有机肥处理。这是因为施用有机肥后有机质增加,可提供大量活性碳源,有利于微生物生长和代谢,加快土壤有机物质分解,促进养分释放和作物吸收。此外,有机肥还包含多种微量元素^[46],在有机质分解过程中,会生成多种中间产物,这些产物的特定活性基团能与土壤中某些微量元素进行络合或螯合反应,进而提高微量元素的有效性,从而提高作物产量^[41]。土壤碳库管理指数是反映土壤碳素动态变化灵敏而有效的指标,碳库管理指数与有机碳、碳库指数和碳库活度均密切相关,可以反映土壤有机碳含量和质量,并能为农田碳固存提供量化依据^[48]。本研究发现,碳库管理指数与有机碳、碳库指数和碳库活度均显著正相关,即碳库管理指数与有机碳的各处理变化趋势基本一致,且深翻施用有机肥的碳库管理指数显著高于其他处理。这可能是由于深翻和施用有机肥均可有效增加土壤有机碳各组分含量,且能促进团聚体形成,提高土壤微生物活性,进而提高碳库管理指数^[49]。此外,本研究各处理的作物产量与碳库管理指数显著正相关。碳库管理指数增大有利于维持土壤碳库的稳定性及其土壤固碳能力,从而增加土地肥力,在一定程度上反映了作物固碳增产效应^[50]。

4 结 论

深翻结合施用有机肥(DM)显著提高了0—40 cm土层土壤有机碳及活性碳组分(EOC、MBC、POC)含量,增强了过氧化氢酶和蔗糖酶活性,并显著提升了碳库管理指数、小麦和玉米产量及周年产量。深翻配合施用有机肥可激发土壤碳相关酶活性,显著提升碳库活性和稳定性,促进养分转化,有效激发土壤生态功能,实现土壤增碳与作物增产的协同提升,是华北平原麦玉两熟区提高土壤有机碳

和作物产量的较优管理措施,为该区域农业可持续发展提供了有效技术途径。

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第一作者简介: 杨杰, 河北农业大学农学院作物栽培与耕作学专业硕士研究生。本科毕业于新疆农业大学种子科学与工程专业。硕士期间荣获校级英语演讲比赛三等奖、校级学业奖学金三等。



通讯作者简介: 王贵彦, 博士, 河北农业大学农学院教授, 博士生导师。兼任中国农学会耕作制度分会常务理事、河北省农业系统学会副理事长。研究方向为高产高效种植制度。近5年主持国家重点研发项目课题和子课题、河北省重点研发项目等4项。共发表学术论文40余篇。获河北省社会科学成果奖二等奖(2022年)、河北省教学成果奖二等奖(2008年)等荣誉。