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施用有机肥提升不同土壤团聚体有机碳含量的差异性

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摘 要: 基于收集已发表文献数据, 建立具备相同有机碳分组方法(湿筛法)、相对独立的43篇文献的319组成对数据, 利用Meta整合分析法研究不同耕地类型、种植制度及土壤质地条件下施肥对各粒径团聚体(>2, 2~0.25, 0.25~0.053, <0.053 mm)有机碳含量的影响程度。结果表明: 与不施肥相比, 施用有机肥和化肥均显著提升了土壤总有机碳(TSOC)及>2, 2~0.25, 0.25~0.053 mm粒径团聚体有机碳含量, 有机肥对总有机碳的提升幅度(38.0%)是化肥(8.8%)的4.3倍, 而对各级团聚体有机碳的提升幅度(39.7%~72.3%)是化肥(4.3%~15.8%)的4.6~9.2倍($P<0.05$)。对于<0.053 mm团聚体有机碳而言, 施用化肥无影响, 但有机肥能显著提升其有机碳含量。在同一条件不同粒径下, 与不施肥相比, 一年两熟、旱地、砂土及黏土下施用有机肥对2~0.25 mm粒径团聚体有机碳含量的提升幅度显著高于其他粒径。在同一粒径不同条件下, 与不施肥相比, 施用有机肥对不同粒径团聚体有机碳含量的提升幅度($P<0.05$)存在显著差异, 分别为2~0.25 mm: 砂土>壤土、黏土; 旱地>水田、水旱轮作; 0.25~0.053 mm和<0.053 mm: 一年一熟>一年两熟; 旱地>水田、水旱轮作。施用化肥与施用有机肥结果类似, 但差异不显著。施用化肥显著降低了水田中<0.053 mm粒径团聚体有机碳含量, 降低幅度为16.4%。>0.25和<0.25 mm粒径团聚体有机碳含量均与TSOC呈极显著正相关关系, TSOC每增加1.00 g·kg⁻¹时, >0.25 mm粒径团聚体有机碳含量的增加幅度(0.61 g·kg⁻¹)要高于<0.25 mm粒径(0.23 g·kg⁻¹)。可见, 施用有机肥有利于农田土壤团聚体有机碳的累积, 尤其是大团聚体(>0.25 mm), 而不同条件下, 尤其在旱地及质地较轻的砂土中, 对土壤团聚体有机碳含量的累积更应该考虑有机肥的投入。

关键词: 施肥; 团聚体有机碳; 耕地类型; 土壤质地; 整合分析法

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Variation in sequestration of organic carbon associated with differently sized aggregates after organic manure application

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Abstract: A data set on soil organic carbon (SOC) was set up based on 319 pairs of data collected using the same soil organic carbon fractionation method (the wet sieving method) and presented in 43 published papers. We conducted a meta-analysis to quantify the response of different fractions of organic carbon associated with >2, 2~0.25, 0.25~0.053, and <0.053 mm aggregates (Agg-OC) to manure (Org-M) or chemical fertilizer (Min-F) application compared to that without fertilizer (Non-F) application under different cropping system, farmland type, and soil texture conditions. Results showed that SOC in bulk soil and Agg-OC in the >2, 2~0.25, and 0.25~0.053 mm aggregates were

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significantly increased by both Org-M and Min-F compared to by Non-F. As for total SOC (TSOC), compared to Non-F, the improvement rate of Org-M over Non-F (38.0%) was 4.3 times higher than that of Min-F over Non-F (8.8%). As for the Agg-OC in different aggregates, the improvement rate of Org-M over Non-F (39.7%~72.3%) was 4.6~9.2 times higher ($P<0.05$) than that of Min-F over Non-F (4.3%~15.8%), respectively. There was no significant effect of Min-F on the <0.053 mm Agg-OC, whereas the effect of Org-M was significant. As for different size aggregates under the same conditions, compared with Non-F, the increase in applying Org-M on the 2~0.25 mm Agg-OC was significantly higher than those in the >2 , 0.25~0.053, and <0.053 mm aggregates for double-cropping, upland, sandy, and clay conditions. In the same-sized particles under different conditions, compared to Non-F, Agg-OC was significantly increased by Org-M application. The orders of the increment were as follows: sandy > loam, clay, upland > paddy, paddy-upland for 2~0.25 mm; monocropping > double-cropping, upland > paddy, paddy-upland for both 0.25~0.053 and <0.053 mm. The effect of Min-F over Non-F on Agg-OC was similar to that of Org-M application, with no significant difference between them. Moreover, Min-F markedly decreased the <0.053 mm Agg-OC by 16.4% compared to Non-F in paddy. There was significant positive correlation between >0.25 and <0.25 mm Agg-OC and TSOC. An increase of $1.00 \text{ g} \cdot \text{kg}^{-1}$ in TSOC resulted in a $0.61 \text{ g} \cdot \text{kg}^{-1}$ increase in >0.25 mm Agg-OC, which was higher than that of <0.25 mm Agg-OC ($0.23 \text{ g} \cdot \text{kg}^{-1}$). In conclusion, manure application benefits accumulation of soil aggregate-associated organic carbon, especially in >0.25 mm aggregates. Manure application is recommended for soil carbon sequestration in aggregates, especially for upland and light texture soil.

Keywords: fertilizer; aggregate-associated organic carbon; farmland uses; soil texture; meta-analysis

土壤有机碳(SOC)是陆地生态系统中最大的碳库,其含量约为大气的两倍,植被的三倍^[1-3];土壤有机碳的微小变化会对大气中碳的浓度产生重要影响,土壤作为碳汇或碳源,已成为全球气候变化研究的主要关注点^[4-6]。土壤团聚体是土壤结构的重要组成单元,有机碳作为团聚体的主要胶结物质,两者相互影响,且稳定的团聚体对提升SOC固存和土壤抗侵蚀能力起着非常重要的作用^[7-10]。而土壤中不同大小颗粒由于其表面化学性质不同,其结合有机碳量及抗分解能力也存在本质区别,对农业管理措施的响应也存在显著差异^[11-13]。

近30年来,许多学者在长期试验区域研究了不同管理措施对土壤团聚体有机碳含量及其稳定性的影响。国内外众多研究表明,施用有机肥的影响一般首先体现在大团聚体上,施入肥料后其分解残体可以激发微生物活性,形成真菌和糖,土壤颗粒由这些物质胶结形成大团聚体^[14-18]。樊红柱等^[19]研究发现,与不施肥相比,施肥(化肥、有机肥)对 >2 mm团聚体有机碳含量的增加幅度最为显著;邸佳颖等^[20]研究表明,2~0.25 mm粒径有机碳含量对SOC的贡献率最大,同时 >2 和2~0.25 mm粒径有机碳含量均与累积碳投入量呈显著正相关。对于不同土壤而言,与不施肥相比,施肥(有机肥或化肥)对各粒径(>2 、2~0.25、0.25~0.053、 <0.053 mm)团聚体有机碳含量或均显著提升,或均未显著提升,甚至显著降低了各粒径团聚体有机碳含量^[21-24]。说明不同粒径团聚体有机碳含量对施肥的响应程度是不同的。金琳等^[25]研究表明,施

用有机肥能显著提升SOC,且水田土壤有机碳含量显著高于旱地;而蔡岸冬等^[26]利用数据整合分析发现,与不施肥相比,施用有机肥和化肥均能显著提升SOC,且不同土壤质地条件下,施肥(有机肥或化肥)对SOC及矿物结合态组分(MOC: <0.053 mm)含量的提升幅度均存在显著差异。

团聚体作为土壤结构的重要组成部分,是形成良好土壤结构的物质基础。明确不同条件下施肥对不同粒径团聚体有机碳含量的提升效果之间的差异性,对提升土壤有机碳及土壤结构稳定性非常重要。到目前为止,团聚体有机碳含量变化研究多数集中在单个试验点位,而大尺度多个试验点位的综合研究相对较少。因此,本研究通过系统搜集我国长期施肥试验下的团聚体有机碳含量变化的研究文献,采用Meta分析方法,定量估算施肥对不同粒径团聚体有机碳含量的提升幅度,分析探讨不同条件下提升幅度之间的差异性,为合理培肥土壤、改善土壤结构提供科学依据。

1 研究方法

1.1 数据收集及数据库建立

本研究数据来自中国知网、百度学术、ScienceDirect 和 Springer Link 这4个文献数据库,通过设置检索“中国农田”、“水稳性团聚体”、“长期施肥”、“有机碳”这4个关键词,文献筛选条件:(1)试验中必须包含对照(如:不施肥)和处理(如:化肥、有机肥和/或秸秆还田等),其他试验条件均与对照和处理一致;(2)采样层次范围为0~30 cm;(3)团聚体分组方法为湿

筛法;(4)若同一试验点位有多年数据,只取最新一年数据;采用Excel 2007软件建立不同条件下长期施肥与团聚体有机碳含量关系的数据库,内容包括:作者、题目、试验地基本情况及初始理化性质、施肥处理、种植制度、土壤质地、土地耕地类型及不同施肥条件下的土壤有机碳及各粒径团聚体有机碳含量等。所有数据均来自文献中的正文、图和表,而图中数据采用GetData Graph Digitizer 2.24提取。土壤有机质(SOM)乘以有机碳转换系数0.58转化为土壤有机碳(SOC)。每组数据均包含平均值(M)、标准差(SD)及样本数(n),若文献中是标准误(SE),则 SD 如下式进行换算:

$$SD=SE\sqrt{n}$$

(1)

若收集的数据中, SD 缺失,则使用整个数据库的变异系数来换算^[27]。

根据以上条件共获得43篇有效文献,319组有效数据(表1)。其中,种植制度分布结果与蔡岸冬等^[26]结果基本一致,另外,不施肥(对照)时TSOC和各粒径团聚体有机碳含量在砂土中平均范围分别为2.8~11.2 g·kg⁻¹和1.7~3.1 g·kg⁻¹,在壤土中平均范围分别为4.1~28.3 g·kg⁻¹和3.0~3.4 g·kg⁻¹,在黏土中平均范围分别为5.4~28.8 g·kg⁻¹和1.3~4.3 g·kg⁻¹。

1.2 数据分析

本文收集的数据均是相互独立的多个研究结果,因此,可利用MetaWin 2.1软件进行数据整合分析。试验中有机碳含量采用自然对数的响应比(Response ratios, RR)作为效应值,则有机碳含量的增加效应^[28]:

$$\ln RR=\ln(SOC_T/SOC_{CK})=\ln SOC_T-\ln SOC_{CK}$$

(2)

式中, SOC_T 和 SOC_{CK} 分别代表处理组和对照组的平均值。

效应值的变异系数可利用处理组和对照组的标准偏差及试验重复数计算,其权重可利用变异系数的倒数表示^[30]。用MetaWin 2.1软件对权重响应比

(Weighted response ratio, RR_{++})(处理相对于对照增减的百分数)以及其95%的置信区间(95% CI)进行计算^[30~31];数据处理时,纳入的各研究结果须要进行异质性检验,若 $P\geq 0.1$ 、 $I^2<50\%$,表明多个研究结果无异质性,则采用固定效应模型(Fixed effect model, FEM)进行分析,若 $P<0.1$ 、 $I^2\geq 50\%$,表明多个研究结果有异质性,则采用随机效应模型(Random effect model, REM)。效应值的标准差越小,分配的权重就越大。若95% CI 包含零值,表明该变量中处理与对照差异不显著($P>0.05$)^[32]。

本研究采用SPSS 17进行数据分析、Excel 2007和SigmaPlot 10.0软件进行绘图。

2 结果

2.1 土壤有机碳对有机肥和化肥的响应

与不施肥处理相比,施用有机肥的响应比($\ln RR$)远高于施用化肥(图1)。与不施肥相比,施用有机肥显著提升了TSOC及各粒径(>2、2~0.25、0.25~0.053、<0.053 mm)团聚体有机碳含量,其均值分别为0.322 1±0.017 6(均值±95% CI ,下同)、0.387 0±0.054 1、0.567 9±0.039 7、0.341 0±0.028 6、0.146 6±0.034 6(图1a、图1c、图1e、图1g、图1i),分别提升了38%、45.6%、72.3%、39.7%、15.9%(图2);同时,施用化肥显著提升了TSOC及>2、2~0.25、0.25~0.053 mm有机碳含量,其均值分别为0.089 9±0.010 2、0.050 3±0.047 0、0.164 1±0.024 3、0.044 4±0.024 5(图1b、图1d、图1f、图1h),分别提升了8.8%、8.9%、15.8%、4.3%(图2),施用化肥并没有显著提升<0.053 mm有机碳含量(0.030 6±0.032 4,图1j)。其中,施用有机肥和化肥对2~0.25 mm粒径团聚体有机碳含量的提升效果均最为显著(图1)。

2.2 有机碳含量 Meta-analysis 结果

2.2.1 施肥对TSOC及团聚体有机碳含量的影响

整体而言,与不施肥相比,施用有机肥及化肥均

表1 施肥对土壤总有机碳及水稳性团聚体组分数据库样本数分布
Table 1 Sample numbers for the meta-analysis on the effect of fertilization practices on TSOC and water-stable-aggregate fraction

区域 Area	种植制度 Cropping system		土壤耕地类型 Farmland types			土壤质地 Soil texture		
	一年一熟	一年两熟	水田 Paddy	旱地 Upland	水旱轮作 Paddy-upland rotation	砂土 Sandy	壤土 Loam	黏土 Clay
	Mono-cropping	Double-cropping						
西北 northwest China	48	74	—	122	—	30	29	63
东北 northeast China	57	—	—	57	—	—	22	35
华北 north China	—	12	—	12	—	—	12	—
南方 south China	6	122	64	25	39	—	97	31

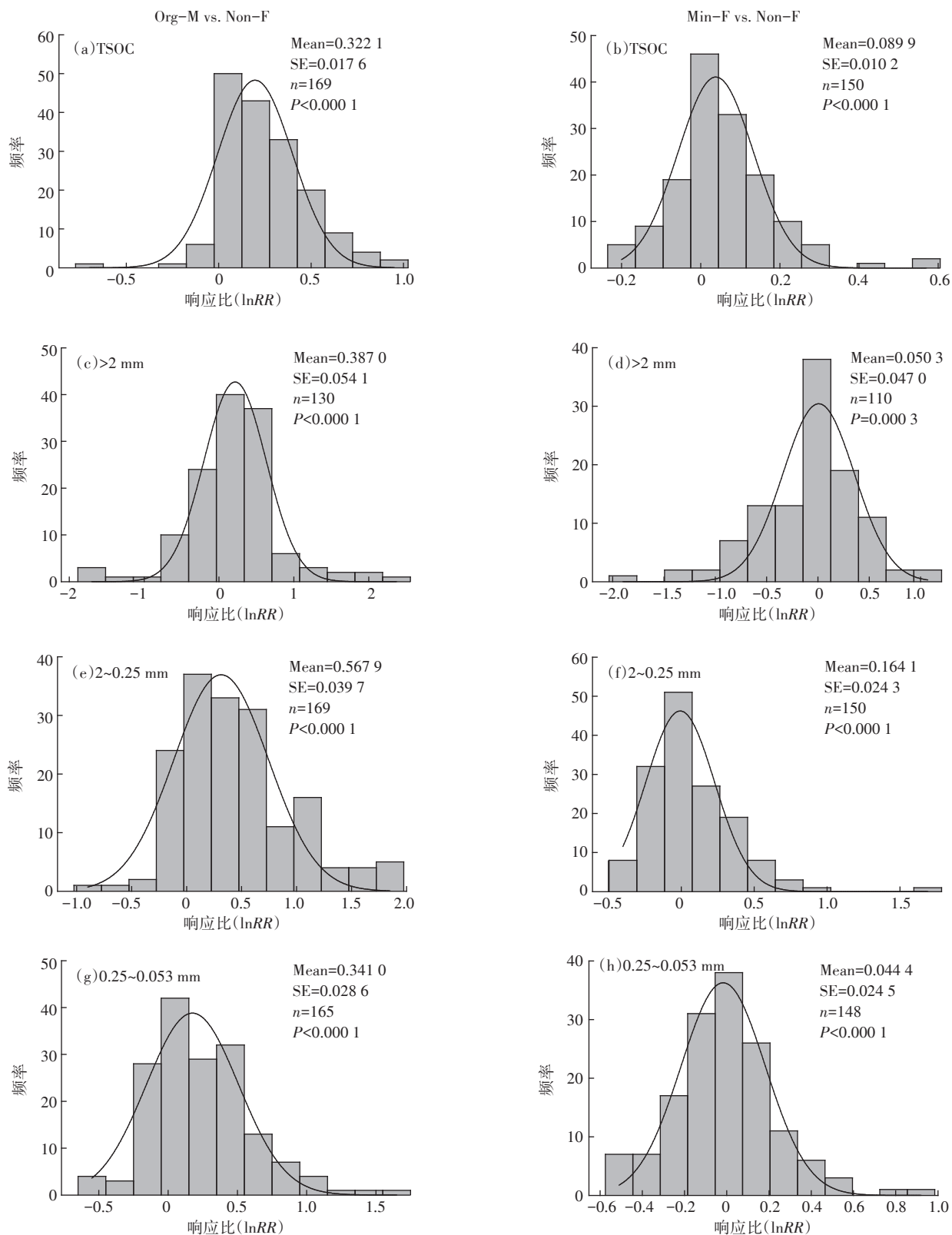
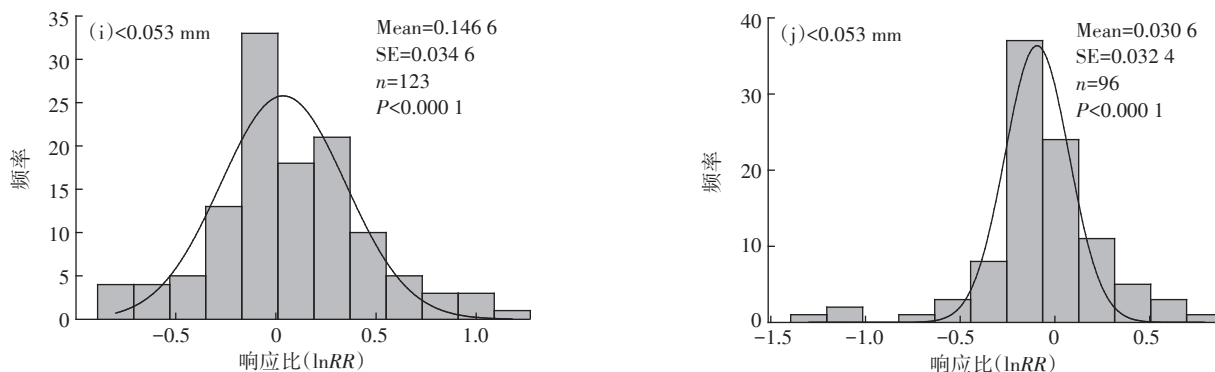


图1 相对于不施肥,施用有机肥和化肥总有机碳(a,b)、 >2 (c,d)、 $2\sim 0.25$ (e,f)、 $0.25\sim 0.053$ (g,h)、 <0.053 mm(i,j) 有机碳含量响应比($\ln RR$)的频率分布(实曲线是与频率数据相适应的高斯分布)

Figure 1 Frequency distributions of response ratios ($\ln RR$) for TSOC(a,b), >2 (c,d), $2\sim 0.25$ (e,f), $0.25\sim 0.053$ (g,h), <0.053 mm(i,j) responses to Org-M and Min-F in comparison with the control group Non-F, respectively (The solid curve is a Gaussian distribution fitted to frequency data)



续图1 相对于不施肥,施用有机肥和化肥总有机碳(a,b)、 >2 (c,d)、 $2\sim0.25$ (e,f)、 $0.25\sim0.053$ (g,h)、 <0.053 mm(i,j) 有机碳含量响应比(lnRR)的频率分布(实曲线是与频率数据相适应的高斯分布)

Continued figure 1 Frequency distributions of response ratios (lnRR) for TSOC(a,b), >2 (c,d), $2\sim0.25$ (e,f), $0.25\sim0.053$ (g,h), <0.053 mm(i,j) responses to Org-M and Min-F in comparison with the control group Non-F, respectively (The solid curve is a Gaussian distribution fitted to frequency data)

能显著提升TSOC含量($P<0.05$),且有机肥的提升幅度(38.0%)显著高于化肥(8.8%),是施用化肥的4.3倍(图2)。在不同种植制度、耕地类型和土壤质地条件下,除施用化肥没有显著提升水旱轮作中TSOC含量外,施用有机肥和化肥均能显著提升TSOC含量(图2)。而与不施肥相比,施用有机肥及化肥均显著提升了 >2 (45.6%和8.9%)、 $2\sim0.25$ (72.3%和15.8%)、 $0.25\sim0.053$ mm(39.7%和4.3%)团聚体有机碳含量,提升幅度上有机肥处理分别是化肥处理的5.1、4.6和9.2倍(图2),对 <0.053 mm团聚体虽然化肥没有显著提升,但有机肥提升作用达到显著(图2)。

2.2.2 不同种植制度下土壤团聚体有机碳含量之间的差异

不同种植制度下,不同施肥对各粒径团聚体有机碳含量的影响存在显著差异。同一种种植制度不同粒径之间,与不施肥相比,一年一熟下,施用有机肥各粒径团聚体有机碳含量均有显著提升;施用化肥 <0.053 mm粒径团聚体有机碳含量虽然没有显著提升,但其他粒径均显著提升;一年两熟下,施用有机肥显著提升了 $2\sim0.25$ mm粒径团聚体有机碳含量(71.2%),且显著高于其他粒径;施用化肥仅显著提升了 >2 和 $2\sim0.25$ mm粒径团聚体有机碳含量(分别为6.8%和13.6%)(表2、图2)。在同一粒径不同种植制度下,与不施肥相比,施用有机肥对一年一熟下 $0.25\sim0.053$ 和 <0.053 mm粒径团聚体有机碳含量的提升幅度均显著高于一年两熟(表2)。

2.2.3 不同耕地类型下土壤团聚体有机碳含量之间的差异

不同的水热条件对团聚体有机碳含量的影响也存在显著差异。同一耕地类型不同粒径下,与不施肥相比,水田和水旱轮作下,施用有机肥和化肥均显著提升了 >2 mm粒径团聚体有机碳含量,其提升幅度分别为53.0%、17.8%(水田)和84.0%、25.6%(水旱轮作),且有机肥的提升效果尤为显著;水田条件下,施用化肥 <0.053 mm粒径团聚体有机碳含量却降低了16.4%;而旱地条件下,施用有机肥和化肥对 $2\sim0.25$ mm粒径团聚体有机碳含量的提升幅度(100.0%和23.6%)均显著高于其他粒径(图2)。同一粒径不同耕地类型下,与不施肥相比,施用有机肥对 $2\sim0.25$ 、 $0.25\sim0.053$ 、 <0.053 mm粒径团聚体有机碳含量的提升幅度为:旱地显著高于水田和水旱轮作,施用化肥也具有相同趋势,但差异并不显著(表2)。

2.2.4 不同土壤质地下土壤团聚体有机碳含量之间的差异

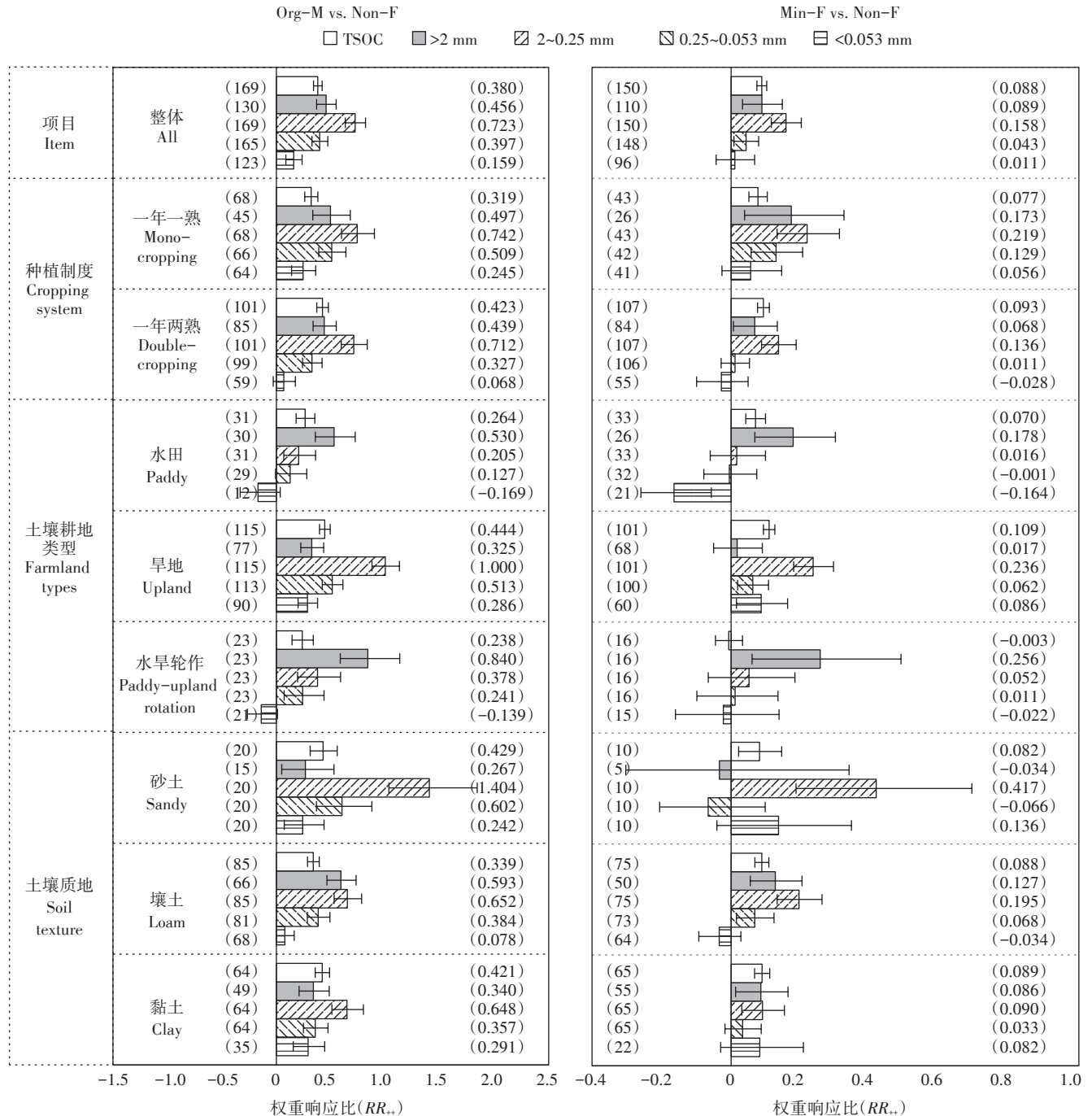
在同一土壤质地不同粒径下,砂土中,施用有机肥相对于CK处理显著提升了各粒径团聚体有机碳含量,且 $2\sim0.25$ mm粒径团聚体有机碳含量的提升幅度显著高于其他粒径,施用化肥仅显著提升了 $2\sim0.25$ mm粒径团聚体有机碳含量;壤土中,施用有机肥和化肥相对于CK处理仅 <0.053 mm粒径有机碳含量没有显著提升;黏土中,施用有机肥相对于CK处理各粒径团聚体有机碳含量均有显著提升,其中 $2\sim0.25$ mm粒径团聚体有机碳含量的提升幅度(64.8%)最为显著,施用化肥仅显著提升了 >2 、 $2\sim0.25$ mm粒径团聚体有机碳含量(图2);同一粒径不同土壤质地下,与不施肥相比,施用有机肥对壤土中 >2 mm粒径有机碳含量

的提升幅度(59.3%)显著高于砂土(26.7%)和黏土(34.0%),施用有机肥对砂土中2~0.25 mm粒径有机碳含量的提升幅度(140.4%)显著高于壤土(65.2%)和黏土(64.8%),施用化肥也具有相同趋势,但差异

并不显著(表2)。

2.2.5 >0.25 和<0.25 mm 粒径有机碳含量与TSOC的相互关系

由图3可知,>0.25 和<0.25 mm 粒径有机碳含量



x轴正轴括号内数据为权重响应比,负轴为样本数,误差线代表95%的置信区间,如果误差线没有跨越零轴表示处理与对照之间差异性显著, $P<0.05$ Numbers near the bars at the positive side of x axis are the RR_w and the numbers at the negative side of x axis are the numbers of comparisons. Error bars denote 95% CI. $P<0.05$, when error bars do not overlap zero

图2 不同种植制度、耕地类型和土壤质地下施用有机肥(左)和化肥(右)对各粒径团聚体有机碳的权重响应比(RR_w)

Figure 2 Different particle size aggregate-associated organic carbon affected by Org-M(left panel) and Min-F(right panel) compared to Non-F in different cropping systems and soil texture

表2 不同种植制度、耕地类型和土壤质地下同一施肥方式对土壤水稳性团聚体有机碳含量提升幅度(%)的差异性比较

Table 2 Difference of the similar fertilization practices in the increments(%) of water-stable-aggregate organic carbon in different cropping systems and soil textures

项目 Item		施肥\粒径	>2 mm	2~0.25 mm	0.25~0.053 mm	<0.053 mm
种植制度 Cropping systems	一年一熟 Mono-cropping	有机肥 Org-M	49.7aA	74.2aA	50.9aA	24.5bA
	一年两熟 Double-cropping		43.9bA	71.1aA	32.7bB	6.8cB
耕地类型 Farmland types	水田 Paddy		53.0aB	20.5bC	12.7bB	-16.9cB
	旱地 Upland		32.5cB	100.0aA	51.3bA	28.6cA
	水旱轮作 Paddy-upland rotation		84.0aA	37.8bB	24.1bB	-13.9cB
土壤质地 Soil texture	砂土 Sandy		26.7bB	140.4aA	60.2bA	24.2bA
	壤土 Loam		59.3aA	65.2aB	38.4bA	7.8cB
	黏土 Clay		34.0bB	64.8aB	35.7bA	29.1bA
种植制度 Cropping systems	一年一熟 Mono-cropping	化肥 Min-F	17.3abA	21.9aA	12.9abA	5.6bA
	一年两熟 Double-cropping		6.8abA	13.6aA	1.1bB	-2.8bA
耕地类型 Farmland types	水田 Paddy		17.8aA	1.6bB	-0.1bcA	-16.4cB
	旱地 Upland		1.7bA	23.6aA	6.2bA	8.6bA
	水旱轮作 Paddy-upland rotation		25.6aA	5.2aB	1.1aA	-2.2aA
土壤质地 Soil texture	砂土 Sandy		-3.4abA	41.7aA	-6.6bA	13.6aA
	壤土 Loam		12.7abA	19.5aA	6.8bA	-3.4cA
	黏土 Clay		8.6aA	9.0aB	3.3aA	8.2aA

注:不同小写字母表示同一条件不同粒径之间同一施肥下对土壤水稳性团聚体有机碳含量提升幅度(%)在5%水平上差异显著,不同大写字母表示同一粒径不同条件同一施肥下对土壤水稳性团聚体有机碳含量提升幅度(%)在5%水平上差异显著

Note: Different lowercase letters are significantly different on the similar fertilization practices on the increments(%) of water-stable-aggregate organic carbon in different particles under the same condition at the 5% level. Different capital letters are significantly different on the similar fertilization practices on the increments(%) of water-stable-aggregate organic carbon in the same particles under the different condition at the 5% level

均与TSOC呈极显著正相关关系,线性拟合的斜率分别为0.61和0.23,表明当有机碳含量每增加1.00 g·kg⁻¹时,>0.25和<0.25 mm粒径有机碳含量分别增加0.61 g·kg⁻¹和0.23 g·kg⁻¹。

3 讨论

土壤有机碳的动态变化主要取决于系统碳的输入与输出水平^[33],而农田土壤有机碳的输入主要来源是根分泌物、根茬、秸秆和有机肥等^[34]。整合分析结果表明,与不施肥相比,施用有机肥及化肥均能显著提升TSOC、>2、2~0.25、0.25~0.053 mm粒径团聚体有机碳含量,且提升幅度上有机肥显著高于化肥。在不施肥条件下,根分泌物与根茬是碳输入土壤的主要途径^[35]。由于根际分泌物的激发作用促进原有土壤有机碳的分解,其分解可能会抵消分泌物对土壤碳的输入,因此,根茬是导致土壤有机碳含量变化的主要碳源因素^[36]。与不施肥相比,施用化肥在增加了作物产量的同时,还增加了作物残茬量,同时促进根的周转和根分泌物的增多,从而增加土壤有机碳的输入

量^[26,37]。而施用有机肥不仅可向土壤直接输入有机碳,且能够改善土壤营养环境状况,增强土壤酶的活力和提升土壤生物多样性,进而极大程度地提升土壤有机碳的含量^[34,38-40]。>0.25和<0.25 mm粒径有机碳含量均与TSOC呈极显著正相关关系,当TSOC含量每增加1.00 g·kg⁻¹时,>0.25和<0.25 mm粒径有机碳含量分别增加0.61 g·kg⁻¹和0.23 g·kg⁻¹,施肥对>0.25 mm粒径团聚体有机碳含量的提升幅度要高于<0.25 mm粒径。说明>0.25 mm粒径团聚体对施肥管理措施最为敏感,且是农业管理措施下有机碳变化的良好指标。这说明了通过有机培肥措施,可以显著提高土壤有机碳含量,使土壤营养状况得到改善,同时随着有机碳的提高,土壤团聚颗粒含量也有了提升,土壤物理性质得到改善,能提高土壤对作物养分供给能力、增加作物产量^[41-42],是农业生产可持续发展的有效施肥模式。

3.1 种植制度对团聚体有机碳含量的影响

研究表明,同一种种植制度不同粒径之间,与不施肥相比,一年两熟下,施用有机肥有利于提升>0.25

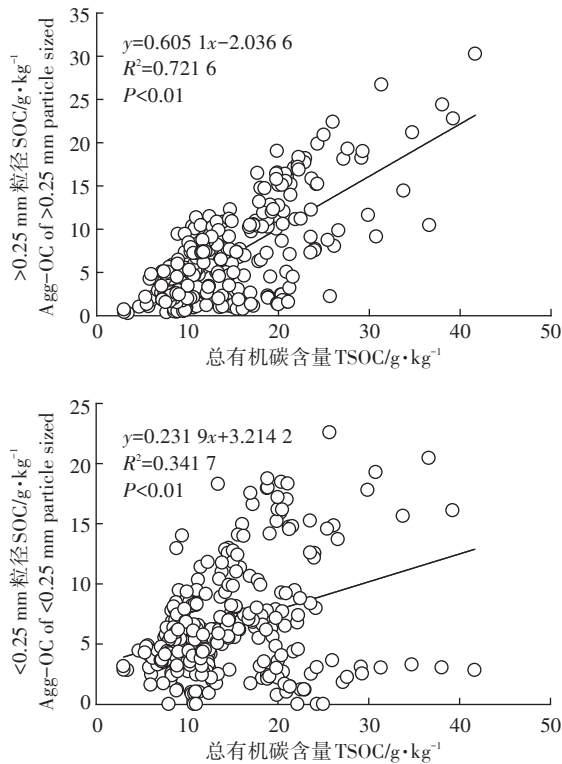


图3 土壤总有机碳含量与>0.25和<0.25 mm粒径团聚体有机碳含量的关系

Figure 3 The relationship of TSOC with >0.25 and <0.25 mm aggregate-associated organic carbon (Agg-OC)

mm 粒径有机碳含量,而<0.053 mm 粒径有机碳含量并未显著提升。其原因可能是施肥对土壤团聚体有机碳的影响往往作用于大团聚体,而对微团聚体的影响较小,且施用有机肥碳投入量往往显著大于当季根茬投入量,外源碳输入对土壤有机碳的增加量可能以颗粒有机碳为主^[39]。微团聚体中的有机碳由于物理保护作用却维持在较稳定的水平^[43-45],因此,施用有机肥对大团聚体的提升效果显著高于微团聚体。

同一粒径不同种植制度下,与不施肥相比,施用有机肥对一年一熟下 0.25~0.053 和<0.053 mm 粒径有机碳含量的提升幅度均显著高于一年两熟(表2)。其原因可能是人为扰动对土壤团聚体造成破裂和分散,导致土壤有机碳物理保护作用破坏,使微团聚体中的有机碳暴露于微生物的分解之下,还可能导致土壤的呼吸作用加强,从而增加微团聚体中有机碳的矿化^[46-47]。

3.2 耕地类型对团聚体有机碳含量的影响

同一耕地类型不同粒径下,与不施肥相比,水田条件下,施用化肥<0.053 mm 粒径团聚体有机碳含量降低了16.4%,其原因可能是施用化肥外源碳的投入

量较低,且施用化肥(尤其是单施N肥)会导致土壤酸化,加速土壤团聚体的周转速率,引起土壤有机碳的矿化分解和损失^[48-49]。而旱地条件下,施用有机肥和化肥均显著提升了2~0.25 mm 粒径团聚体有机碳含量,且显著高于其他粒径(图2)。众多研究表明,有机碳积累伴随着粗团聚体(>0.25 mm)的形成和增多,细团聚体(<0.25 mm)相应减少,新积累的碳主要储存于>0.25 mm 团聚体中^[50-51],尤其是活性颗粒有机碳主要存在于较大的团聚体中^[52-53]。

同一粒径不同耕地类型下,与不施肥相比,施用有机肥对2~0.25、0.25~0.053、<0.053 mm 粒径团聚体有机碳含量的提升幅度为旱地显著高于水田和水旱轮作。大量研究表明,在干旱的条件下,土壤有机碳矿化速率都比较低,干湿交替能促进土壤有机碳的分解^[54-56],水田和水旱轮作耕地类型属于好氧与厌氧交替的环境^[57],且主要分布在南方地区(表1),其积温高于旱地,同时高温易于加速有机碳的周转。

3.3 土壤质地对团聚体有机碳含量的影响

同一土壤质地不同粒径下,与不施肥相比,砂土中,施用有机肥显著提升了各粒径团聚体有机碳含量,且2~0.25 mm 粒径团聚体有机碳含量的提升幅度显著高于其他粒径,施用化肥趋势相近,但并不显著,其原因可能是有机肥的化学组成较易与砂粒有机碳结合,较易存在于砂粒之间的孔隙中,因此投入后直接增大了砂土中砂粒结合有机碳的含量,而砂土主要分布在西北地区(表1),气候干旱,早晚温差较大,作物根茬分解极为缓慢,腐熟程度很低,因此施用化肥对增加砂粒结合有机碳含量贡献较小^[8]。壤土中,施用有机肥和化肥仅<0.053 mm 粒径团聚体有机碳含量没有显著提升。Kool 等^[58]和 Gulde 等^[59]发现不同碳库可能存在着饱和等级现象,即团聚体粒径越小,固碳潜力越低,会优先达到碳饱和,新进入的有机碳主要先积累于大团聚体中,而壤土本身有机碳含量相对较高,<0.053 mm 粒径团聚体有机碳含量可能已经接近饱和,因此施肥效果不显著。土壤矿质结合态有机碳(MOC)是指粉粒和黏粒通过配位体交换、氢键及疏水键等作用吸附有机碳,属于惰性有机碳库;土壤中矿物颗粒对有机碳的吸附作用被认为是土壤固持有机碳的重要机制之一^[60]。因此,<0.053 mm 团聚体可作为土壤固碳水平的可靠指标。今后需要进一步从有机碳组分水平探讨长期施肥下土壤养分转化及固碳潜力差异机制,从而揭示有机肥及化肥对提升土壤肥力的作用。

同一粒径不同土壤质地下,施用有机肥对砂土中2~0.25 mm粒径有机碳含量的提升幅度(140.4%)显著高于壤土(65.2%)和黏土(64.8%)。对于不同土壤而言,自身有机碳含量越低,则越有利于外源碳的输入,即碳素的固定^[61],其原因可能是砂土透气透水性好,根系生长范围大、活力高,各种微生物活性高,从而有利于地下生物量的提高^[62]。朱毅等^[63]认为砂土结构松散,地下生物量能够直接影响POC含量。而孙中林等^[64]研究表明砂壤土的固碳能力要高于黏壤土。同时,不施肥时2~0.25 mm团聚体有机碳含量壤土($3.4 \text{ g} \cdot \text{kg}^{-1}$)和黏土($3.3 \text{ g} \cdot \text{kg}^{-1}$)约为砂土($1.9 \text{ g} \cdot \text{kg}^{-1}$)的1.8倍(表1),因此,施肥(尤其是施用有机肥)更有利于砂土中有机碳的累积。施用化肥与施用有机肥具有类似趋势,但差异并不显著(表2)。

4 结论

通过利用Meta-analysis综合分析不同条件下施肥对土壤团聚体有机碳含量的影响,发现有机肥的施用对各粒级团聚体有机碳含量的提高幅度显著高于化肥,而在不同管理措施、质地等条件下,有机肥的提升幅度存在显著差异。

(1)在同一条件不同粒径下,与不施肥相比,一年两熟、旱地、砂土及黏土下施用有机肥对2~0.25 mm粒径团聚体有机碳含量的提升幅度显著高于其他粒径。

(2)在同一粒径不同条件下,与不施肥相比,施用有机肥对不同粒径团聚体有机碳含量的提升幅度($P < 0.05$)存在显著差异,分别为:2~0.25 mm,砂土>壤土、黏土,旱地>水田、水旱轮作,0.25~0.053 mm和<0.053 mm,一年一熟>一年两熟,旱地>水田、水旱轮作。

(3)>0.25和<0.25 mm粒径有机碳含量均与TSOC呈极显著正相关关系,经相关分析推测,当有机碳含量每增加 $1.00 \text{ g} \cdot \text{kg}^{-1}$ 时,>0.25 mm和<0.25 mm粒径有机碳含量分别增加 $0.61 \text{ g} \cdot \text{kg}^{-1}$ 和 $0.23 \text{ g} \cdot \text{kg}^{-1}$ 。

本研究未探讨不同理化性质、气候等因素对团聚体有机碳含量的影响,需进一步探讨不同pH、初始SOC、全氮、气候等因素对团聚体有机碳含量的综合影响,同时综合分析不同团聚体质量比与其有机碳含量之间的关系等。

参考文献:

[1] Batjes N H. Total carbon and nitrogen in the soils of the world[J]. *European Journal of Soil Science*, 1996, 47: 151–163.
[2] Lal R. Soil carbon sequestration to mitigate climate change[J]. *Geoderma*, 2004, 123: 1–22.

[3] Zhang C, Liu G, Xue S, et al. Soil organic carbon and total nitrogen storage as affected by land use in a small watershed of the Loess Plateau, China[J]. *Eur J Soil Biol*, 2013, 54: 16–24.
[4] Johnston C A, Groffman P, Breshears D D, et al. Carbon cycling in soil[J]. *Frontiers in Ecology and the Environment*, 2004, 2: 522–528.
[5] Degryze S, Six J, Paustian K, et al. Soil organic carbon pool changes following land-use conversions[J]. *Global Change Biol*, 2004, 10: 1120–1132.
[6] Laganèrre J, Angers D A, Paré D. Carbon accumulation in agricultural soils after afforestation: A meta-analysis[J]. *Global Change Biol*, 2010, 16: 439–453.
[7] San Jose Martinez F, Munoz Ortega F J, Caniego Monreal F J, et al. Soil aggregate geometry: Measurements and morphology[J]. *Geoderma*, 2015, 237–238: 36–48.
[8] 蒋劭博. 长期施肥对灰漠土团聚体形成及有机碳固存影响机制研究[D]. 乌鲁木齐: 新疆农业大学, 2016.
JIANG Mai-bo. Study on aggregate formation and its carbon sequestration driving mechanisms for grey desert soil under long-term fertilization[D]. Urumchi: Xinjiang Agricultural University, 2016.
[9] Li C L, Xu J B, He Y Q, et al. Dynamic relationship between biologically active soil organic carbon and aggregate stability in long-term organically fertilized soils[J]. *Pedosphere*, 2012, 22(5): 616–622.
[10] Das B, Chakraborty D, Singh V K, et al. Effect of integrated nutrient management practice on soil aggregate properties, its stability and aggregate-associated carbon content in an intensive rice-wheat system[J]. *Soil Tillage Research*, 2014, 136: 9–18.
[11] Schulten H R, Leinweber P. Influence of long-term fertilization with farmyard manure on soil organic matter: Characteristics of particle-size fractions[J]. *Biology and Fertility of Soils*, 1991, 12: 81–88.
[12] Chan K Y, Heenan D P, Oates A. Soil carbon fractions and relationship to soil quality under different tillage and stubble management[J]. *Soil and Tillage Research*, 2002, 63: 133–139.
[13] Christensen B. Physical fractionation of soil and structural and functional complexity in organic matter turn-over[J]. *European Journal of Soil Science*, 2001, 52: 345–353.
[14] Kushwaha C P, Tripathi S K, Singh K P. Soil organic matter and water-stable aggregates under different tillage and residue conditions in an tropical dry land agroecosystem[J]. *Applied Soil Ecology*, 2001, 16: 229–241.
[15] Post W M, Kwon K C. Soil carbon sequestration and land use change: Processes and potential[J]. *Global Change Biol*, 2000, 6: 317–327.
[16] Whalen J K, Hu Q C, Liu A G. Compost applications increase water-stable aggregates in conventional and no-tillage systems[J]. *Soil Sci Soc Am J*, 2003, 63: 1842–1847.
[17] Guggenberger G S, Frey D, Six J, et al. Bacterial and fungal cell-wall residues in conventional and no-tillage agroecosystems[J]. *Soil Sci Soc Am J*, 1999, 63: 1188–1198.
[18] Mikha M M, Rice C W. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen[J]. *Soil Sci Soc Am J*, 2004, 68: 809–816.

- [19] 樊红柱, 秦鱼生, 陈庆瑞, 等. 长期施肥紫色水稻土团聚体稳定性及其固碳特征[J]. 植物营养与肥科学报, 2015, 21(6): 1473-1480.
FAN Hong-zhu, QIN Yu-sheng, CHEN Qing-rui, et al. Distribution and stability of soil aggregates and carbon sequestration in purple paddy soil under long-term fertilization[J]. *Journal of Plant Nutrition and Fertilizer*, 2015, 21(6): 1473-1480.
- [20] 邸佳颖, 刘小粉, 杜章留, 等. 长期施肥对红壤性水稻土团聚体稳定性及固碳特征的影响[J]. 中国生态农业学报, 2014, 22(10): 1129-1138.
DI Jia-ying, LIU Xiao-fen, DU Zhang-liu, et al. Influences of long-term organic and chemical fertilization on soil aggregation and associated organic carbon fractions in a red paddy soil[J]. *Chinese Journal of Eco-Agriculture*, 2014, 22(10): 1129-1138.
- [21] 鲁艳红. 长期施肥条件下红壤性水稻土有机质特征及其与土壤质量的关系[D]. 长沙: 湖南农业大学, 2011.
LU Yan-hong. Studies on characteristics of soil organic matter and its relate to soil quality in reddish paddy soil under long-term fertilization [D]. Changsha: Hunan Agricultural University, 2011.
- [22] 张久明, 迟凤琴, 韩锦泽, 等. 长期不同施肥黑土团聚体有机碳分布特征[J]. 土壤与作物, 2017, 6(1): 49-54.
ZHANG Jiu-ming, CHI Feng-qin, HAN Jin-ze, et al. SOC distribution characteristics of mollisols aggregates in different long-term fertilization systems[J]. *Soils and Crops*, 2017, 6(1): 49-54.
- [23] 曾希柏, 柴彦君, 俄胜哲, 等. 长期施肥对灌漠土团聚体及其稳定性的影响[J]. 土壤通报, 2014, 45(4): 783-788.
ZENG Xi-bo, CHAI Yan-jun, E Sheng-zhe, et al. Effects of long-term fertilization on soil aggregate and its stability in irrigated desert soil of China[J]. *Chinese Journal of Soil Science*, 2014, 45(4): 783-788.
- [24] 李昌新. 长期施肥对红壤旱地玉米生产力和土壤肥力的影响及其机制研究[D]. 南京: 南京农业大学, 2009.
LI Chang-xin. Effects of long-term fertilization on corn productivity and soil fertility as well as its mechanisms under upland red soil in subtropical China[D]. Nanjing: Nanjing Agricultural University, 2009.
- [25] 金琳. 农田管理对土壤碳储量的影响及模拟研究[D]. 北京: 中国农业科学院, 2008.
JIN Lin. Effect of cropland management on soil carbon stock and modeling study[D]. Beijing: Chinese Academy of Agricultural Sciences, 2008.
- [26] 蔡岸冬, 张文菊, 杨品品, 等. 基于 Meta-Analysis 研究施肥对中国农田土壤有机碳及其组分的影响[J]. 中国农业科学, 2015, 48(15): 2995-3004.
CAI An-dong, ZHANG Wen-ju, YANG Pin-pin, et al. Effect degree of fertilization practices on soil organic carbon and fraction of croplands in China-Based on meta-analysis[J]. *Scientia Agricultura Scini-ca*, 2015, 48(15): 2995-3004.
- [27] Geisseler D, Scow K M. Long-term effects of mineral fertilizers on soil microorganisms: A review[J]. *Soil Biology and Biochemistry*, 2014, 75: 54-63.
- [28] Hedges L V, Gurevitch J, Curtis P S. The meta-analysis of response ratios in experimental ecology[J]. *Ecology*, 1999, 80(4): 1150-1156.
- [29] Adams D C, Gurevitch J, Rosenberg M S. Resampling tests for Meta-analysis of ecological data[J]. *Ecology*, 1997, 78(4): 1277-1283.
- [30] Curtis P S, Wang X. A meta-analysis of elevated CO₂ effects on woody plant mass, form, and physiology[J]. *Oecologia*, 1998, 113(3): 299-313.
- [31] Luo Y, Hui D, Zhang D. Elevated CO₂ stimulates net accumulations of carbon and nitrogen in land ecosystems: A meta-analysis[J]. *Ecology*, 2006, 87(1): 53-63.
- [32] Niu L A, Hao J M, Zhang B Z, et al. Influences of long-term fertilizer and tillage management on soil fertility of the north China Plain[J]. *Pedosphere*, 2011, 21(6): 813-820.
- [33] 解丽娟. 长期施肥下我国典型农田土壤有机碳与全氮分布特征[D]. 北京: 中国农业科学院, 2011.
XIE Li-juan. Distribution characteristics of soil organic carbon and total nitrogen under long-term fertilization in typical arable land soil of China[D]. Beijing: Chinese Academy of Agricultural Sciences, 2011.
- [34] 蔡岸冬, 张文菊, 申小冉, 等. 长期施肥土壤不同粒径颗粒的固碳效率[J]. 植物营养与肥科学报, 2015, 21(6): 1431-1438.
CAI An-dong, ZHANG Wen-ju, SHEN Xiao-ran, et al. Soil carbon sequestration efficiency of different particle-size fractions after long-term fertilization[J]. *Journal of Plant Nutrition and Fertilizer*, 2015, 21(6): 1431-1438.
- [35] Dijkstra F A, Cheng W X. Interactions between soil and tree roots accelerate long-term soil carbon decomposition[J]. *Ecology Letters*, 2007, 10(11): 1046-1053.
- [36] Luo Y Q, Weng E S, Yang Y H. Ecosystem ecology[M]//Hastings A, Gross L. Sourcebook in theoretical ecology. California: The University of California Press, 2011: 219-229.
- [37] 何亚婷. 长期施肥下我国农田土壤有机碳组分和结构特征[D]. 北京: 中国农业科学院, 2015.
HE Ya-ting. Characteristics of soil organic carbon fraction and chemical composition under long-term fertilization in upland soil of China [D]. Beijing: Chinese Academy of Agricultural Sciences, 2015.
- [38] Banger K, Kukal S S, Toor G, et al. Impact of long-term additions of chemical fertilizers and farmyard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in semi-arid tropics [J]. *Plant Soil*, 2009, 318: 27-35.
- [39] Jiang M B, Wang X H, Liusui Y H, et al. Diversity and abundance of soil animals as influenced by long-term fertilization in grey desert soil, China[J]. *Sustainability*, 2015, 7: 10837-10853.
- [40] Zhao B Z, Chen J, Zhang J B, et al. Soil microbial biomass and activity response to repeated drying-rewetting cycles along a soil fertility gradient modified by long-term fertilization management practices[J]. *Geoderma*, 2010, 160: 218-224.
- [41] 高飞, 贾志宽, 韩清芳, 等. 有机肥不同施用量对宁南土壤团聚体粒级分布和稳定性的影响[J]. 干旱地区农业研究, 2010, 28(3): 100-106.
GAO Fei, JIA Zhi-kuan, HAN Qing-fang, et al. Effects of different organic fertilizer treatments on distribution and stability of soil aggregates in the semiarid area of south Ningxia[J]. *Agricultural Research in the Arid Areas*, 2010, 28(3): 100-106.

- [42] 林葆, 林继雄. 长期施肥的作物产量和土壤肥力变化[J]. 植物营养与肥料学报, 1994, 1(1): 6-18.
LIN Bao, LIN Ji-xiong. The changes of crop yield and soil fertility with long-term fertilizer application[J]. *Plant Nutrition and Fertilizer Science*, 1994, 1(1): 6-18.
- [43] Ayuke F O, Brussaard L, Vanlauwe B, et al. Soil fertility management: impacts on soil macrofauna, soil aggregation and soil organic matter allocation[J]. *Applied Soil Ecology*, 2011, 48, 53-62.
- [44] Franco N G, Mena M M, Goberna M, et al. Changes in soil aggregation and microbial community structure control carbon sequestration after afforestation of semiarid shrublands[J]. *Soil Biology & Biochemistry*, 2015, 87: 110-121.
- [45] An S S, Mentler A, Mayer H, et al. Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China[J]. *Catena*, 2010, 81: 226-233.
- [46] Roberts W P, Chan K Y. Tillage-induced increases in carbon dioxide loss from soil[J]. *Soil and Tillage Research*, 1990, 17: 143-151.
- [47] Rovira A D, Greacen E L. The effect of aggregate disruption on the activity of microorganisms in the soil[J]. *Crop and Pasture Science*, 1957, 8: 659-673.
- [48] Zhang H M, Wang B R, Xu M G, et al. Crop yield and soil responses to long-term fertilization on a red soil in Southern China[J]. *Pedosphere*, 2009, 19: 199-207.
- [49] Chivenge P, Vanlauwe B, Gentile R, et al. Organic resource quality influences short-term aggregate dynamics and soil organic carbon and nitrogen accumulation[J]. *Soil Biology & Biochemistry*, 2011, 43: 657-666.
- [50] 李辉信, 袁颖红, 黄欠如, 等. 长期施肥对红壤性水稻土团聚体活性有机碳的影响. 土壤学报, 2006, 43(3): 422-427.
LI Hui-xin, YUAN Ying-hong, HUANG Qian-ru, et al. Effects of long-term fertilization on labile organic carbon in soil aggregates in red paddy soil[J]. *Acta Pedologica Sinica*, 2006, 43(3): 422-427.
- [51] 黄欠如, 胡锋, 袁颖红, 等. 长期施肥对红壤性水稻土团聚体特征的影响[J]. 土壤, 2007, 39(4): 608-613.
HUANG Qian-ru, HU Feng, YUAN Ying-hong, et al. Effects of long-term fertilization on aggregates characteristic of red paddy soil[J]. *Soil*, 2007, 39(4): 608-613.
- [52] 徐江兵, 何园球, 李成亮, 等. 不同施肥处理红壤生物活性有机碳变化及与有机碳组分的关系[J]. 土壤, 2007, 39(4): 627-632.
XU Jiang-bing, HE Yuan-qiu, LI Cheng-liang, et al. Relationship between biologically active organic carbon pool and carbon fractions in upland soils different in fertilization[J]. *Soil*, 2007, 39(4): 627-632.
- [53] 袁颖红, 李辉信, 黄欠如, 等. 长期施肥对水稻土颗粒有机碳和矿物结合态有机碳的影响[J]. 生态学报, 2008, 28(1): 353-360.
YUAN Ying-hong, LI Hui-xin, HUANG Qian-ru, et al. Effects of long-term fertilization on particulate organic carbon and mineral organic carbon of the paddy soil[J]. *Acta Ecologica Sinica*, 2008, 28(1): 353-360.
- [54] Wu J, Brookes P C. The proportional mineralization of microbial biomass and organic matter caused by air-drying and rewetting of a grassland soil[J]. *Soil Biology & Biochemistry*, 2005, 37: 506-515.
- [55] 王志明, 朱培立, 黄东迈, 等. 水旱轮作条件下土壤有机碳的分解及土壤微生物量碳的周转特征[J]. 江苏农业学报, 2003, 19(1): 33-36.
WANG Zhi-ming, ZHU Pei-li, HUANG Dong-mai, et al. Decomposition of soil organic carbon and turnover of soil microbial biomass carbon under condition of rotation between upland crop and paddy rice [J]. *Jiangsu Journal of Agricultural Sciences*, 2003, 19(1): 33-36.
- [56] 杨长明, 杨林章, 颜廷梅, 等. 不同养分和水分管理模式对水稻土质量的影响及其综合评价[J]. 生态学报, 2004, 24(1): 63-70.
YANG Chang-ming, YANG Lin-zhang, YAN Ting-mei, et al. Effects of nutrient and water regimes on paddy soil quality and its comprehensive evaluation in the Taihu Lake region[J]. *Acta Ecologica Sinica*, 2004, 24(1): 63-70.
- [57] Witt C, Cassman K G, Olk D C, et al. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems[J]. *Plant and Soil*, 2000, 225 (1/2): 263-278.
- [58] Kool D M, Chung H, Tate K R, et al. Hierarchical saturation of soil carbon pools near a natural CO₂ spring[J]. *Global Change Biology*, 2007, 13(6): 1282-1293.
- [59] Gulde S, Chung H, Amelung W, et al. Soil carbon saturation controls labile and stable carbon pool dynamics[J]. *Soil Science Society of America Journal*, 2008, 72(3): 605-612.
- [60] Hassink J. The capacity of soil to preserve organic C and N by their association with clay and silt particles[J]. *Plant and Soil*, 1997, 191: 77-87.
- [61] 吕元春, 薛丽佳, 尹云锋, 等. 外源新碳在不同类型土壤团聚体中的分配规律[J]. 土壤学报, 2013, 50(3): 534-539.
LÜ Yuan-chun, Xue Li-jia, Yin Yun-feng, et al. Distribution of fresh carbon in aggregate fractions of different soil types[J]. *Acta Pedologica Sinica*, 2013, 50(3): 534-539.
- [62] Jastow J D, Miller R M. Soil aggregate stabilization and carbon sequestration: Feed backs through organomineral associations[M] // Lal R, Kimble J M, Follett R F, et al. Soil processes and the carbon cycle. New York: CRC Press, 1998: 207-233.
- [63] 朱毅, 侯新村, 武菊英, 等. 氮肥对两种沙性栽培基质中有机碳类物质含量的影响[J]. 草业学报, 2013, 22(2): 38-46.
ZHU Yi, HOU Xin-cun, WU Ju-ying, et al. The effects of nitrogen fertilizer on the contents of TOC, POC, SMBC and WSOC in two kinds of sandy substrates[J]. *Acta Prataculturae Sinica*, 2013, 22(2): 38-46.
- [64] 孙中林, 吴金水, 葛体达, 等. 土壤质地和水分对水稻土有机碳矿化的影响[J]. 环境科学, 2009, 30(1): 214-220.
SUN Zhong-lin, WU Jin-shui, GE Ti-da, et al. Effects of soil texture and water content on the mineralization of soil organic carbon in paddy soils[J]. *Environmental Science*, 2009, 30(1): 214-220.