

农田土壤有机碳固定潜力研究进展

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摘要: 土壤有机碳的贮存和损失的研究是目前国际上前沿研究领域之一。研究农田土壤有机碳固定过程, 对于了解农业生产过程和生态过程的关系具有十分重要的意义。在农田土壤中, 发生变化的有机碳主要是年轻或轻组有机碳, 而且土壤有机碳的损失或固定都是在土壤表层和有限的时间内发生, 且数量巨大。传统的耕作体系是造成土壤有机碳损失的主要原因。为了增加农田土壤有机碳的保有量, 农业管理措施应该从增加有机碳的输入量(如草田轮作、保留残茬以及施用肥料等)和减少土壤有机碳的矿化(少、免耕等)两方面入手。

关键词: 农田; 有机碳; 固定潜力

Soil organic carbon sequestration potential in cropland

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Abstract: Soil organic carbon (SOC) and its different pools are keys to optimizing crop production, minimizing negative environmental impacts, and thus improving soil quality. Investigation of SOC storage and loss are global foci research subject. The research on soil organic carbon sequestration potential in croplands, is an important way to realize a relationship between agricultural processes and ecological processes. Progresses and problems have been reviewed out in this paper.

Cultivation and cropping has led to a substantial loss of SOC from cropland in the world. Land degradation at least partly due to OC loss, and contribution to greenhouse gas emissions from the loss in OC from cropland soil is increasing. Since SOC is heterogeneous in nature, the significance and functions of its various components are ambiguous. It is essential that the relationship between levels of total SOC or the identifiable components and the most affected soil properties be established and then quantified before the amounts of SOC and/or its components can be used as a performance indicator. Furthermore, the environmental role of organic carbon in the soil requires further investigation.

Long-term SOC loss often takes place in the top soil of cropland. Loss of labile components of SOC has been even higher. Management practices that lead to improvement in plant biomass production would likely lead to increased C inputs and hence to increased OC in soil. Compare with intensive agriculture, the adoption of ley-cereal rotation, conservation tillage, and manure applications may reduce soil degradation and sequester carbon.

Key words: organic carbon; sequestration potential; cropland

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土壤有机碳含量大约占陆地生物圈碳库的三分之二, 而每年进入土壤的贮存和以 CO₂ 形式释放的碳量大约占土壤有机碳总量的 4%, 因而土壤中的有机碳既是碳汇又是碳源。由于全球长期和大面积的农垦, 不仅使土壤碳库和大气碳之间的碳循环

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平衡遭到破坏,而且造成大量土壤有机碳被氧化并以 CO_2 等的形式释放到大气中去^[1],增加了温室气体的排放。另外,土壤的有机碳含量常被认为是评价土壤质量一个重要指标,是一项重要的土壤性质。因此,大量土壤有机碳的损失还造成了土壤的退化和农业持续性的降低^[2]。

通过增加土壤有机碳的固定来减少大气中 CO_2 含量是一个有效的、具有中长期利益的措施。土壤的有机碳固定潜力的大小既取决于其地面植被、矿物组成、风化层厚度、水分、通气和温度状况,还取决于土壤本身保持及累积腐殖物质能力的大小^[3]。另外,土壤的有机碳固定潜力还与土壤有机质的化学性质和其抵抗微生物分解的能力有很大的关系。因此,即使在农田这样一个高度控制的生物圈组件中,评估其土壤有机碳固定潜力的大小以及与全球碳平衡之间的关系也是十分复杂的。

农田土壤有机碳的含量和组成不仅反映着土壤有机质的水平,而且还与农田质量的可持续能力密切相关。人们普遍认为,人类的耕种活动经常会造成农田土壤有机碳含量的减少。这主要是因为耕作和种植作物导致了土壤温度、湿度和空气状况的改变,有机物料输入的减少以及造成了土壤侵蚀。但是,近年的研究发现^[2,4],少免耕的大面积应用已经使土壤表层的有机碳含量得到一定程度的恢复。因此,各国都加强了对农田土壤有机碳固定的影响因素及其对环境贡献等方面的研究工作,也取得了积极的进展。本文主要讨论了农田有机碳固定机制及其影响因素。

1 农田土壤有机碳库的类型

温度和湿度是决定植物生物量的主要因素,同时随着土壤类型的不同,也决定着土壤有机碳的含量及其在不同土地利用方式下的变化速率。土壤有机碳含量取决于土壤有机物料输入和损失相对速率的变化。一些研究已经表明^[2,5],土壤有机质的不同组分其分解速率也不同,但是,却很难定义土壤有机质不同组分的确切功能。Dala 和 Chan^[2]把土壤有机碳分为 3 个部分,即活跃碳库、非活跃碳库和惰性碳库。

活跃碳库(active C pool)的特征就其在土壤中的更新速率快,能迅速得到更新。活跃碳一般指的是颗粒有机质(particulate organic matter),或者是指大致为保存在粒径 $> 20\mu\text{m}$ 或 $> 53\mu\text{m}$ 砂粒中的有机碳^[6,7]。通常把轻组有机质($< 1.6\text{mg}/\text{m}^3$ 或 $< 2.0\text{mg}/\text{m}^3$)中的碳也作为是活跃碳库。Parton 等^[8]建议活跃碳库为微生物碳库的 2~3 倍,但是 Dala 和 Chan^[2]认为活跃碳库为微生物碳库的 10 倍。活跃碳库有机质绝大部分由植物残体的分解物质、微生物的菌丝和存在于粉粒和粘粒级别上的很小但数量很大的微生物生物量及其产物组成。土壤中活跃碳库中的碳含量变化范围很大,主要通过 KMnO_4 来提取^[9]。

非活跃碳库(slow C pool)就是指总有机碳减去活跃碳库和非活跃碳库后剩下的碳,一般保存在粉粒($2\sim 20\mu\text{m}$)中^[2]。非活跃碳库中有机碳损失速率显著低于活跃碳库的^[6]。惰性碳库(passive C pool)被认为是土壤中存在的炭性碳(charcoal C)和被物理保护的有机碳,如在粘粒中的有机质^[10,11]。一般认为,粘粒中的有机碳的分解速率小于其它土壤粒级中的有机碳以及土壤总有机碳的分解速率,因此,长期耕作会相对地增加粘粒中的有机质占土壤总有机质的比例。通常认为土壤管理措施和作物种植对惰性碳库中的碳基本上没有影响。

2 农田土壤有机碳的影响因素

2.1 气候因素

许多研究发现土壤的最初有机碳含量和耕种后的有机碳含量均与年平均降水量密切相关^[6,12]。但是,在自然植被条件下,每 1mm 降水量的增加所导致的土壤 0~10cm 土层内有机碳含量的增加速率是农田的 2 倍,这可能是由耕作使土壤有机质分解加速和减少了植物有机残体的归还量两方面的原因所致^[2]。另外,Dala 和 Mayer^[13]发现,在相邻的地域内,微生物碳随年平均降水量的增加而增加,土壤活跃碳也有同样的趋势。

温度既影响土壤中有机质的分解速率,又影响植物残体有机碳进入土壤的速率。一般来说,湿热环境条件使土壤有机碳分解加快^[14],热带地区土壤有机质的分解速率比亚热带和温带地区的大。在澳大利亚昆士兰州的亚热带半干旱地区 50 多年的耕作使土壤的有机碳损失了 59%,而在其热带半湿润地区 10 余年的耕作就使土壤的有机碳损失了 56%^[15,16]。Ladd 等^[17]的研究显示温度提高 10℃,植物残体的分解速率加快 2 倍。随着气候变得干旱和温暖,土壤对有机碳的固定减小,土壤活跃碳或轻组有机碳含量占土壤总有机碳含量的比例迅速下降,而土壤粘粒中保持的有机碳比例则显著增加^[18,19]。黄耀等^[20]研究认为在温度较低的情况下,升高温度促进有机碳的分解,在温度较高的情况下,升高温度对有机碳分解的促进作用降低;温度对有机碳分解的影响随时间的延长而逐步减小。

季节短期变化对土壤有机碳,特别是对活跃碳的影响,主要是通过影响植物残体或植物生长时有机碳的输入状况来反映的^[21]。

2.2 土壤质地

不同的土壤类型的土壤有机质损失速率和更新周期的差别很大,土壤有机碳大部分保存在粉粒和粘粒中^[22]。土壤的粘粒含量对有机质的分解速率有一定影响,质地越粘重的土壤,其有机质的分解速率也越小。研究发现土壤有机质分解速率的降低与土壤粘粒含量的增加有关,二者呈指数关系^[23]。另外,土壤有机质的稳定性除了与土壤粘粒含量密切相关以外,还和土壤中

有机胶体以及铁铝氧化物等无机胶体的含量有关^[24-27]。然而, Giardina 等^[28]的研究认为土壤碳、氮矿化速率与土壤粘粒含量无关。

2.3 农田管理措施

自然植被覆盖下或草原土壤的开垦会导致土壤有机质含量的降低^[5, 29, 30]。长期耕作管理显著地改变了土壤有机碳组分的物理和化学性质^[10, 31]。也有的研究认为耕种并不会使土壤的有机质的化学性质发生本质改变^[10]。Six 等^[32]发现林地土壤有机碳总量、颗粒有机碳含量以及团聚状况均比农田的高。在耕种方式长期不变的情况下, 开垦土壤的有机质含量最终会维持在较低的水平上, 其形成速率将与分解速率相等, 但是微生物碳与总有机碳的比率基本一致^[33]。因此, 可以认为, 在植物残体等有机物质归还量较高的情况下, 土壤能够固定更多的有机碳。

作物轮作通过影响作物根系或残体归还的数量和质量, 从而影响土壤有机质的矿化和固定过程以及土壤活跃有机碳的数量^[34]。作物根系以及微生物残体主要影响土壤水溶性有机碳和微生物碳的变化^[30, 35, 36]。与裸露农田相比, 生长作物的农田土壤粒状有机碳或矿质结合态有机碳的含量比较高^[25]。在作物不同的生长发育阶段, 土壤有机碳的排放和固定量也不同^[37]。另外, 土壤有机质的化学稳定性也是影响土壤有机碳的累积的关键因素^[38]。但是, 也有研究发现无论在免耕或传统耕作条件下, 作物轮作或休闲不能提高土壤有机质的含量^[39, 40]。因此, 在不同气候和土壤条件下, 轮作对土壤有机碳累积作用的影响不同。

施用有机肥可以迅速提高土壤有机碳含量, 而且这种影响是持久的^[41]。张付申^[42]的研究发现长期施用有机肥能显著提高土壤活跃有机碳含量, 而施用化肥则提高了惰性有机碳的含量, 提高了土壤有机碳的氧化稳定性。一些研究认为化肥对土壤有机碳的固定并不产生直接作用, 而只是通过增加作物秸秆的归还量而对土壤有机碳的贮存产生影响^[43-46]。

源自添加有机物料的土壤有机碳占总有机碳的比例随着土粒粒径的减小而降低。因此, 不同粒径土壤团聚体中的有机碳含量就可以反映土壤有机碳的动态变化情况。有的研究认为^[47], 土壤粉粒中保持的碳可以作为添加有机碳的中期碳库, 而在砂粒中保持的碳可以作为反映土壤管理措施影响土壤有机碳变化的指标。另外, Franzluebbers^[48]认为土壤有机碳分层比率也可以作为反映土壤有机碳管理的指标。

3 耕作条件下农田土壤有机碳损失的机制

耕作常常被认为是引起农田土壤有机质含量下降的主要原因。耕作的机械作用使土壤破碎、分散和混合, 直接或间接地造成土壤有机质含量的下降^[49]。一个广泛认同的观点是耕作使土壤团聚体破碎, 从而导致土壤有机质的物理保护层的破坏, 使有机质暴露于微生物的分解之下, 因而造成在耕种条件下土壤有机质的下降^[50]。另外, 耕作的机械扰动还会导致土壤呼吸作用的增强, 有研究发现由土壤呼吸作用的增强而导致分解的有机碳量通常较低^[50, 51]。

农田土壤的管理措施基本上是在土壤表层进行的, 因此, 在耕种过程中, 土壤表层环境经常处于变动之中。一些研究发现^[52, 53], 农田土壤有机碳的损失主要发生在 0~30 cm 土层内, 特别是 0~10 cm 土层。在传统耕作体系中, 土壤有机碳、氮的损失主要发生在土壤的较大颗粒上 (100~2000 μm)^[54, 55]。耕作会导致富碳大团聚体的减少, 而使低碳微团聚体的含量增加^[56]。Roscoe 和 Buuman^[27]研究发现土壤有机碳的损失速率的顺序依次是轻组有机碳、重组有机碳和闭蓄态轻组有机碳。许多研究认为轻组有机碳或颗粒有机碳对土壤耕作比较敏感, 是反映在不同农田管理措施下土壤质量变化较好的指标^[22, 27, 57, 58]。

在长期耕作的土壤上, 其表层和亚表层的土壤有机碳比自然植被下的土壤损失了 40%~60%, 而在短期耕作的土壤上, 其表层和亚表层的土壤有机碳比自然植被下的土壤损失了 60%~75%^[54]。Chan 等^[58]认为耕作对土壤有机碳减少的影响比焚烧秸秆大; 而且耕作主要导致颗粒有机碳 (> 53 μm) 的减少, 而焚烧秸秆则造成结合态有机碳 (< 53 μm) 的减少。除了上述的作用之外, 土壤流失和风蚀也是农田土壤有机碳的损失的原因^[27]。土壤侵蚀主要造成了大量土壤有机碳的再分布, 以及强烈地改变了土壤微生物的种群和活性, 从而影响土壤有机碳的矿化过程。因此, 农田裸地休闲造成土壤有机碳损失甚至比耕作的大^[59, 60]。因此, 避免裸地休闲也是降低农田土壤有机碳损失的重要途径。

4 农田土壤有机碳恢复措施

保护性耕作可以减少土壤有机碳的损失, 这主要是因为保护性耕作减少了土面作业, 降低了土壤扰动, 同时保留残茬也能通过降低雨滴的击溅来加强土壤水的入渗, 从而减少了含有较高有机碳的表层土壤的流失。与传统耕作比较, 免耕可以显著提高 0~5 cm 土层内土壤有机碳和颗粒有机碳含量^[61, 62]。

West 和 Post^[63]在分析了全球 67 个长期定点试验的共 276 对处理的数据之后, 发现免耕替代传统耕作之后, 土壤有机碳贮存的每年平均增加 $C\ 57 \pm 14\ \text{g/m}^2$; 而加强轮作的复杂性之后, 土壤有机碳的贮存每年平均增加 $C\ 20 \pm 12\ \text{g/m}^2$ 。他们还认为, 免耕替代传统耕作之后, 在最初的 5~10 a 间土壤有机碳的贮存变化最大, 而后其变化逐渐减小, 并在 15~20 a 间达到一个新的平衡; 随着轮作的复杂性的加强, 土壤有机碳含量将会在 40~60 a 间达到一个新的平衡。

澳大利亚 Waite 研究所的长期定位试验 (始于 1926 年) 的结果表明^[40, 64], 在小麦-草地轮作系统中, 随着草地种植次数的增加, 土壤有机碳含量呈现增高的趋势; 而在 68 a 后, 小麦-休闲系统中土壤有机碳含量则下降了 60%; 在 34 a 后, 长期的草地 (始

于 1950 年)的土壤有机碳含量几乎恢复到 1925 年试验开始时的水平。李恋卿等^[62]在研究植被恢复对退化红壤的影响时也发现,植被恢复特别是豆科-禾本科植物轮作能较快地增加土壤有机碳的贮存,这种碳贮存表现为 2~ 0.25mm 团聚体的建成,而且对微团聚体稳定性同位素的组成分异产生影响。Curtin 等^[65]研究表明在加拿大的半干旱草原地区的传统小麦-休闲耕作转变为免耕小麦连作 14a 后,免耕小麦连作的表层土壤比传统小麦-休闲耕作的土壤能多固定 C 5~ 6t/hm²。但是,一些研究发现^[66~ 69],在免耕替代传统耕作之后的开始阶段,土壤有机质基本处于稳定状态,耕层土壤有机质含量并无显著差异,但是有机碳在土壤剖面上的分布呈现随深度增大而减少的趋势。

Joseph 等^[70]认为秸秆还田能显著增加土壤表层的轻组有机碳($\rho < 1.7 \text{ g/cm}^3$)的含量,却对与土壤矿质颗粒紧密结合的多糖类有机碳($\rho > 1.7 \text{ g/cm}^3$)含量没有影响。沈宏等^[71]研究认为长期施用有机肥或有机肥和 NPK 矿质肥料配合施用,有利于土壤总有机碳、活性碳、微生物碳和矿化碳含量的提高;NPK 矿质肥料对土壤总有机碳的贡献主要是提高了稳态碳的含量。徐阳春等^[72]研究认为由于长期免耕,连年施用的有机肥和作物残体等多积累于地表,使 0~ 5cm 土层内的土壤微生物特性发生较大变化,与常规耕作比较该层次的土壤微生物碳、氮均显著增加。Peterson 等^[73]还建立了土壤有机碳含量与作物、耕作和施肥类型的回归函数模型,来预测土壤有机碳含量的变化。黄东迈等^[74]研究认为如果旱地和水田的土壤条件均适宜于微生物的活动,水田土壤的有机碳的分解速率和分解量比旱地土壤的高。因此,在传统耕作条件下,可以通过选择合理的轮作作物和施用氮肥对耕层土壤有机碳进行管理。另外,结合少免耕制度,高度集约的农作制可以增加土壤有机碳的固定,从而有效降低农田的 CO₂ 排放量^[46, 65, 75]。但是, Doran 等^[52]发现在小麦-休闲轮作 22~ 27a 后,无论免耕和常规耕作,土壤有机碳含量降低了 12%~ 32%,因此,他们认为通过集约种植所增加的有机碳的归还数量,仅仅是减缓了土壤有机碳的损失。

5 小结及展望

土壤有机碳含量的变化取决于其有机碳输入和输出的平衡。一般而言,能够提高植物生物量的农业措施就有可能增加土壤有机碳的输入水平,因而也会提高土壤有机质含量。这也就是说,为了增加农田土壤有机碳的含量,农业管理措施必须从增加有机碳的输入量(如草田轮作、保留残茬以及施用肥料等)和减少土壤有机碳的矿化(少免耕等)两方面入手。

在农田土壤中,发生变化的有机碳主要是年轻或轻组有机碳,而且土壤有机碳的损失或固定都是在土壤表层和有限的时间内发生,且数量巨大。传统的耕作体系是造成土壤有机碳损失的主要原因。所以,采用保护性耕作体系、改善轮作体系、缩短休闲期等措施不仅可以减少农田土壤原有有机碳的损失,而且还可以增加农田土壤对有机碳的固定。在美国,仅改进耕作方式和农作制就能使土壤每年拥有 3000~ 15000 万 t 的有机碳固定潜力^[76]。因此,虽然气候、土壤质地等环境因素对土壤有机碳的固定有很大影响,但是,农田土壤中有机碳的保持最终还是要依靠改善农作和土壤管理措施来解决。

目前,在发展可持续的土地利用管理方式当中,如何平衡对农产品及其它土地利用需求与减少土壤退化要求之间的关系是一个巨大的挑战。迄今为止,现行的农作制度已经造成了农田土壤有机碳的数量和质量上的损失。农田土壤有机质的损失不仅在一定程度上加剧了农田土壤的退化,而且也加剧了温室气体的排放。由于土壤有机碳的异质性,研究土壤有机碳不同组分的作用和重要性有助于推动土壤有机碳动力学特征的模拟以及更好地预测土地利用方式和污染物对土壤有机碳的影响。同时,研究农田地上与地下生物量的数量以及地上与地下碳库的转化速率,可以深入了解农田土壤有机碳的固定潜力。另外,应加强土壤有机碳的环境作用的研究,特别是在土壤有机质、微生物多样性以及农药等的相互作用方面还需要进一步的深入研究。

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