生物炭修复土壤有机碳矿化的温度敏感性研究进展

朱昊天　兰国新*
重庆三峡学院重庆市三峡库区水环境演变与污染防治重点实验室

DOI:10.12238/eep.v8i3.2585

[摘　要] 工业革命以来,人类活动导致大气二氧化碳(CO_2)浓度显著上升,加剧全球气候变化。土壤作为陆地生态系统中最大的有机碳库,其碳库稳定性对调控大气CO_2浓度具有关键作用。本文系统综述了土壤有机碳矿化的过程、影响因素及温度敏感性(Q_{10})机制,并探讨生物炭修复的调控效应。研究表明,温度、水分、pH及外源碳输入对矿化速率具有显著影响,Q_{10}与碳质量、微生物活性及土壤理化性质密切相关。生物炭通过稳定芳香族碳组分、抑制微生物代谢活性及改变土壤团聚体结构,显著降低土壤有机碳矿化速率。其热解温度、添加量及土壤性质共同调控修复后土壤的碳矿化温度敏感性。未来需结合多因子耦合机制与智能模型优化,推动生物炭技术在固碳减排及气候智慧型农业中的应用。

[关键词] 土壤有机碳矿化；温度敏感性(Q_{10})；生物炭；碳封存
中图分类号：S15　**文献标识码：**A

Research Progress on the Temperature Sensitivity of Organic Carbon Mineralization of Biochar-amended Soils

Haotian Zhu　Guoxin Lan*
Key Laboratory of Water Environment Evolution and Pollution Prevention in Chongqing Three Gorges Reservoir Area, Chongqing Three Gorges University

[Abstract] Since the Industrial Revolution, human activities have significantly elevated atmospheric carbon dioxide (CO_2) concentrations, intensifying global climate change. As the largest organic carbon reservoir in terrestrial ecosystems, soil plays a pivotal role in regulating atmospheric CO_2 levels. This review systematically examines the processes and influencing factors of soil organic carbon (SOC) mineralization, mechanisms of temperature sensitivity (Q_{10}), and the regulatory effects of biochar remediation. Studies indicate that temperature, moisture, pH, and exogenous carbon inputs significantly alter mineralization rates, while Q_{10} is closely linked to carbon quality, microbial activity, and soil physicochemical properties. Biochar suppresses SOC mineralization by stabilizing aromatic carbon components, inhibiting microbial metabolic activity, and modifying soil aggregate structure. The pyrolysis temperature, application rate of biochar, and soil properties collectively regulate the temperature sensitivity of carbon mineralization in amended soils. Future research should integrate multifactor coupling mechanisms and intelligent modeling to advance biochar technology in carbon sequestration and climate-smart agriculture.

[Key words] Soil organic carbon mineralization; Temperature sensitivity (Q_{10}); Biochar; Carbon sequestration

引言

自工业革命以来，人类活动对全球气候的影响与日俱增。政府间气候变化专门委员会(IPCC)最新的《气候变化评估报告》指出，全球大气二氧化碳(CO_2)浓度从工业革命前的278ppm增加到2020年的410ppm；同时，陆地地表温度升高了约1.59° C[1]。大气二氧化碳浓度的增加被广泛认为是全球变暖的主要原因，人们迫切希望通过增加碳汇来遏制因大气二氧化碳浓度高而加剧的气候变化[2]。

土壤是陆地生态系统中最大的碳库，贮存了约2000Pg(1Pg=10^{15}g)有机碳[3]，是大气和地表植被碳储量的2~3倍，是人类活动碳排放量的6~8倍[4]，保持土壤碳库的稳定性对控制大气二氧化碳浓度至关重要。

1 土壤有机碳的矿化

土壤有机碳矿化指土壤中的有机碳在微生物和酶的作用下，分解转化为无机碳和释放能量的过程。微生物通过分泌酶降解复杂有机物质，将其转化为简单的有机化合物，最终释放出二氧化碳等气体[5]。此外，土壤有机碳矿化产生富含氮、磷和微量元素的副产物对植物生长至关重要，它们被植物根系重新吸收，在

生态系统构成了复杂的养分循环[6,7]。土壤有机碳的矿化直接关系到土壤养分元素的供应及释放、温室气体的形成等,在生态系统功能、碳循环及人类活动中具有多重作用,既有自然调节功能,也带来潜在的环境挑战。

1.1土壤有机碳的研究方法。目前,有关土壤有机碳分解的实验可以分为野外实验和室内培养实验两种。但由于野外环境不稳定,各种影响因素相互作用,难以研究特定因素对土壤有机碳分解的影响机制,因此目前还是多采用室内培养的方法。土壤有机碳矿化速率的测定方法主要包括以下三种[8,9]：

(1)碱液吸收法。碱液吸收法利用NaOH等碱液对土壤有机碳矿化产生的二氧化碳进行捕获,再通过酸碱滴定或仪器定量测定溶液中含碳离子的含量从而得到土壤有机碳矿化速率。(2)气相色谱法。气相色谱法利用仪器内固定相与气体的物理吸附和毛细管作用,将气体样品中的组分分离出来,再通过流动相将分离后的组分输送至检测器从而测定二氧化碳含量[10]。(3)红外分析法。红外分析法基于气体分子的红外线吸收原理,通过测定气体样品中二氧化碳分子对特定波长红外线的吸收程度来确定二氧化碳浓度[11]。

Meta分析、机器学习等统计分析方法也常用于研究土壤碳矿化。通过整合多源数据和挖掘复杂关系,能有效弥补传统实验方法的局限性。这些统计分析方法可突破单一实验的尺度限制,为土壤有机碳矿化的研究提供从控制实验到真实生态系统的桥梁。

1.2影响土壤有机碳分解的主要因素。温度是影响土壤有机碳分解的最主要的环境因素之一。随着温度升高,土壤有机碳矿化速率一般随之上升。根据一项为期两年的实验结果推断,估计由于本世纪气温上升4° C,全球热带森林土壤有机碳储量将损失超过13%(65PgC)[12]。温度升高会加速土壤微生物周转,促进土壤有机碳的分解。

土壤水分是土壤中一系列生化反应的载体,也是控制土壤有机碳矿化的关键因素之一[13]。氧气和有机碳在土壤中的扩散需要土壤水分的参与。一般认为中等的土壤水分条件下土壤有机碳矿化速率最大,随着土壤含水量持续上升,土壤有机碳矿化速率大致呈先增后减的抛物线形状[14]。

土壤pH通过影响土壤生物,尤其是土壤微生物的生物化学反应而影响土壤有机碳的矿化。各种微生物有不同的最适pH范围。pH过高或过低都不适合微生物活动,从而抑制土壤有机碳的矿化作用[15,16]。只有当pH适宜时,微生物的活性和酶的活性最高。

土壤有机碳的矿化还受到外源碳添加的影响。例如,植物凋落物、根系分泌物等外源碳输入土壤后刺激了土壤原生有机碳矿化,这被定义为激发效应[17]。外源碳输入会改变微生物的底物有效性,改变土壤微生物的活性和数量,还会引起微生物群落结构的改变,进而影响土壤有机碳的矿化。

2 温度敏感性的相关概述

土壤环境条件的差异(如含水量、养分含量、微生物群落结构等)会使有机碳矿化对温度变化产生的响应不同。土壤碳库对温度升高的响应程度和反馈作用的大小主要取决于土壤有机碳对温度敏感性的大小[18]。土壤有机碳矿化速率对温度的响应通常用温度敏感性系数Q_{10}表征。它被定义为温度每升高10° C,土壤有机碳矿化增加的倍数。它是评估二氧化碳排放与全球变暖之间反馈强度的重要参数,Q_{10}值越大,表明土壤有机碳分解对温度的变化越敏感[19]。

碳质量-温度假说是过去广泛接受的解释Q_{10}变化的理论,它描述了土壤碳质量和Q_{10}之间的关系,并预测低碳质量的有机质比高碳质量的有机质具有更大的温度敏感性。根据酶促动力学的基本原理,分子结构越复杂的土壤有机碳(生物化学难分解性越强),被分解时所需活化能越高,对温度的响应更加敏感。该假说被大量实验证实[20,21]。

土壤有机碳矿化的温度敏感性受很多因素影响。温度是主要影响因素之一。土壤中酶活性与温度直接相关,温度高于或低于酶的最适温度都会使其活性降低。一项对北极、温带和热带地区的土壤样品进行的室内培养实验发现,北极地区土壤有机碳矿化Q_{10}值最大,为3.4,其次是温带地区的2.9和热带地区的2.1[22]。

土壤含水量是影响土壤有机碳矿化温度敏感性的另一主要因素。水分参与了土壤中微生物所需氧气和可溶性有机物等养分的扩散。Zhang等(2015)发现土壤含水量与Q_{10}呈先正相关后负相关的抛物线关系,具体表现为在土壤含水量较低时,土壤含水量与Q_{10}正相关；而土壤含水量较高时,土壤含水量与Q_{10}负相关[23]。

土壤的其他理化性质(包括土壤pH、黏粒含量、有机质含量、氮含量等)也会影响有机碳矿化的温度敏感性。例如,pH会改变微生物群落结构,进而影响土壤有机碳矿化的温度敏感性[24]。土壤有机碳含量一般与Q_{10}值正相关[25]。土壤团聚体对有机质的物理保护会降低其对温度的响应,从而抑制土壤有机碳矿化的温度敏感性[26]。

3 生物炭对土壤有机碳矿化的影响及其修复的温度敏感性分析

3.1生物炭的相关概述。生物炭是生物质在限氧条件下进行热化学转化产生的稳定残留物[27]。生物炭的碳含量通常显著高于其原料,包含大量的氮、磷、钾等营养元素,还有着孔隙度和比表面积的特点,施用到农田中能显著增加土壤碳封存并改善土壤的理化性质[28]。

生物炭具有吸收大气二氧化碳并在其生产和使用过程中产生生物质能的能力,因此被认为是加强土壤碳固存和减缓气候变化的很有前途的材料[29,30]。生物炭中存在着大量的芳香族基团,具有很高的稳定性,难以被微生物分解利用,也不容易在空气中被氧化,使其在土壤中能够持续较长时间不被降解,达到封存碳的作用。因此,生物炭的施用可使土壤中的有机碳以生物炭为媒介长期贮存在芳香族等稳定有机物[31]。

添加生物炭将会显著改变土壤的理化性质。生物炭通常呈碱性,可中和酸性土壤的pH;生物炭的多孔结构改善了土壤微观结构,促进氧气和水分扩散分布;生物炭可能含多环芳烃(PAHs)或酚类化合物等有毒物质,抑制特定微生物的生命活动,从而改

变微生物群落的丰度和多样性;此外,生物炭的施用可能对土壤团聚体的形成和稳定产生了正面效应,添加的生物炭会与土壤颗粒结合形成有机-无机复合体,促使土壤团聚体的形成与稳定,并在团聚体的物理保护作用下长期存留[32,33]。

土壤中的酶主要来源于微生物、植物根系和土壤动物,作用于土壤的方方面面。土壤有机碳的分解与养分释放,微生物的呼吸等代谢活动等,都离不开酶的作用。土壤中的酶活性是衡量土壤生态功能的重要指标,反映了土壤微生物的代谢能力和生物化学过程的强度。生物炭的强吸附性质,增加了土壤中酶活性的复杂性。生物炭通过表面官能团吸附有机质和养分(如氮、磷),减少淋失,并通过缓慢释放为酶提供持续底物,但也会通过静电作用或表面吸附直接固定酶分子或底物(如有机质、无机离子),降低其有效性。此外,生物炭对土壤酶的影响与生物炭的性质、土壤类型以及酶类型有关。研究表明高温和低温下裂解的生物炭能使酶活性产生不同的变化[34]。另一项试验发现花生壳生物炭添加量在0.5~5%范围内时,蔗糖酶活性与生物炭添加量呈正相关关系。土壤中添加生物炭会提高参与利用氮和磷等矿质元素相关的土壤酶活性,降低土壤碳矿化等生态学过程的土壤酶活性[35]。生物炭对土壤酶活性的影响具有“双刃剑”效应,总体表现为低剂量促进、高剂量抑制,且不同酶的响应差异显著。

3.2生物炭对土壤有机碳矿化的影响。生物炭在一定程度上能够促进土壤有机碳矿化。其机制主要为:生物炭有着多孔结构,比表面积巨大,可以改善土壤中的水分、养分和通气状况,有利于土壤中碳和氮与微生物接触,从而营造出一个适合微生物生长和繁衍的环境,增加土壤二氧化碳的排放量[36]。此外,生物炭中也有着易分解有机物,加入到土壤中后,其被微生物利用后呼吸产生二氧化碳的排放量增大。在一项对添加了木质生物炭的碱性粉砂质黏壤土的为期16天的培养试验中,相比于未添加生物炭的对照组,实验组土壤呼吸量增加了52.0%~84.6%[37]。

生物炭对土壤有机碳矿化更多的还是抑制作用。其机制为:土壤中添加生物炭后,会形成大量的微生物难以分解利用的芳烃等物质,从而抑制微生物对有机物的利用,最终减少二氧化碳的排放量。一项野外实验表明,在农业和森林土壤中,使用玉米秸秆制成的生物炭可使土壤二氧化碳排放减少15%~17%[38,39]。

3.3生物炭修复土壤有机碳矿化的温度敏感性。气候变暖增加了生物炭修复土壤中有机碳的矿化。大量实验表明,增温促进了生物炭修复的农田土壤的二氧化碳排放量[40-43]。生物炭来源、添加量、增温幅度和土壤性质等因素均可能影响生物炭修复土壤的有机碳矿化的温度敏感性[44,45]。

生物炭对微生物代谢的影响很大程度上取决于生物炭的热解温度,且受增温影响较大。热解温度会影响生物炭的理化性质,如pH值、矿物质营养成分含量、物理结构等,尤其是生物炭的碳组分[46]。热解温度越高,有机碳矿化的温度敏感性越高。随着热解温度的升高,芳香碳在生物炭中的比例和缩聚量都在上升[47-49]。高温生物炭降低了水稳性团聚体的百分比和结构稳定性指数,从而降低了结构稳定性。低温生物炭含有更多的非热解有机残留物和有机营养物质,如脂肪族分子等低分子量挥发物[50-52]。然而,生物炭可能通过介导土壤微生物处理而不是直接输入其有机质来改变土壤有机质成分的组成[53]。

生物炭的添加率是决定生物炭修复土壤二氧化碳排放的增温效应的一个正相关变量。生物炭是一种顽固性物质,添加率越高,分解所需要的活化能越高。在一项研究中秸秆生物炭添加量为20和40thm^{-1}的实验组的农田土壤微生物活化能显著高于添加量为10thm^{-1}和不添加生物炭的对照组[54]。活化能越高,温度升高的促进作用越强,因此生物炭的添加量与增温效应呈正相关。这种正相关关系支持了碳质量-温度假说。

土壤性质也会影响生物炭修复后有机碳矿化的温度敏感性。温度升高的过程中,农田比森林更脆弱。在自然生态系统(如草地和森林)向耕地土壤的转化过程中会产生有机碳损失[55]。土壤pH是重要的影响因素,在不同pH下土壤中占群落主导的微生物种类不同。比如,酸性土壤中更适合真菌生长繁殖,因此更多的难降解有机化合物将被分解,并对增温表现出积极的响应[56,57]。

4 总结与展望

土壤有机碳矿化是调控陆地碳循环与气候变化反馈的核心过程。生物炭修复是一种被广泛应用的固碳技术,修复后土壤的温度敏感性受生物炭和土壤理化性质的复杂影响。未来需深化多因子耦合机制研究,量化长期尺度下生物炭的碳稳定性与生态风险,结合修复技术与智能模型优化施用策略,推动其从理论到气候智慧型农业的转化,为全球碳中和目标提供基于自然的解决方案。

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作者简介：

朱昊天(1997--),男,汉族,江西人,在读硕士研究生,研究方向：生态环境与修复。

***通讯作者：**

兰国新(1984--),男,汉族,山东人,博士,副教授,研究方向：环境遥感与环境污染控制。