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水力侵蚀对土壤碳循环及土壤微生物多样性影响的研究进展

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摘 要:[**目的**]针对水力侵蚀对土壤碳循环“源汇”效应争议,综述水力侵蚀对土壤有机碳矿化作用和土壤微生物多样性的影响机制,提出未来定量研究的方向与注意事项。[**方法**]在提出水力侵蚀对土壤碳循环“源”“汇”效应概念和理论的基础上,分析现阶段研究中水力侵蚀对土壤碳循环“源汇”效应争议的核心问题,进而探讨水力侵蚀导致不同种类土壤微生物多样性变化的差异及其作用机制。[**结果**]水力侵蚀过程导致土壤有机碳矿化作用形成碳循环中的“源”效应,而沉积过程导致有机碳迁移至低洼处固存形成碳循环中的“汇”效应,微生物的呼吸和分解作用可能解释土壤碳循环中消失的碳“汇”问题;水力侵蚀过程削弱细菌群落结构复杂性,而沉积过程可增加细菌群落结构的复杂性,但侵蚀和沉积过程都可能降低土壤真菌的 α 多样性和群落结构复杂性;水力侵蚀过程通过影响土壤有机碳含量、植被覆盖度和土壤 pH 等因素间接影响土壤微生物多样性。[**结论**]未来研究应强化不同尺度水力侵蚀过程对土壤碳循环的影响机制、水力侵蚀过程与土壤微生物多样性的相互作用机制及水力侵蚀过程中土壤微生物对碳循环的影响机制相关量化研究。

关键词: 水力侵蚀; 有机碳; 碳循环; 土壤微生物
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Research Progress on the Effects of Hydraulic Erosion on Soil Carbon Cycle and Soil Microbial Diversity

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Abstract: [**Objective**] In response to the controversy over the “source-sink” effects of hydraulic erosion on soil carbon cycle, the impact mechanism of hydraulic erosion on soil organic carbon mineralization and soil microbial diversity were reviewed and the directions and precautions of quantitative research in this field in the future were presented. [**Methods**] Based on the conception and theory of “source effects” and “sink effects” of hydraulic erosion on soil carbon cycle, the core issues of the current controversy over the “source-sink” effects of hydraulic erosion on soil carbon cycle were analyzed, and then the differences of soil microbial diversity changes among different types of soil microorganisms caused by hydraulic erosion and their mechanisms were discussed. [**Results**] The “source effects” of hydraulic erosion on soil carbon cycle were mainly caused by the organic carbon mineralization during erosion progress, while the “sink effects” were mainly caused by the migration of soil organic carbon to the low-lying areas for sequestration during deposition process. The respiration and decomposition of soil microorganisms resulted in the disappearance of

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carbon "sinks" in the soil carbon cycle. Hydraulic erosion process weakened the complexity of bacterial community structure, while the deposition process increased the complexity of bacterial community structure. However, both erosion and deposition processes weakened the α-diversity and the structure complexity of fungal community. Hydraulic erosion process indirectly impacted soil microorganisms diversity mainly through altering the soil organic carbon content, vegetation cover and soil pH. [**Conclusion**] Further research should strengthen the quantitative research on the influence mechanism of hydraulic erosion process on soil carbon cycle at different scales, the interaction mechanism between hydraulic erosion process and soil microbial diversity, as well as the influence mechanism of soil microorganisms on soil carbon cycle during hydraulic erosion progress.

Keywords: hydraulic erosion; soil organic carbon; carbon cycle; soil microorganism

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土壤侵蚀发生在世界上不同国家,是共有的环境问题,其中,中国、美国、俄罗斯、澳大利亚、印度和欧洲的部分地区水土流失较严重[1]。中国深受土壤侵蚀的影响,每年约 5.29 Gt 的土壤因侵蚀而流失或迁移,其中有机碳流失或迁移量约为 180 Mt[2]。人类活动加速了土壤侵蚀进程,导致土壤侵蚀速率远大于自然土壤的形成速率,进而引发耕地质量退化、粮食作物减产、生态环境质量下降等问题,严重威胁粮食安全和生态系统稳定[3-5]。

碳是构成生物组成的基本元素,是所有有机物质的核心,碳以有机态或无机态广泛存在于地球的大气、海洋、陆地以及动植物体内[6],而土壤中碳储量可达 1 270 Gt,比大气 CO_2 含量高 2～3 倍[7-8]。因而,土壤碳库的微小变化对土壤健康和土地生产力产生很大影响,甚至影响全球气候变化[9]。由于长期受到水力、风力、冻融等外营力的交互影响,土壤有机碳库空间格局随侵蚀过程[10]而发生迁移和再分布[11]。水力侵蚀是影响土壤碳库迁移转化的主要驱动因子[12]。尽管土壤侵蚀对陆地生态系统碳循环影响的重要性得到广泛认可,但仍缺乏量化模型以明确土壤侵蚀对碳循环影响的程度和机制[11]。

土壤微生物多样性对土壤环境变化的反应敏感性较强,是生态环境稳定性的一个重要生物指标[13]。土壤侵蚀导致侵蚀坡位的土壤微环境发生改变,进而影响土壤微生物多样性[14]。部分研究[15-16]认为,土壤侵蚀改变原有位置土壤细菌和真菌的数量,也有研究[17-19]认为,土壤侵蚀改变土壤有机碳含量、水分含量以及土壤 pH,进而影响土壤微生物多样性。土壤侵蚀和土壤微生物的关系密不可分,但较少研究指示土壤侵蚀是否影响土壤微生物的功能特征,土壤微生物与碳循环之间的关系及其侵蚀环境的响应机制有待进一步研究。

水力侵蚀是指土壤及土壤母质受到水力作用后,被破坏、分离、搬运、沉积等过程,在全球范围内分布最广泛,约占全球土壤侵蚀类型的 50%[20]。在人类活动较多以及经济发展程度较高的地区,由于人口压力和经济发展需求,过度开垦、植被破坏、过度放牧、不合理耕种等情况日益严重,水蚀区平均侵蚀强度约为 3 800 t/(km^2·a)[21]。中国主要水力侵蚀区包括东北黑土区、北方土石山区、西北黄土高原区、南方红壤区、西南紫色土区和西南岩溶区[22]。根据第三次遥感数据调查结果,中国水土流失面积达到267.42万 km^2,其中水力侵蚀面积为 110.58 万 km^2[23],约占国土面积的 11.56%,占水土流失总面积的41.35%[24],水力侵蚀成为导致土壤退化、粮食作物减产的重要驱动因素之一。因此,研究水力侵蚀对土壤碳循环以及土壤微生物多样性影响,明确土壤退化对水力侵蚀的响应机制,对保护和提升耕地质量,提高粮食产量具有重要的理论与实践意义。

1　水力侵蚀对碳循环的影响

水力侵蚀导致土壤中的矿物质以及有机碳发生迁移,对土壤物理、化学以及生物特性产生难以修复的影响,进而影响土壤肥力和粮食产量[25]。众所周知,水力侵蚀加速土壤碳库的转化,有机碳在侵蚀部位损耗,但随着侵蚀土壤的迁移,有机碳会沉积部位累积[26-27]。早在 20 世纪 70 年代,相关学者在估算全球碳收支平衡时就发现,全球碳循环中存在很大一部分 CO_2 失汇的情况[28-29]。碳循环研究面临已知"碳汇"不能平衡已知"碳源"的问题,存在"未知汇"的挑战[11]。1998 年著名泥沙学家 STALLARD[30]提出将陆地生态系统碳循环机制和泥沙迁移过程耦合起来,指出土壤侵蚀在碳循环"源汇"问题中扮演不可忽视的重要角色。已有研究[31]表明,与大气交换的土壤有机碳占整个生态系统碳储量的2/3,然而长期以来的研究并未有效解释土壤侵蚀对全球碳循环作用及

影响。当前土壤侵蚀在全球碳循环仍存在广泛争议—土壤侵蚀在碳循环过程中到底是作为“碳源”，还是“碳汇”，其角色定性问题仍然缺乏统一的认识和解释[32]。

1.1 水力侵蚀对碳循环的“源”效应

部分学者[33]认为，水力侵蚀在碳循环问题中扮演“碳源”的角色，认为水力侵蚀影响土壤有机碳的稳定性，进而影响碳排放，相比于未受到水力侵蚀的区域，土地的净生产力降低。LAL[34]研究认为，水力侵蚀导致土壤团聚体稳定性被破坏，进而释放出来的有机碳被矿化，增加 CO_2 的排放量，水力侵蚀导致土壤质量下降，从而影响土壤生物量的积累，削弱大气中 CO_2 的吸收[35]。这些作用被认为是碳循环的“源”效应。

JACINTHE 等[36]通过模拟降雨研究，首次证明由于水力侵蚀导致释放出来的有机碳被矿化的定量证据，可作为大气 CO_2 的来源。LAL[12]的研究同样表明，每年因水力侵蚀导致的 CO_2 的释放量达到 1.00～1.14 Gt。研究[37]表明，^{137}Cs 活性与＜0.25，0.25～0.5，0.5～1 mm 的团聚体相关的 SOC 含量呈极显著正相关。基于同位素^{137}Cs 的土壤侵蚀研究[38]表明，^{137}Cs 的迁移模式与土壤团聚体中的 SOC 类似。2007 年 VANOOST 等[39]通过^{137}Cs 试验以及碳库存的测量，证明了由侵蚀引起的大气碳汇大约相当于因侵蚀迁移碳的 26%。JACINTHE 等[40]研究结果同样表明，在侵蚀过程中约有 20%～30%的碳被释放。且部分学者[41]研究认为，这部分因为侵蚀被迁移的有机碳，在侵蚀迁移过程中已经被完全矿化，迁移到沉积区的碳已经很少。

1.2 水力侵蚀对碳循环的“汇”效应

有学者[42]认为，水力侵蚀有助于增加和保护土壤碳库的稳定。被水力侵蚀迁移的碳通过植物生长作用重新被利用；同时，被水力侵蚀迁移的有机碳在低洼处聚集因缺氧导致微生物的分解利用作用受到限制，使得这部分有机碳被封存[43-44]。其次，水力侵蚀导致土壤表面富含硅酸盐的土壤裸露在空气中，而这部分富含硅酸盐土壤的风化作用需要消耗空气中的 CO_2，也被认为是水力侵蚀对碳循环的“汇”效应[45]。

由于水力侵蚀粒径分选作用可导致侵蚀区坡面土壤粗化[46]，而细颗粒泥沙在沉积区富集，从而导致土壤颗粒组成与土壤有机碳在坡面的再分布过程[47-48]。例如，DU 等[49]研究发现，侵蚀区＞0.25 mm 直径的颗粒越来越多，沉积区则富集＜0.053 mm 直径的细小颗粒。发生水蚀时，土壤有机碳不仅发生横向迁移和沉积，同时也发生纵向沉积，溶于水的有机碳随着土壤的淋溶作用向更深层次的土壤纵向沉积[50]。DE 等[51]研究发现，经过长期侵蚀的坡地，侵蚀区的有机碳含量显著低于沉积区，改变了有机碳分配格局。土壤有机碳在侵蚀区由于侵蚀外营力的作用经常更新，在沉积区由于源源不断的小颗粒有机碳汇入并且长期深埋导致土壤稳定性增加[52-53]。越来越多的学者[33]认为，侵蚀可能导致土壤碳库增加。有机碳矿化对坡度以及径流和泥沙的迁移非常敏感。径流作为水力侵蚀的主要驱动力，可通过影响土壤与有机碳再分配而影响土壤碳库的稳定性[54]。DU 等[49]研究表明，侵蚀坡面的 CO_2 排放量随着坡度的增加而减少，但沉积带的 CO_2 排放量随着坡度的增加而增加，这可能受到径流和泥沙迁移的共同作用，侵蚀和沉积共同作用可减缓土壤有机碳矿化和增强土壤碳库稳定。

1.3 水力侵蚀对碳循环“源”“汇”效应争议

关于水力侵蚀对碳循环的作用仍存在争议。水力侵蚀对土壤有机碳矿化和固存既有积极影响，也有消极影响[11]，例如，受侵蚀而矿化的有机碳可因团聚体的破坏而加速，也可因为在低洼处的深埋而固存。同样，低洼处深埋的有机碳可因为缺氧导致土壤微生物利用分解能力受限而被固存，也可因为厌氧性的甲烷细菌的作用而被利用和分解[55]。也有研究[56]指出，在短时间和小尺度区域进行试验时，土壤侵蚀诱发了大气 CO_2 的“源”，而在长时间和大尺度的研究中，水力侵蚀对碳循环的“源”和“汇”作用均有体现。土壤微生物在碳循环作用中扮演着重要的角色，已经证明侵蚀环境中的土壤微生物丰度和种群多样性下降[57]，然而土壤微生物对有机碳矿化的影响也存在争议[58]。部分学者[59-60]认为，土壤有机碳矿化主要受土壤微生物群落结构的调节，侵蚀区域的土壤微生物丰度和种群多样性下降对矿化率有负面影响；也有部分学者[61-63]研究表明，侵蚀导致的土壤微生物丰度和种群多样性下降对矿化作用并无显著影响。

目前，已经越来越多学者关注水力侵蚀对碳循环的影响，但侵蚀沉积过程中的土壤有机碳矿化机制仍未明确，尚未量化由于侵蚀而发生矿化作用的有机碳量[39]，具体可包括明确侵蚀沉积区原位土壤有机碳矿化机制、侵蚀过程中因矿化作用损失的碳量、沉积过程中富集在沉积区的有机碳矿化机制等[26]。从研究方法看，目前关于水力侵蚀对土壤有机碳矿化机制研究大多基于室内模拟试验，需加强野外长期观测和定量研究，将野外观测和室内模拟试验相结合来探究水力侵蚀土壤有机碳矿化机制的影响。

2　水力侵蚀对土壤微生物多样性的影响

同样,土壤微生物在土壤有机碳循环过程中也扮演着不可忽视的角色,在计算全球碳收支数据时,需要考虑侵蚀沉积过程中土壤微生物的呼吸作用和分解作用[55]。土壤微生物是土壤生态系统中最活跃的组分,是土壤有机质形成与转化过程中不可或缺的组成部分[64]。土壤微生物的菌群组成、结构、功能对水力侵蚀导致的环境变化敏感[65],进而影响温室气体排放以及碳循环和养分循环[66]。

2.1　水力侵蚀导致土壤微生物多样性变化

已有研究[67]表明,水力侵蚀对土壤微生物(细菌、真菌)多样性的影响具有差异。对于土壤细菌而言,水力侵蚀过程可降低土壤细菌的 α 多样性,削弱细菌群落结构复杂性,而沉积过程可增加细菌的 α 多样性和群落结构复杂性[19]。KONG 等[68]利用 16S rRNA 基因扩增子测序的方法同样发现,虽然侵蚀显著降低土壤细菌的丰富度和多样性,但这种损失在沉积区得到很大恢复。而对于土壤真菌而言,侵蚀和沉积过程[19]都可能降低土壤真菌的 α 多样性和群落结构。部分研究对于导致水力侵蚀对土壤细菌和真菌多样性影响差异的主要原因进行探究,发现真菌具有较强的耐水性和较高的进化水平,且真菌的直径在 3～8 μm 大于细菌的直径 0.5～1 μm,细菌通常被保护在微孔和团聚体内部,而真菌则分布在大孔和团聚体表面[69],真菌对土壤侵蚀更敏感[70]。HONG 等[71]研究发现,相比于未开垦土壤,长期耕作的土壤的细菌多样性增加而真菌的多样性减少,土壤真菌群落相比于细菌和古菌更敏感。

目前,对于水力侵蚀对土壤微生物多样性影响的研究尚处于探索阶段,学者们多注重长期侵蚀沉积作用的典型坡地土壤微生物的种群数量和丰富度变化,而有关土壤微生物多样性对水力侵蚀过程的动态响应,以及在水力侵蚀过程中土壤微生物与有机碳的相互作用研究尚有不足。

2.2　水力侵蚀对土壤微生物多样性作用机制

水力侵蚀对土壤微生物多样性的作用机制引起了学者的研究兴趣[72]。部分研究[73]发现,土壤有机碳水平可影响水力侵蚀对土壤微生物多样性的作用。例如,WITZGALL 等[74]研究指出,因为土壤有机碳组分中难降解有机碳中的芳香结构难以被土壤微生物分解利用,因而土壤难降解有机碳含量越高,土壤可蚀性越小,从而减弱土壤侵蚀对微生物多样性的影响。HAO 等[19]通过黄土高原长期田间试验,对照不同有机碳水平(低、中、高)侵蚀区和沉积区微生物的多样性发现,有机碳水平的增加可抑制或减少水力侵蚀,从而改变水力侵蚀对微生物多样性的改变。水力侵蚀可能通过影响植被覆盖而影响土壤微生物多样性。GAN 等[75]研究表明,增加秸秆覆盖有利于土壤微生物活动,增加土壤微生物多样性;LI 等[76]研究表明,土壤微生物间接受到植被恢复的影响。水力侵蚀导致植被退化[77],这种作用可能间接影响土壤微生物的结构,但相关研究较少。土壤水分是微生物活动的重要决定因素,影响着土壤微生物的活性、转录和组成[78],土壤 pH 也是影响土壤微生物多样性和群落结构的主要因素[79]。水力侵蚀可能通过影响土壤水分和 pH[80],进而影响土壤微生物多样性,但相关研究较少。

虽然越来越多的学者关注土壤微生物在侵蚀过程中扮演的角色,但水力侵蚀对土壤微生物多样性的改变,及其对土壤碳循环的影响尚处于探索阶段,水力侵蚀对土壤微生物多样性的作用机制有待进一步量化研究,进而明确水力侵蚀过程中土壤微生物多样性与土壤碳循环的关系。

3　结论与展望

3.1　量化研究不同尺度水力侵蚀过程对土壤碳循环的影响机制

水力侵蚀对碳循环的研究已经取得丰硕的成果,但碳循环的“源汇”问题仍然是一个比较有争议的话题,其核心挑战在于水力侵蚀过程中有机碳矿化机制。未来应强化野外观测试验与室内人工模拟试验相结合,量化水力侵蚀全过程(剥离、搬运、沉积)有机碳矿化机制研究,明确不同尺度水力侵蚀过程对土壤碳循环的影响程度和影响机制。

3.2　量化研究水力侵蚀过程与土壤微生物多样性的相互作用机制

水力侵蚀过程对土壤微生物多样性的影响研究尚处于初步阶段,特别是水力侵蚀对不同类型土壤微生物多样性影响机制尚不明确。同时,土壤微生物的改变也会影响土壤侵蚀过程,两者相互作用机制有待进一步明确。多数研究停留在长期侵蚀下典型坡地侵蚀区和沉积区微生物种群相对丰度和多样性指标对比,缺乏土壤微生物对水力侵蚀过程的动态响应研究。基于野外观测和室内人工模拟降雨试验,揭示土壤微生物对水力侵蚀过程的动态响应机制,进而量化水力侵蚀过程与土壤微生物多样性的互作机制及其影响因素,是未来需着重关注的方向。

3.3　量化研究水力侵蚀过程中土壤微生物对碳循环的影响机制

水力侵蚀过程中土壤微生物对碳循环的影响机制研究尚处于探索阶段,特别是在水力侵蚀过程中微

生物对有机碳的矿化作用,以及在沉积过程中微生物对有机碳的分解利用和固存作用尚未量化。未来应加强多种典型坡地的野外试验观测,强化土壤微生物对水力侵蚀过程的动态响应机制,探讨水力侵蚀各过程微生物对有机碳迁移转化的作用机制,量化水力侵蚀过程中土壤微生物对碳循环的影响机制。

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