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植被恢复对土壤碳氮循环的影响研究进展*

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摘 要 植被恢复重建是治理水土流失的主要手段之一,能够有效地促进侵蚀土壤发育、提高土壤肥力、增强土壤微生物活性,进一步影响土壤碳氮循环.因此,植被的恢复重建过程对土壤有机碳库、氮库累积以及温室气体的排放具有一定作用.本文综述了植被恢复对土壤碳、氮循环过程的影响以及土壤质量与植被修复之间的协同效应,并提出了今后进一步研究的方向.对评价植被恢复在应对全球气候变化中所起的作用具有借鉴与参考价值,对促进土壤肥力改善和退化生态系统的恢复及可持续发展也有重要的现实意义.

关键词 植被恢复 土壤碳 土壤氮 循环
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Effects of vegetation restoration on soil carbon and nitrogen cycles: A review. WENG Bo-qi[1], ZHENG Xiang-zhou[2], DING Hong[2], WANG Huang-ping[2] ([1]*Institute of Agricultural Ecology, Fujian Academy of Agricultural Sciences, Fuzhou* 350013, *China*; [2]*Institute of Soil and Fertilizer, Fujian Academy of Agricultural Science, Fuzhou* 350013, *China*). -*Chin. J. Appl. Ecol.*, 2013, **24**(12): 3610-3616.

Abstract: Vegetation rehabilitation is one of the main means in managing soil and water loss, being able to effectively promote the development of eroded soil, improve the soil fertility level, enhance the soil microbial activities, and in further, affect the soil carbon and nitrogen cycles. Therefore, vegetation rehabilitation plays definite roles in the accumulation of soil organic carbon and nitrogen pools and the mitigation of greenhouse gases emission from soil. This paper summarized the effects of vegetation rehabilitation on the soil carbon and nitrogen cycles and the synergetic effects between soil quality and vegetation rehabilitation, and put forward the further research directions, which could provide the reference for the evaluation of the roles of vegetation rehabilitation in response to global climate change, and the practical guidance for the improvement of soil fertility and the recovery and sustainable development of degraded ecosystems.

Key words: vegetation rehabilitation; soil carbon; soil nitrogen; cycle.

土壤侵蚀(水土流失)是当今世界上最严重的环境问题之一.它不仅导致土壤退化、直接威胁到农业生产和粮食安全,而且作为一个重要的生物学过程,能够引起土壤有机C、N的组分和含量发生较大变化,对土壤碳氮平衡、陆地碳氮循环和全球气候变化产生很大的影响.据统计,我国已成为世界上水土流失最严重的国家,截至2004年,全国水土流失面积达 356×10^4 km^2,占国土面积的37%[1].

进入21世纪以来,我国先后启动实施了黄土高原淤地坝、京津风沙源、东北黑土区、珠江上游南北盘江、丹江口库区及上游、云贵鄂渝世行贷款和岩溶地区石漠化治理等一系列国家水土流失重点防治工程[2].恢复植被作为水土流失治理中的一项重要措施,有利于促进侵蚀土壤发育、改善土壤特性、提高土壤肥力[3].研究表明,植被类型显著影响林地土壤腐殖质形态、营养成分、碳氮和磷的矿化速率以及硝化和反硝化速率[4-5],从而进一步影响土壤碳氮的循环过程[6].

本文综述了生态修复过程与土壤碳氮循环过程的交互作用,试图揭示植被修复与土壤碳氮循环间的协同效应,以期为相关领域的深入研究提供理论参考与实践借鉴.

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1 植被恢复对土壤有机碳积累的影响

土壤有机碳库是陆地碳库的主要组成部分,在陆地碳循环研究中有着重要的作用[7]. 有资料显示,土壤有机碳(SOC)含量约占陆地生物圈碳库的三分之二,而每年有约占总量 4% 的 SOC 进入土壤碳库并以 CO_2形式释放,因而土壤中的有机碳既是碳汇又是碳源[8]. Lal[9]认为,水土流失地区的植被恢复重建具有很大的固碳潜力,估计全球范围内退化土壤恢复的固碳潜力高达 0.3 ~ 0.8 Pg · a^{-1}. 同时,植被恢复还能够通过有效控制土壤侵蚀减少土壤碳损失 0.6 ~ 1.1 Pg · a^{-1},是增加土壤碳汇的重要手段.

Garcia 等[10]和 Gil-Sotres 等[11]指出,水土流失地区植被恢复一方面增加了地表的植被覆盖,减少了土壤侵蚀和养分的流失;另一方面,植物残体、根系以及根系分泌物的存在还增加了向土壤输入的有机物质. 因此,在植被修复的过程中,水土流失区土壤质量得到较大幅度提升,有机碳库储量明显增加. Post 和 Kwon[12]研究也表明,植被恢复能够大幅度提高土壤有机碳含量,退耕还林和还草的年均固碳速率分别为 33.8 和 33.2 g · m^{-2},持续时间可达 50 ~100年. 还有研究指出,在一些树龄大于 400 年的老龄林,土壤(0 ~20 cm)仍具有较高的碳积累能力,达到每年 610 kg · hm^{-2} [13].

近年来,我国许多学者对黄土高原水土流失区植被恢复后土壤质量演变进行研究,发现植被恢复后土壤养分状况得到显著改善,土壤中有机碳储量明显提高[14-15]. 黄宗胜等[16]、郑华等[17]、Tang 等[18]、Zuo 等[19]在我国喀斯特地区、红壤侵蚀区和科尔沁沙地的研究也得出了相似的结果. 在侵蚀退化地区植被修复过程中,植被通过光合作用向土壤输送有机物质,并从土壤中吸收养分,从而对土壤有机碳的周转和积累产生深刻的影响. 从现有的研究结果看,植被恢复地区每年都有大量枯枝落叶进入土壤,经微生物腐解后形成较多腐殖质,使土壤有机质增加,土壤理化性质得到明显改善,土壤有机碳库储量显著增加. 因此,植被恢复被证明是一个重要的碳汇.

马祥华和焦菊英[20]的研究进一步表明,在整个修复过程中,土壤有机碳库呈先减少后增大的趋势. 但不同的植被恢复类型对土壤有机碳累积的贡献存在很大差异[21]. 从现有的研究结果看,植被恢复地区的有机碳累积速率多表现为林地>灌木>草地>撂荒地[22],其中,次生林又大于人工林[17].

也有学者认为,在水土流失情况下,植被恢复对土壤碳素积累的贡献会因土壤侵蚀而减弱,甚至还有可能增加土壤碳的流失[23]. 黄荣珍等[24]在我国南方红壤区的研究也印证了这一看法,侵蚀退化红壤分别修复为马尾松林和湿地松林后,0 ~ 80 cm 土层的土壤有机碳储量分别增加至 49.06 和 83.17 t · hm^{-2},但仍低于我国亚热带常绿阔叶林和亚热带、热带常绿针叶林及亚热带、热带灌丛矮林的土壤有机碳储量(95 ~124 t · hm^{-2})[25]. Dou 等[26]指出,由于存在水土流失,长汀县红壤侵蚀地修复时间为 10 年的马尾松林土壤中的碳含量和未修复土壤相比并没有得到显著增加,同时,老碳的衰变速率还要高于恢复龄为 18 ~30 年的森林土壤.

植被恢复不仅影响土壤有机碳含量,还对有机碳在土壤中的分布和组成产生影响. 有研究表明,植被恢复对土壤有机碳的影响存在着较强的表聚效应,尤其是 0 ~10 cm 土层土壤有机碳含量和储量受植被恢复的影响最大,40 cm 以下深度土层有机碳受植被恢复的影响很小[22]. 同时,植被恢复治理还明显提高了侵蚀地土壤的腐殖质品质[27],土壤中活性有机碳的含量和比例也随着恢复的年限增加逐渐提高[28].

总之,植被恢复进程实际上就是植被与土壤相互影响和相互作用的过程,期间植被-土壤复合系统通过相互作用增加了土壤有机物的输入,明显增加了土壤有机碳库的累积,还对提高土壤有机质品质起到积极作用.

土壤呼吸是土壤有机碳损失的主要形式,也是温室气体 CO_2产生的主要途径. 一般来说,随着植被覆盖度的提高,生态系统向土壤输入的碳素增加,同时也增大了土壤呼吸所释放的碳素[29-30]. 从现有的研究结果看,植被修复过程显著增加了土壤的呼吸作用,在一定程度上也增加了土壤的碳排放量. 究其原因主要在于两方面:一方面,土壤有机碳是土壤呼吸的底物,植物修复会提高土壤有机碳含量,导致土壤中更易被微生物利用的活性有机碳含量增加[27-28];另一方面,植被恢复能通过改善土壤微生物群落的组成和结构、增强微生物活性来促进土壤呼吸作用[28].

2 植被恢复对土壤氮累积的影响

氮是植物生长和发育所需的大量营养元素之一,也是植物从土壤中吸收量最大的矿质元素[31].

在植被恢复的过程中,植物主要通过根系分泌物和植物残体向土壤提供碳、氮,影响土壤氮的输入,进而显著改变土壤性质[32]. 同时,植被修复还有效防止了由于土壤侵蚀而造成的氮素损失,有利于土壤中氮库的积累.

Knops 和 Tilman[33]研究结果表明,沙原撂荒地植被自然恢复明显提高了土壤养分含量. 近年来,不少学者对我国各个植被恢复区生态恢复状况展开研究,发现植被恢复均显著提高了土壤中全氮和速效氮含量[34-35]. 王国梁等[36]研究发现,在 11 种不同的植被恢复类型下,表层土壤(0 ~20 cm)的全氮含量均大于 20 ~40 cm 土层,反映出植被恢复对土壤氮素累积的影响呈现向上富集的规律. 这与植被恢复过程中土壤有机碳的富集规律一致. 但不同植被类型对土壤氮素累积速率的影响存在明显差异[34]. 王凯博等[37]、李贵才等[38]认为,与人工林相比,天然恢复植被(天然次生林)土壤中的有机碳、全氮积累速度更快,因而对土壤氮库累积的作用效果更明显. 这可能与凋落物的种类和数量有关. 植被类型决定凋落物的积累,天然恢复植物群落的物种丰富度、多样性指数均明显高于人工林,大量凋落物和根系分泌物为土壤提供了充足的养分,因此土壤中有机碳和总氮含量也相对较高. 王春阳等[39]研究表明,与单种凋落物相比,不同种类植物凋落物混合加入土壤,明显增加了土壤微生物碳氮含量,降低了土壤矿质氮含量,减少了无机氮损失,增加土壤氮素的固持. 在植被恢复重建过程中采用不同种类植物搭配,有利于土壤氮素的累积. 但是刘西军等[40]发现,针叶林(人工杉木林)土壤中的氮含量反而高于针阔混交林. 这可能与当地的植被修复时间较短,且杉木为速生树种,在植被恢复初期,杉木林的生物量累积速率高于针阔混交林有关. 然而,目前关于不同植被修复措施对土壤氮素累积影响的相关机理研究还比较少.

就土壤中的无机氮形态而言,有不少研究表明,植被恢复后森林土壤中的无机氮以 NH_4^+-N 为主,并且随着植被的恢复进程,土壤中 NO_3^--N/NH_4^+-N 逐渐下降[38,41]. 而李明锐和沙丽清[42]认为,NO_3^--N 是无机氮的主要存在形式,氮的净矿化速率与硝化速率呈正相关,这可能和不同的植被修复类型有关. 赵溪等[43]研究表明,虽然不同植被类型间土壤硝态氮和铵态氮含量存在差异,但季节间无机氮的差异远大于植被类型间的差异,而且硝态氮的季节变化幅度较铵态氮大.

经过植被恢复治理,植被修复地区土壤中氮素储量(全氮含量)和供应强度(无机氮含量)均得到一定程度的改善,特别是在植被恢复的前期(10 ~20 年)土壤中的全氮含量迅速增加,之后逐渐趋于稳定,甚至随着群落的衰退开始降低[44-45]. 同时,植物恢复还对土壤氮素转化过程及存在形态都产生很大影响,但在不同区域(土壤母质以及气候条件)、不同植被修复类型下其影响效果不一致.

3 植被恢复对土壤碳氮交互作用的影响

土壤碳氮循环是生态系统的重要功能过程,二者相互作用、相互影响,共同调节和维持着生态系统的生产力和稳定性,并且与全球变化密切相关. 土壤碳氮循环之间的交互作用已经逐渐成为了当前的研究热点之一. 近年来,国内外不少学者针对土壤中碳氮循环的交互作用展开了研究.

土壤有机碳库动态变化包括积累和矿化两个过程[46]. 相关性分析发现,地表群落的生物量与土壤中全氮含量呈极显著的正相关关系. 因此,土壤中的氮主要通过影响作物生长来影响土壤有机物的输入量,进而造成土壤有机碳含量的差异[47]. 随着植被恢复年限的增加,水土流失区土壤中有机碳和全氮含量逐渐增加,二者呈显著的正相关关系. 土壤有机碳的矿化指土壤中的有机质在微生物作用下分解释放 CO_2的过程. 该过程受到很多因素的影响与调节,其中土壤氮素含量变化必将直接对土壤有机碳矿化作用产生影响[48].

土壤氮转化直接影响到氮素在土壤中的累积及其有效性,是陆地氮素循环中最重要的环节之一. 这一过程受到土壤温度、含水量、理化性质以及微生物活性等诸多因子的影响. 有机质(有机碳)作为土壤微生物的碳源和能源物质,其在土壤中的含量和组成情况必将对氮素转化过程产生重要影响. 有研究表明,土壤氮素的矿化作用和反硝化随土壤有机质(有机碳)含量升高而增强[49-50]. 这主要是由于随土壤有机质含量的提高,土壤中可矿化有机氮与可被微生物利用的活性碳的比例逐渐升高. 然而,对于土壤有机质(碳)与氮素硝化作用之间的相关关系,不同学者的研究结果存在较大差异. 如 Merino 等[51]和 Gill 等[52]研究发现,外源有机碳的添加明显促进了土壤的硝化作用;然而,贾俊仙等[49]认为,在红壤水稻土上,不论是外源有机碳的添加还是自身有机碳含量的差异均不对其硝化作用产生明显影响;还有学者认为,有机碳加入土壤可促进微生物活动,使

O_2供应不足，导致自养微生物参与的硝化作用减弱[53].

在水土流失地区植被重建的过程中，不同的植被类型和恢复时间通过影响土壤有机碳和氮的含量及组分，对土壤碳氮的交互作用产生影响. 然而目前对于植被恢复过程中土壤氮碳循环之间的相互关系的研究还比较少.

近年来，有些学者对植被恢复下土壤微生物 C、N 的变化展开研究，发现随着恢复年限的增长，土壤微生物生物量 C、N 显著升高[43,54]，这与土壤中 SOC 和总氮(TN)的变化规律一致. Jia 等[55] 指出，土壤微生物量与土壤 SOC、TN 之间呈现极显著的正相关关系($P<0.01$). 但不同的植被修复类型对土壤微生物 C、N 的影响效果明显不同. 张水印等[56] 在南方红壤区的研究结果表明，植被重建对土壤微生物 C、N 的影响表现为阔叶林优于针阔混交林优于无林荒草地，针叶林的恢复效果最差；薛莲等[57] 在黄土高原区的研究则认为，混交林的作用效果最佳，纯林次之，无林荒草地的作用效果最差. 土壤微生物生物量 C、N 对于评价植被修复的效果具有很大价值. 它不但能够快速反映土壤理化性质的变化趋势，还能够在植被修复的早期就区分出不同修复类型间作用效果的差异.

4　水土流失区植被恢复过程与土壤质量的协同效应

采用水土保持措施实现水土流失地区的植被修复，不仅可以有效保持水土、减少土壤侵蚀，还可以通过植物-土壤系统的协同作用改善侵蚀地区土壤理化性质，增加土壤微生物种群和数量等，达到修复土壤质量的目的. 不少研究发现，水土流失地区植被重建除了能够增加土壤有机碳库以及化学养分含量外，还显著降低了表层土壤(0 ~ 20 cm)容重，增加了土壤孔隙度和田间最大持水量[58-59]. Zhu 等[60] 研究还发现，植被恢复过程明显提高了表层土壤中 >0.25 mm 水稳性团聚体的含量，土壤物理结构得到明显改善. 此外，与土壤中有机碳、氮的累积规律相似，随着植被的恢复，表层土壤物理结构的改善幅度明显大于下层土壤[57].

土壤肥力也是植物演替过程的重要驱动因素[61]. 在植被恢复过程中，土壤为植物生长提供了水分和矿质营养，其含量不仅影响植物的个体发育，更进一步决定着植物群落的类型、分布和动态[62]. 何小琴等[63] 研究发现，随着恢复植被群落的演替，土壤中有机质和 N、P 等养分不断发生改变，植被群落通过影响 N、P 等元素的生物地球化学循环过程，反过来又决定了群落演替的进展方向. 杜峰等[61] 的研究也间接印证了这一看法，撂荒初期植物群落能迅速利用现有土壤养分资源，因此在这一阶段群落的生物量相对较高；之后，随着植物的消耗，土壤养分开始成为植被恢复的限制因子，植物群落逐渐演替为生长较慢、更耐贫瘠的种群；随着土壤养分的逐步修复，恢复植被群落的生物量又开始随着增加. 当然，由于区域气候条件、土壤母质和恢复群落类型的差异，土壤质量对群落结构与演替的影响也不尽相同.

研究发现，植被恢复地上生物量与土壤总孔隙度、大团聚体、水稳性大团聚体、有机质含量、全氮、磷、钾、速效钾和速效磷含量和微生物量(碳、氮、磷)之间呈正相关关系，是限制植被恢复的主导因素[64-65]. 马祥华等[65] 认为，土壤有机质含量对植被的影响最显著. 杜峰等[61] 指出，恢复植被地上生物量与土壤全氮含量的相关性最高，这可能与不同土壤母质条件和植物群落的构成有关.

在水土流失(土壤侵蚀)地区的植被恢复过程中，植被与土壤系统相互作用、相互影响，共同决定着植被恢复重建的进程.

5　研究展望

目前，国内外许多学者围绕不同植被恢复措施对土壤质量(包括土壤碳氮的变化)的影响进行了深入探讨，对指导水土流失区的植被恢复与生态重建实践起到了积极作用. 由于水土流失和植被恢复重建过程的复杂性，相关研究工作还存在着不少薄弱环节. 今后应该加强以下几个科学问题的研究.

1)要加强植被恢复重建过程对土壤氮库和碳库累积的机理研究. 关于植被恢复后土壤质量演变已展开了大量研究工作，但大多集中在植被恢复后土壤养分和物理学肥力的演变上. 关于植被恢复对土壤碳氮积累的影响机制以及碳氮驱动下土壤质量演变机理等的研究还比较少. 加强相关科学问题的研究可以深入了解植被恢复重建进程与土壤碳库、氮库形成之间的交互作用，为土壤碳汇的构建以及氮素的有效性评价提供科学依据.

2)要加强生态恢复过程中土壤碳库、氮库累积与损失过程的综合研究. 在生态恢复过程中，随着地表植被的恢复，土壤中的有机碳、全氮含量也随之增加. 尽管土壤侵蚀程度得到改善，但因水土流失所带

来的碳素和氮素损失可能反而增加. 在侵蚀严重的地区,一般土壤中营养元素的基础含量也较低. 侵蚀劣地植被恢复后,向土壤中输入的碳、氮也相应增多,从而增大了其因侵蚀损失的可能性. 目前的大多数研究还是仅仅考虑生态恢复与土壤有机碳、氮存量之间的相关关系,而把侵蚀这一重要过程割裂开来,缺少对植被恢复重建过程中土壤作为碳库、氮库源和汇的综合性评价. 加强相关领域的研究能够进一步明确植被恢复过程对土壤碳氮累积的影响机理.

3)要加强植被恢复与土壤温室气体排放的相关机制研究. 植被恢复增加了土壤中有机碳和氮素含量,增大了土壤呼吸所释放的碳素,也为硝化反硝化过程提供了反应底物以及较为充足的能源,因此有可能会对土壤温室气体(主要是 CO_2 和 N_2O)的排放产生影响,进而影响到全球气候变化. 然而,目前国内外对这一过程带来的 CO_2 和 N_2O 等温室气体排放的研究工作相对缺乏,加强相关研究可以更全面地认识植被恢复过程与全球气候变化的关系.

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