DOI: 10.20103/j.stxb.202303070424
赵广, 张扬建.大气 CO_2浓度升高对土壤碳库稳定性的影响.生态学报,2023,43(20):8493-8503.
Zhao G, Zhang Y J.Effect of elevated CO_2 on the persistence of soil carbon pool.Acta Ecologica Sinica,2023,43(20):8493-8503.

大气 CO_2 浓度升高对土壤碳库稳定性的影响

赵 广[1,*], 张扬建[1,2,3]
1 中国科学院地理科学与资源研究所, 生态系统网络观测与模拟重点实验室, 拉萨高原生态试验站, 北京 100101
2 中国科学院青藏高原地球科学卓越创新中心, 北京 100101
3 中国科学院大学资源与环境学院, 北京 100190

摘要:工业革命以来,大气 CO_2浓度持续上升,升高的 CO_2浓度会改变植物光合产物积累、土壤碳库的碳输入和碳输出过程,进而通过影响有机碳组成和周转特征来调控土壤碳库动态变化。土壤碳库是陆地生态系统碳库的重要组成部分,其碳储量的微小变化都会对大气 CO_2浓度和气候变化产生巨大影响。但目前关于 CO_2浓度升高对土壤碳库动态和稳定性的影响还不清楚,很大程度上限制了预测陆地生态系统碳循环对气候变化的反馈。系统综述国内外大气 CO_2浓度升高对植被生产力、植被碳输入和土壤碳库影响的研究进展,旨在揭示土壤碳库物理、化学组成以及周转特征对 CO_2浓度升高的响应过程和机理,探讨 CO_2升高情境下土壤微生物特征对土壤碳库稳定性的影响和驱动机制,为深入理解全球变化下的土壤碳循环特征提供理论支撑。
关键词:气候变化;土壤有机质;碳循环;土壤微生物

Effect of elevated CO_2 on the persistence of soil carbon pool

ZHAO Guang[1,*], ZHANG Yangjian[1,2,3]
1 *Lhasa Station, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Science and Nature Resources Research, Chinese Academy of Science, Beijing* 100101, *China*
2 *Center for Excellence in Tibetan Plateau Earth Science, Chinese Academy of Science, Beijing* 100101, *China*
3 *College of Resources and Environmental, University of Chinese Academy of Science, Beijing* 100190, *China*

Abstract: Human activities have raised CO_2 concentrations in the atmosphere more than 40% above their pre-industrial level, and this rising trend is projected to continue for the coming decades. As a critical part of climate change, elevated CO_2 and its subsequent effects on terrestrial ecosystems have been increasingly investigated, either solely or in combination with other environmental factors. Numerous studies suggest that elevated CO_2 can enhance photosynthesis, productivity, and net ecosystem productivity, suggesting stronger CO_2 uptake by ecosystems, which could counteract the global warming. As a primary carbon pool, small changes in soil organic carbon can drive tremendous variations in atmospheric CO_2 concentrations, increasing the uncertainties in forecasting climate change. However, the impact of elevated CO_2 on the dynamics and persistence of soil carbon pools remains unclear, which largely limits the prediction accuracy of terrestrial carbon cycling in response to climate change. This paper systematically reviews the domestic and international research progress of elevated CO_2 on plant net primary productivity, plant inputs, and soil carbon pools, aiming to reveal the response mechanism of physical, chemical composition, and turnover characteristics of soil carbon pools under elevated CO_2. We further explore the driving mechanisms of soil microorganisms and nitrogen availability on the dynamics and persistence of the soil carbon pool under elevated CO_2, providing theoretical support for an in-depth understanding of soil carbon cycling with further global changes.

基金项目:国家自然科学基金项目(42101067)
收稿日期:2023-03-07; **采用日期**:2023-07-21
* 通讯作者 Corresponding author.E-mail: zhaoguang@ igsnrr.ac.cn

Key Words: climate change; soil organic matter; carbon cycling; soil microorganisms

大气CO_2浓度自工业革命以来持续升高,预计21世纪末大气中的CO_2浓度将达到600—800×10^{-6}[1]。大气CO_2浓度升高可以增强植被光合作用、生态系统净生产力和固碳能力,在一定程度上可能会降低CO_2浓度持续升高的趋势,进而减缓全球变暖。然而,这些报道主要集中在陆地生态系统地上过程[2—3],对地下过程的研究还相对较少[4—5]。

土壤有机碳库是陆地生态系统碳库的主要组成部分[6],其碳储量的微小变化都会对大气CO_2浓度和气候变化产生巨大影响[7]。CO_2浓度升高可以改变植物光合产物积累、土壤碳库的碳输入和碳输出过程,进而通过影响有机碳的组成、周转和稳定性来调控土壤碳库动态变化[8—10]。目前,土壤碳库对大气CO_2浓度升高的响应仍存在较大不确定性[11],极大地限制了对未来气候变化的准确评估和预测[12]。一方面,大气CO_2浓度上升可以通过提高植物光合能力和植物固碳量来增加对土壤的碳输入,使土壤逐渐成为一个潜在的碳汇[13]。另一方面,增加的外源碳输入会促使土壤有机碳矿化产生正的"激发效应",加速土壤有机碳矿化分解和周转,从而降低土壤有机碳含量并使之成为潜在的碳源[4,14]。这些不确定性的一个重要原因是土壤有机碳形成过程、赋存形态和稳定机制还不明确[7,15],少有研究从有机碳的组成、周转和土壤微生物这三个关键过程综合揭示土壤碳循环的响应过程和机制。因此,CO_2浓度升高对土壤有机碳组成、周转过程的影响及其微生物驱动机制成为全球变化领域亟待解决的重要科学问题,厘清大气CO_2浓度上升情景下土壤碳库动态特征和稳定机制,对于探明气候变化下土壤"碳源/汇"功能具有重要意义。本文通过综述国内外大气CO_2浓度升高对土壤有机碳库影响的研究进展,旨在揭示土壤碳库物理、化学组成以及周转特征对CO_2浓度升高的响应过程和机理,探讨CO_2升高背景下土壤碳库稳定性的变化和微生物驱动机制,为深入理解全球变化下的土壤碳循环特征提供理论支撑。

1 大气CO_2富集试验研究方法

人工气候室(CE)、开顶式气室(OTC)和自由空气CO_2浓度升高技术(FACE)是国内外模拟生态系统对大气CO_2浓度升高响应和适应最常用的3种方法[16]。其中,人工气候室易形成"气室效应",研究结果很难客观反映自然环境下大气CO_2升高对植物和土壤的真实效应,应用逐渐减少。FACE试验没有采用任何隔离设施,是最接近自然环境的CO_2浓度升高技术,因此成为研究大气CO_2浓度升高对生态系统影响最理想的方法[17]。1989年,美国科学家在亚利桑那州的农田建设了第一个FACE试验,随后在全球范围内陆续建设了几十个基于森林、农田、草地和荒漠的FACE试验,极大地推动了大气CO_2浓度变化对陆地生态系统碳循环影响的研究[17]。但在某些长年多风区域,FACE系统很难将空气CO_2浓度升高并稳定在一定浓度,且其高昂的运行成本限制了该方法大规模推广和应用。OTC法是目前世界上另一种应用较多的空气CO_2浓度控制方法,其顶部或者底部可以通风,其内部环境较为接近自然状态,研究结果具有一定说服力。国内相关研究始于20世纪90年代,现已有学者采用FACE法或OTC法开展大气CO_2升高对森林、农田和草地生态系统影响的研究[18—23],取得了一系列成果。

2 CO_2浓度升高对植被生产力和碳输入的影响

大气CO_2浓度上升对植物生长的影响已取得基本共识,即CO_2浓度上升提高植物群落的光合能力、地上生物量、净初级生产力,从而增大了地上植被对土壤碳库的碳输入[24—26],但是不同植被类型生产力对的响应程度存在差异[27]。例如,森林和其他生态系统类型相比在CO_2富集下表现出更强的光合能力和生产力的提升[28—29],这与森林水分利用效率显著升高有关。基于遥感数据的研究也发现,近三十年撒哈拉以南的非洲地区树木覆盖率增加了8%[30],表明未来CO_2浓度升高可能会导致树木向干旱半干旱区草原生态系统入侵,从而增加对土壤的碳输入。此外,相较于C_4植物,C_3植物对CO_2富集具有更高的敏感性,C_3植物的光合作用对

CO_2 升高的响应更强且生产力增加量更大[24]。这可能是因为 C_4 植物本身叶片结构具有较强的 CO_2 吸收和固定能力,导致对外界环境中升高的 CO_2 浓度不敏感。因此,C_4 植物的竞争力在大气 CO_2 浓度持续升高背景下会减弱[31]。

大气 CO_2 浓度升高除了直接影响植被碳输入的数量,也会影响碳输入的质量。一方面,许多研究发现大气 CO_2 浓度升高会升高植物组织碳氮比(C∶N),而凋落物分解过程一定程度上受到植物组织 C∶N 比的影响[32—33],这对陆地生态系统的碳循环和碳固存产生重要影响[34—35]。此外,CO_2 施肥效应很大程度上受到生态系统氮有效性的限制[36—38],近几十年持续的大气氮沉降可能会在一定程度上降低氮限制对 CO_2 施肥效应的影响[39],通过降低凋落物 C∶N 比[40]促进土壤碳库增加。另一方面,CO_2 浓度升高也会影响植物的化学组成。Hall 等[41]对桃金娘栎(*Quercus myrtifolia*)叶片化学组成的分析显示,CO_2 浓度提升会显著增加叶片中木质素和半纤维素的含量。在农田生态系统,CO_2 浓度升高可以增加秸秆中非结构碳水化合物和总糖的含量[42],但是对作物籽粒的氮、锌、镁等营养元素会产生稀释作用,未来有降低作物品质的风险[43]。

CO_2 浓度升高也会影响植被不同器官之间的生物量分配[44]。由于植被地上和地下凋落物处在不同的环境条件(温度和湿度)中,植物凋落物的分解速率存在显著差异,进而对土壤碳循环过程产生重要影响[12,45—46]。有研究发现,土壤根际微生物对土壤稳定性有机碳的形成具有更高效率,因为从地下输入的植被碳可以更有效地形成土壤矿质结合态有机碳[47]。即如果环境变化导致植被地下碳输入增加,土壤有机碳库的稳定性可能会升高。因此,研究 CO_2 浓度升高下的植物生物量分配策略对于探讨和预测土壤碳库的稳定性具有重要意义。目前,CO_2 浓度升高对植物生物量分配还没有统一结论,其分配策略因物种和生态系统类型而异[14,48]。例如,研究表明豆科和非豆科木本植物的总生物量在 CO_2 浓度升高下均显著升高,但其生物量分配策略却存在差异:豆科木本植物将更多的生物量分配至地上,而非豆科木本植物倾向于分配到地下根系生长,表明相较于非豆科植物,豆科植物可能未产生明显的氮限制[49]。对于 C_3 和 C_4 植物,CO_2 浓度升高显著 C_3 植物细根生物量,而 C_4 植物细根生物量则没有受到影响[50]。基于全球整合分析发现,虽然 CO_2 浓度升高刺激生态系统地上和根的生物量增加,但是显著升高了植物根冠比(+8.5%),促进植物根系系统发育。从生态系统类型来看,草地生态系统根冠比升高幅度最大(+17.1%),农田作物根冠比增加 12.2%,森林根冠比变化最小(+3.5%)。草地和农田生态系统可能通过增加对植被地下根系的氮和生物量分配,来缓解 CO_2 浓度升高引起的土壤氮限制[51—53]。而对于森林生态系统,其根冠比变化不大,有些森林甚至会在大气 CO_2 浓度升高时减少对地下生物量分配,这与 CO_2 浓度升高提升植物水分利用效率、缓解森林水资源限制有关[54],因为水资源需求下降会降低对植物根系的依赖[55]。

此外,越来越多的研究发现,大气 CO_2 浓度升高对植被生产力和生物量分配的影响与生态系统养分有效性有关[56—58],二者共同影响土壤碳库大小和稳定性。Terrer 等[59]通过分析全球 CO_2 加富试验的数据,发现 CO_2 浓度升高对土壤有机碳储量的影响与植物生物量呈负相关。即当植物生物量受到 CO_2 施肥效应促进时,土壤有机碳储量下降;相反,当植被生物量受到施肥效应的促进较弱时,土壤有机碳储量增加。这种权衡与植物的养分获取策略有关,如果植物通过矿化土壤有机质获取养分来增加生物量,土壤有机碳储量就会下降。全球范围内,尽管草地生态系统生物量的增加比例(9±3%)远低于森林生物量增加量(23±2%),但草地土壤有机碳储量随着 CO_2 浓度升高显著增加(8±2%),而森林则未呈现明显增加趋势(0±2%)。这些报道为今后 CO_2 浓度升高对陆地生态系统碳循环研究提供了新的思路。

3　CO_2 浓度升高下土壤微生物介导的土壤碳库稳定性变化

土壤微生物群落特征是影响土壤有机碳动态及其稳定性变化的重要因素[60—61]。大气 CO_2 浓度上升可以通过改变凋落物的质量、数量以及土壤微生物环境,影响微生物群落结构及其演替过程,导致土壤微生物对有机质的分解偏好和分解速率发生变化[3,62—63],一定程度上决定了土壤有机碳的分解过程和稳定性[64—67]。研

究表明,CO_2浓度升高可能通过改变微生物组成,降低土壤碳库稳定性。例如,在半干旱生态系统中,土壤真菌丰度和多样性在 CO_2浓度升高时显著升高,土壤有机碳矿化速率加快[68—69]。普遍认为土壤真菌在有机质分解后期有优势,可降解植物残体中较难被利用的组分[70](如木质素),表明 CO_2浓度升高可以通过改变微生物群落组成来影响土壤不同碳库分解过程。Carney 等[64]和 Drigo 等[71]也发现土壤真菌和细菌比值在大气 CO_2浓度升高后上升,并认为这可能会降低土壤有机碳含量,不利于土壤持续固碳。然而也存在相反的结论,如连续十年的大气 CO_2加富试验虽然提高草地土壤总的微生物量和细菌生物量,但对土壤真菌生物量无明显影响,与惰性碳分解相关的微生物丰度也没有发生变化[65]。Brenzinger 等[72]和 Koyama 等[73]也发现土壤微生物结构在大气 CO_2浓度升高过程中变化不显著,并认为研究区的植被和土壤类型是决定微生物群落特征更为重要的因素。近几年基因功能芯片技术日趋成熟,把对土壤微生物的认识上升到基因功能水平,极大拓展了对土壤微生物群落结构和功能的认识,是研究大气 CO_2浓度升高对土壤微生物影响的有效手段。例如,基于基因功能芯片的研究发现,CO_2浓度升高改变了土壤中参与碳循环的功能基因丰度,如与淀粉、纤维素和半纤维素分解相关的功能基因丰度显著升高,与氮循环相关的两种功能基因(*nifH* and *nirS*)丰度也随之升高[74]。另一项研究显示,与有机碳降解相关的微生物基因明显受到 CO_2升高的促进作用影响,而与碳固定相关的微生物基因则基本保持不变[75],这种响应程度很可能受到生态系统氮有效性的影响[76]。目前,土壤微生物对大气 CO_2浓度升高的响应还没有较为一致的结论,很大程度上与微生物群落真实存在的响应差异以及各生态系统的自身复杂性有关[62],而研究方法或技术的多样性可能会导致研究结果产生差异[65]。

土壤氮素有效性是研究大气 CO_2浓度升高背景下土壤微生物驱动土壤有机碳动态变化不可忽视的因素[61]。全球多数生态系统受到氮限制[37],这种限制在大气 CO_2升高的条件下会加剧[77]。大气 CO_2浓度上升时,植物光合能力升高,促进对土壤有机碳的输入增加,间接导致更多氮素被固定在土壤有机质中[78],进而降低土壤有效氮含量[36,60—61]。渐进氮限制理论[36]认为,随着碳素和氮素不断被固定在植物体和土壤有机质中,土壤氮素有效性的限制作用加强,逐渐成为调控有机质分解的主要限制性因素。土壤氮的有效性和土壤微生物群落特征紧密联系,土壤有效氮含量可以直接或间接影响土壤微生物生长速率和群落结构[79],反过来土壤微生物可以通过调节土壤 C∶N 比来影响土壤有机碳的矿化分解过程[61]。例如,大气 CO_2浓度升高后,土壤氮限制促使土壤微生物优先分解缓性有机碳,因为缓性有机碳相对于活性有机碳具有更低的 C∶N[80]。Butterly 等[81]发现,与土壤有机质碳、氮矿化、硝化以及反硝化作用等相关的功能基因丰度在大气 CO_2浓度上升时降低,同时和土壤 C∶N 比表现出显著相关性。相反,一些研究发现通过加快土壤氮矿化速率、提高氮吸收效率、增强土壤氮的有效性可以部分满足由大气 CO_2升高引起的氮需求。此外,通过激发特定的微生物功能,例如 N_2固定基因[70,82—83],也可以提高升高生态系统氮的有效性。同时,研究发现在氮限制生态系统中,通过外源氮添加可以缓解大气 CO_2浓度升高带来的土壤氮限制[84],但当外源氮输入超过一定限度时,土壤有效氮浓度过高会抑制土壤微生物的活动,不利于土壤有机碳增加[85]。

4 CO_2浓度升高对土壤碳库组成及其稳定性的影响

大气 CO_2浓度升高对土壤碳库储量和稳定性的影响还存很大在争议[3,4],土壤有机碳储量增加、减少或者维持不变的结果均有报道[86],碳库的稳定性变化趋势还不清晰。这除了和土壤有机碳库储量巨大、短时间变化不易甄别外,更多的与土壤有机质理论滞后和测试技术限制有关。传统的土壤腐殖质经典理论认为土壤有机碳的形成与植物源有机碳密切相关,即植物残体被分解成小分子化合物随后经过复杂的腐殖化过程形成高分子多聚物[87]。然而,随着研究手段和分析技术的快速发展,越来越多的研究发现土壤微生物在有机碳的形成和转化过程中起重要作用:土壤微生物既可以作为分解者调控非生物源碳的周转过程,也可以作为贡献者影响微生物来源碳的形成[12,88—89]。基于此,土壤有机质被定义为是由一系列大小各异,分解程度不同的植物源和微生物源有机碳组成的混合连续体组成[90]。这些动植物及微生物残体,经由复杂的微生物和土壤物理

化学转化过程,以不均匀混合物状态稳定存在于土壤中。整体而言,土壤有机质的来源和组成复杂、周转速率各异,非微生物和微生物来源物质对有机质形成和积累起重要作用。

由于凋落物的质量和数量、微生物代谢过程、土壤呼吸分解以及环境因素变化等都会影响土壤有机碳特征及其稳定性[17],使土壤有机碳在大气 CO_2浓度升高后表现出在物理组成上[91—94]、化学组成上[41, 73, 95—96]和周转上[4,85,97]变化的复杂性。可见,为阐明 CO_2浓度升高对土壤有机碳库的形成与稳定机制,需进一步刻画土壤有机碳的物理和化学组成变化和周转机制,从机理上提升对土壤有机碳库循环的理解(图 1)。

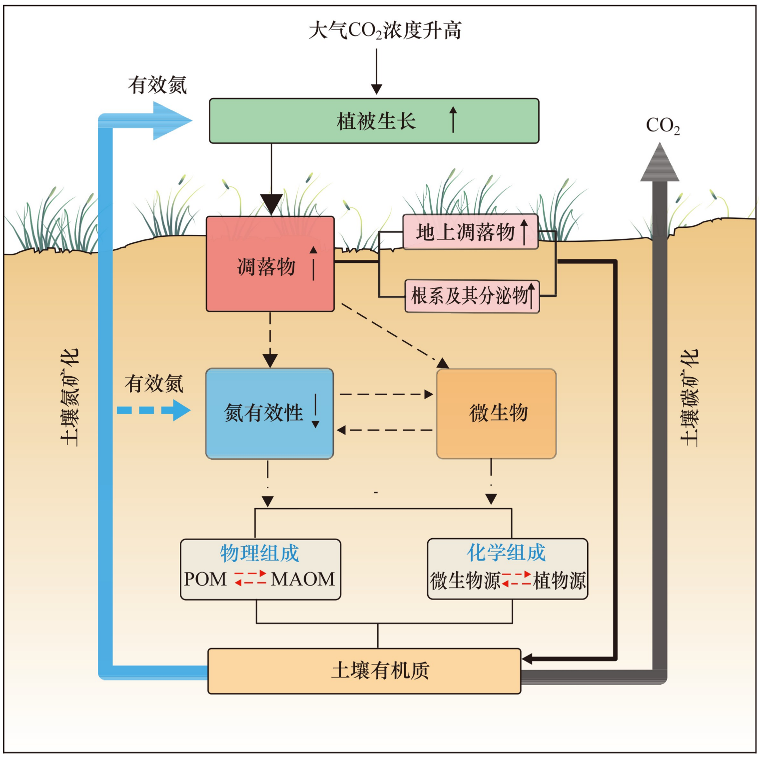

图 1　大气 CO_2浓度升高对土壤碳循环及其稳定性的影响

Fig.1　Conceptual framework, representing the soil organic matter cycling under elevated CO_2

POM: 颗粒态有机质 Particulate organic matter; MAOM: 矿质结合态有机质 Mineral-associated organic matter

4.1　CO_2浓度升高对土壤有机碳物理组成的影响

在土壤有机碳物理组成方面,有研究发现 CO_2浓度升高会改变土壤活性碳库组分,而对土壤稳定碳库的无显著影响[11,98]。土壤物理结构对有机碳的稳定性具有重要作用,作为土壤碳库中相对稳定的组分,微团聚体组分与粉-黏团聚体组分中的有机碳性质相对不活跃, 对土壤微生物的降解有较强的抵抗力, CO_2浓度升高引起的微生物活动增强对粉-黏团聚体有机碳的分解效应较小,因而有利于土壤碳库稳定性[99]。传统研究方法将土壤有机碳库作为一个整体或分解为几个简单的碳库, 难以有效甄别不同有机碳组分对环境变化的响应。为了更有效地研究土壤有机碳的形成和稳定机制,越来越多的学者建议将土壤有机质划分为成颗粒态有机质和矿物结合态有机质来研究土壤有机碳对气候变化的响应[100]。Procter 等[94]发现大气 CO_2浓度升高使黑土和沙壤土的粗颗粒有机碳含量分别升高 400%和 50%,而粗颗粒碳是较为活跃的有机碳组分, 表明 CO_2富集会增加土壤中不稳定有机碳的比例。陈栋等[101]发现,FACE 试验下的表层稻田土有机碳总含量虽然无显著变化,但颗粒态有机碳显著增加了93.7%,表明表层土壤有机质稳定性会下降。

但有试验显示,土壤稳定碳库在高 CO_2浓度下也会发生变化,如佛罗里达矮栎林土壤稳定碳库在大气 CO_2浓度升高六年后显著下降[102]。在高寒生态系统的开展的 CO_2富集试验发现, CO_2浓度升高后为满足对

氮的需求会提高土壤微生物活性,加速土壤矿质结合态有机质矿化分解[43]。这部分有机质虽然难分解,但 C:N 较高、含氮丰富,加速矿化可以增加土壤有效氮含量。同时,粗颗粒态组分有机质的分解受到抑制,最终会导致土壤有机质稳定性下降。综上可以看出,不管是通过增加粗颗粒有机碳或是降低矿质结合态有机碳含量,CO_2浓度升高表现出降低土壤有机碳稳定性的趋势。

4.2 CO_2浓度升高对土壤有机碳化学组成的影响

传统研究技术很难去定量检测土壤不同碳库组分间的变化,这种“黑箱”理论使大多数研究只能关注CO_2浓度升高导致的碳库变化最终结果,而忽略实际的土壤有机质变化过程[15]。近些年来,先进的成像观测技术在土壤学领域的快速发展,使得精确甄别土壤有机质的分子结构信息成为可能。例如,热裂解气相色谱质谱法(Py-GC/MS)可以获取的土壤有机质的化学分子结构和性质,具体归类为烷烃、烯烃、多糖、木质素、含氮化合物、酚类、芳香烃、多环芳烃、脂肪酸和萜烯类等[103]。基于此,研究发现 CO_2浓度升高增加了土壤有机质中正烷烃的丰度,由于长链正构烷烃主要来自于草本植物和木本植物的叶片蜡质结构[73],表明 CO_2浓度升高后会增加土壤有机质中的植物源物质。而对农田的研究发现,CO_2浓度升高会导致水稻根际土有机质中杂环氮化合物、酚酸和酚类化合物的相对丰度分别增加[104]。

在土壤有机质分解过程中,微生物被认为会优先分解那些具有化学不稳定结构的碳源,而较难分解的烷基结构则会保留下来成为土壤稳定的有机碳库[105]。因此,可以从土壤有机质化学组成的分子水平评估 CO_2浓度升高对土壤碳库稳定性的驱动机制。例如,对 Duke 森林土壤有机质进行核磁共振检测(NMR)发现,CO_2浓度升高时微生物促进了木质素和水解脂类等土壤有机质(SOM)成分的分解,从而导致植物源性顽固性结构(如烷基碳)在土壤中富集[106]。而采用傅里叶变换离子回旋共振质谱(FT-ICR/MS)对美国内华达州荒漠生态系统土壤有机质组成测定,发现 CO_2浓度升高通过增加根分泌物和有机酸等不稳定化合物组成的凋落物,从而使土壤中不稳定化合物的丰度升高[96]。Phillips 等[107]在森林生态系统中也报道了相似的结果,即CO_2浓度升高通过加大碳输入增强土壤激发效应,从而降低了土壤有机质中酚类等难分解化合物的相对丰度。以上研究表明,由于土壤有机质化学组成复杂和不同生态系统的异质性,CO_2浓度升高对土壤有机质化学结构的影响并没有统一结论,未来需结合多种分析测试手段综合探讨土壤有机质的稳定机制。

4.3 CO_2浓度升高对土壤有机碳周转的影响

在大气 CO_2升高条件下,增大的植物碳输入速率会增加土壤中易分解碳源的比例,导致土壤中原有难分解有机质的矿化加速,即“激发效应”[108]。此外,植物水分利用效率在高 CO_2浓度下会升高,从而减少了通过蒸腾作用造成的土壤水分损失,并增加土壤含水量。由于低水分有效性限制了土壤微生物的生理性能及其对基质的获取,CO_2浓度升高引起的土壤含水量增加可能会加快干旱和半干旱生态系统的分解速率[109]。因此,CO_2浓度变化可能会通过影响土壤微生物活性和土壤有机质分解速率来影响土壤碳库动态和稳定性。

稳定碳同位素示踪技术是研究土壤有机碳的周转的有效手段,通过测定 CO_2加富处理中土壤 $\delta^{13}C$ 值的变化,可定量计算植物碳的输入以及土壤碳周转,阐明土壤有机碳来源和周转过程。自然状态的大气 CO_2中 $\delta^{13}C$ 值约为-8‰,但试验中使用人工^{13}C 贫化的 CO_2进行熏蒸,其 $\delta^{13}C$ 值大在-18‰到-45‰之间[110]。在 CO_2富集处理中,被植物光合作用固定并新输入土壤的碳为^{13}C 标记,即^{13}C 丰度不同于原有土壤,因此光合作用新固定碳对土壤有机碳的贡献率可以通过二元混合模型计算。基于稳定碳同位素的研究发现,大气 CO_2浓度升高会显著增加有机碳组分中“新碳”的含量,对“老碳”的影响很小[4,93],其中“新碳”大部分属于易分解的土壤活性碳库。而基于模型模拟的数据也发现,全球范围内 CO_2浓度升高导致碳输入增加 19.8%,而土壤碳周转速率加快了 16.5%[85],这意味着土壤碳库不一定会增加而稳定性却有可能下降。因此,从周转过程看,短期内大气 CO_2浓度升高可以促进植被生长,增加土壤有机碳积累,但长期看则会促进土壤微生物呼吸,缩短土壤有机碳的周转时间[58],限制土壤有机碳积累[111]。

5 土壤碳库对大气 CO_2浓度升高响应的不确定性

当前土壤碳库响应大气 CO_2浓度升高还存在以下不足:

(1)以往 CO_2富集试验研究多关注于表层土壤有机碳,而深层土壤有机碳储量巨大,其长期稳定机制还不清晰。例如,基于表层土壤有机碳研究表明 CO_2浓度升高可能会促进有机质分解,不利于土壤有机碳固持。而有报道指出,CO_2浓度升高可能会促进植物根系向底层土壤的生长,以此获取更多的养分[3,112],同时将新鲜有机碳输送向底层土壤,提高底层微生物的活性、加快底层土壤有机碳降解。

(2)不同生态系统对 CO_2浓度升高的响应程度不同, 导致不能完全用单一理论的来解释和预测陆地生态土壤有机碳循环对未来全球变化的响应和反馈。例如,我国北方干旱半干旱区草地生产力主要受到降水限制,而青藏高原高寒草地主要受到温度限制,当考虑土壤有机碳循环过程对气候变暖的响应时,高寒草地的响应可能会更加敏感。因此,开展跨区域的 CO_2加富联网试验可为理解土壤有机碳对全球变化的响应和适应提供重要的数据基础,有助于发展更具普适性的机制和理论。

(3)土壤碳循环受多种驱动要素影响,然而这些因素间的作用并非单一的简单加和作用,需要考虑多因子交互作用对土壤有机碳的影响。例如,大气 CO_2浓度升高背景下,随着氮素不断被固定在植物体和土壤有机质中,土壤氮素有效性的限制作用加强,逐渐成为调控土壤有机碳分解的主要限制性因素。但是随着全球范围的氮沉降加剧,生态系统氮限制有可能得到一定程度的缓解,有利于陆地生态系统土壤有机碳固持。

6　未来研究展望

目前,大气 CO_2浓度升高对土壤碳库动态、周转和稳定性变化的影响尚不清楚。除了不同生态系统之间自身存在的异质性外,很大一部分不确定性是因为土壤碳库储量巨大、空间上变异大、周转缓慢等因素而产生的,这导致大气 CO_2升高背景下土壤碳动态的微小变化难以捕捉。同时,当大气 CO_2浓度升高时,部分新输入土壤的碳可能会被正的“激发效应”所抵消,使土壤有机碳周转加速,通过影响土壤有机质的稳定性和矿化过程对土壤碳库产生重要影响。显然,准确预测大气 CO_2升高情景下土壤碳库的变化需要深入了解土壤碳周转过程和微生物驱动机制,而基于土壤有机质的物理、化学结构和碳循环模型将土壤碳分为不同周转速率和稳定机制的碳库组分,精准构建土壤有机碳周转过程是未来评估土壤碳库动态和稳定性的重要手段。

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