土壤矿质结合态有机碳形成及稳定机制的研究进展

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摘要：随着分子生物学的发展，微生物的作用改变了科学界对土壤有机碳(SOC)形成和固持的认知。土壤微生物残体与矿物结合形成矿质结合态有机碳(mineral-associated organic carbon，MAOC)加深了对 SOC 固存的理解。MAOC 是以土壤微生物残体 C 为主的 SOC 组分，主要由分子量相对较低且可识别的微生物残体与矿物表面结合而成。由于 MAOC 对草地和农田生态系统土壤 C 库的贡献超过 50%，且周转时间较长(百年—千年尺度)，研究其形成过程和稳定机制已成为碳中和背景下土壤碳汇的焦点。现阶段的研究明确指出，MAOC 的形成和稳定不仅与微生物残体 C 密切相关，还与土壤矿物有着非常紧密的联系。基于此，聚焦土壤微生物“碳泵”调控 SOC 形成这一前沿科学问题，围绕土壤微生物残体贡献 MAOC 形成这一科学构架进行概述，旨在揭示不同来源 LMW—DC(溶解态低分子量 C 底物)对 MAOC 形成的贡献，探讨土壤矿物对 LMW—DC 选择性吸附机理，探究 MAOC 贡献稳定 C 库的影响因素。并对该研究领域未来的发展进行展望，以期能从分子水平出发，探究不同生态系统、土壤类型及土层深度微生物的调控差异，为土壤有机碳固持的研究提供理论参考，为丰富土壤 C 源/汇功能提供科学依据。

关键词：土壤矿质结合态有机碳；溶解态低分子量 C 底物；植物残体 C；微生物残体 C；土壤矿物；土壤团聚体

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Advance in the Formation and Stabilization Mechanisms of Soil Mineral-Associated Organic Carbon

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Abstract: With the development of molecular biology, the role of soil microorganisms has changed the scientific understanding of formation and sequestration of soil organic carbon (SOC). Microbial residue combined with soil minerals to form mineral-associated organic carbon (MAOC), which has improved our understanding of soil organic carbon sequestration. MAOC is a fraction of soil organic carbon dominated by soil microbial residue carbon. It is mainly composed of identifiable microbial residue with low molecular weight bound to the mineral surface. As MAOC contributes more than 50% to soil organic carbon pool of grassland and agricultural ecosystems and has a long turnover time (centennial-millennial scale), the study of MAOC formation process and stabilization mechanism has become the focus of soil carbon sink in the context of carbon neutrality. Recent studies clearly indicate that the formation and stability of MAOC are not only

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mainly related to microbial residue carbon, but also closely associated with soil minerals. Based on this, we focus on the cutting-edge scientific issue of microbial carbon pump regulating soil organic carbon and provide an overview of the scientific framework on soil microbial residue contribution to MAOC. The aim is to reveal the contribution of LMW-DC (low molecular weight dissolved carbon substrate) from different sources to MAOC formation, and to explore the mechanism of selective adsorption of LMW-DC by soil minerals. Meanwhile, the relevant factors affecting the contribution of MAOC to stabilizing carbon pools are also discussed. It also provides an outlook on the future development of this research field, with a view to exploring the differences in the regulation of soil microorganisms in different ecosystems, soil types and soil depths from the molecular level, so as to provide a theoretical reference for the research on soil organic carbon sequestration and a scientific evidence for enriching soil carbon source/sink functions.

Keywords: mineral-associated organic carbon (MAOC); low molecular weight dissolved organic carbon (LMW-DC); plant residue carbon; microbial residue carbon; soil mineral; soil aggregates

土壤碳(carbon, C)库是陆地生态系统最大的 C 库,具有调节气候变化和影响全球 C 循环的重要作用[1-2]。聚焦土壤有机碳(SOC)形成、转化和稳定机制是精准预测陆地 C 循环未来发展的关键[3-5],也是我国实现 2060 年"碳中和"目标的重要理论支撑[6-7]。随着 SOC 相关理论的发展和新测试技术方法的应用,学术界对 SOC 周转和截获的认知已经从早期经典的腐殖质理论逐渐转为土壤微生物核心调控,微生残体 C 贡献 SOC 积累的新共识[8-13]。从植物残体的逐级分解模型、SOC 形成的连续体模型,到土壤微生物"碳泵"(体内周转和体外修饰途径)的差异调控、"续埋效应"贡献 SOC 的积累,再到土壤微生物残体与矿物结合形成矿质结合态有机碳(mineral-associated organic carbon, MAOC)促进土壤 C 库的稳定。这些土壤微生物核心调控理论的提出加深对 SOC 固存的理解。越来越多的研究[14-17]证实,土壤微生物源 C 对 SOC 的贡献在以往的研究中被低估,微生物残体 C 的"续埋机制"才是 SOC 固存的关键,贡献率超过 50%[18-22]。Wang 等[23]采用 meta 分析对全球农田、草地和森林生态系统表层土壤的微生物残体 C 进行估算发现,其对 SOC 的贡献分别为 51%,47%和 35%;Liang 等[19]通过对温带不同生态系统的估算也得出类似的结论。近年来,一些研究从 SOC 的稳定过程入手将其划分为颗粒态(particle organic carbon, POC)和矿质结合态(mineral-associated organic carbon, MAOC)两部分[17,24-25]。其中,MAOC 由于可以在土壤中缓慢循环成百上千年,逐渐成为 SOC 固存研究的焦点[26-28]。

1　MAOC 的提出

1.1　被低估的微生物残体 C

近 20 年来,随着同位素示踪技术和各类光谱手段的发展和应用,地下"黑箱"逐渐解密,越来越多的研究意识到微生物残体 C 的续埋效应才是稳定 C 库积累的关键。早在 21 世纪初,研究者就发现土壤稳定 C 库中包含大量结构不稳定的有机化合物,如多糖和蛋白质[29-30],这将 SOC 研究的关注点开始从植物 C 源向微生物 C 源偏移[31-32]。Simpson 等[15]首先通过对植物体、腐殖质、土壤、浸提微生物及培养微生物的化学基团进行 NMR(H 谱和 diffusion-edited)分析发现,微生物来源化学基团(蛋白质/多肽)对 SOC 的贡献比例超过 50%,而纯植被样品中类似的化学基团相对较少。随后,Miltner 等[33]通过^{13}C 细菌的培养试验同样发现,固存在土壤中的微生物来源 C 约占 50%,其中 10%来自活体微生物,40%为微生物残体。同时,Liang 等[34]利用吸收马尔科夫链(absorbing markov chain)首次估算出微生物残体 C 对土壤碳库的相对贡献率高达 82%。人们逐渐认识到微生物 C 源的贡献比例才是 SOC 固存的关键,其中活体生物量较微生物残体的贡献相对较小。

1.2　MAOC 的认知过程

早期的研究[35]表明,地上部分植物残体 C 是土壤的主要 C 源,调控 SOC 的累积速率。随着分子生物学的发展,土壤微生物的作用改变科学界对 SOC 形成的认识。从植物残体的逐级分解模型[36]和 SOC 形成的连续体模型[10],到土壤微生物碳泵体内周转和体外修饰途径的差异调控、土壤微生物残体 C 的续埋效应贡献 SOC 的积累[37],再到微生物源 C 与土壤矿物结合形成 MAOC 促进土壤 C 库稳定[17],这些土壤微生物核心调控理论的提出加深对 SOC 形成和稳定的认知。由于 SOC 物理分组对土壤原状结构和形态的破坏较小,从 SOC 稳定过程入手研究以土壤微生物残体为主的有机碳组分 MAOC,更能揭示土壤 C 库的稳定机制[38]。

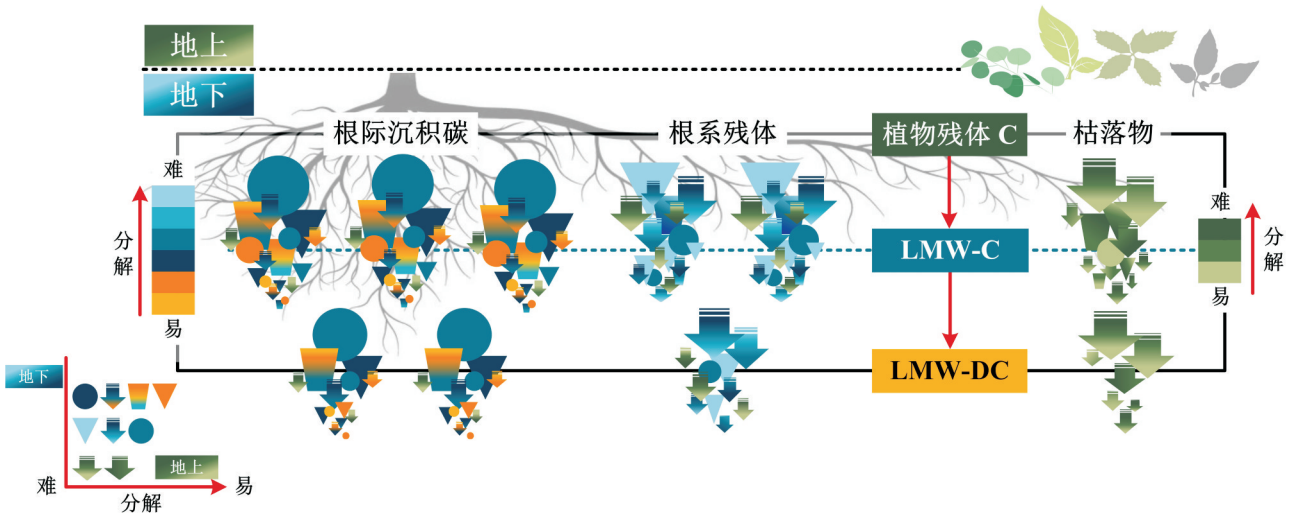
早在 20 世纪 60 年代,Sørensen[39]明确表示,黏土矿物对有机碳的保护比碳水化合物更强。黏土矿

物和次生金属(氢)氧化物在成土过程中大幅度增加[40-41],改变 SOC 储量[42],土壤中高达 90%的有机碳固存与矿物密切相关[43]。矿物表面的有机碳通常比其他组分的周转速度慢,矿化程度也远低于游离态部分[44-46]。但长期以来,MAOC 一直被认为是高分子聚合物"腐殖质"与矿物表面相互作用的结果[47]。随着腐殖化理论研究[48-49]的深入,腐殖质由于组分复杂且边界模糊遭到越来越多研究者的质疑[8,50-51]。与此同时,Collins 等[52]认为黏土矿物的选择性吸附过程可能是活性生物聚合物固存的结果;Keil 等[53]也指出,MAOC 是由矿物表面原位(*in-situ*)微生物转化形成的;Sutherland[54]和 Kögel-Knabner 等[55-56]进一步说明,微生物衍生物可以作为调节膜(conditioning films)促进矿物与有机碳的结合。扫描电镜技术结果显示,土壤矿物表面几乎没有完整细胞,多是 200～500 nm 的有机拼接碎片(破碎的细胞壁),包含大量 C/N 低、斥水性强的微生物来源生物标识物[33]。这些研究均为土壤微生物残体贡献 MAOC 的形成提供直接或间接证据[57-58]。

2 MAOC 的形成

2.1 土壤微生物"碳泵"调控不同来源的溶解态低分子量 C 底物(LMW-DC)

Sokol 等[27]提出低分子量 C 底物(low molecular weight carbon, LMW-C<600 Da)是微生物残体 C 形成的物质基础,包括一系列可同化的含 C 化合物,如糖、氨基酸、部分酚酸和芳香族化合物[59-61]。从图 1 可以看出,根际沉积 C 和根系残体等地下植物残体 C 的周转对 LMW-C 的形成占主导地位[16,62-67],其中还包括大量根系代谢产物,如脱落细胞、分泌物和低分子量聚合物[68-70]。而生物量相对较少的地上部分,LMW-C 主要来源于枯落物层、腐殖质层和界面土层的淋溶析出[71-72],但因季节动态[73]、微生物代谢消耗[74]及淋溶扩散作用,使进入土壤的 LMW-C 量逐级递减[27,75]。



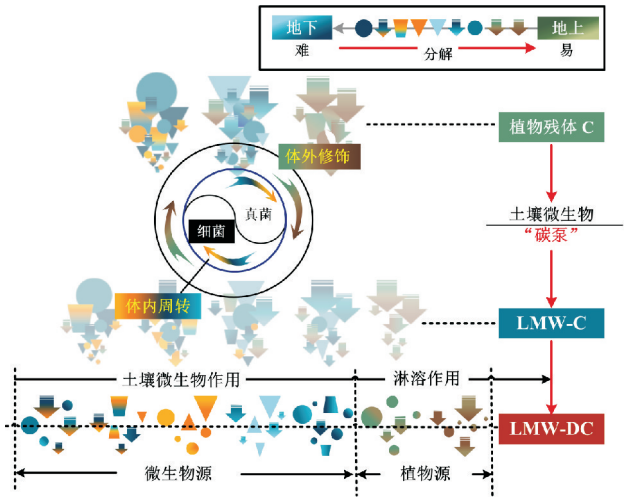
注:LMW-C 为低分子量碳底物。

图 1 地上地下植物残体 C 周转对 LMW-C 的贡献差异

需要强调的是,LMW-C 作为贡献 MAOC 的物质基础,需以溶解态的形式进入土壤才更容易与矿物表面作用[37,76-77]。由图 2 可知,植物残体中可溶性组分进入土壤后可直接参与 MAOC 的形成[78-80],其部分则需在土壤微生物"碳泵"调控下,经体内周转或体外修饰途径完成植物残体 C 向溶解态的低分子量 C 底物(LMW-DC)的转化。当进入土壤的植物残体 C 是易被微生物利用的小分子或简单组分时,则以体内周转途径为主;而当植物残体 C 是不易被微生物直接截获的大分子结构(如木质素)时[29,56,81],微生物选择体外修饰途径。释放目标胞外酶首先对大分子化合物进行降解,再通过微生物捕获—同化合成—生长增殖—死亡等方式完成转化[28,37,68,82-83]。但关于土壤微生物"碳泵"调控 LMW-DC"源"的问题一直存在争议。一些学者[33,84]认为,大部分 LMW-DC 是微生物残体 C,包括土壤和矿物表面 2 个空间维度体内周转产生的微生物残体 C(图 3);另一些学者[26]则认为,LMW-DC 由"植物性 C 源"提供,虽然这些植物源的 LMW-DC 在被矿物吸附之前也经过体外修饰作用,但由于复杂大分子的植物衍生特征掩饰掉微生物作用[81]。实际上,LMW-DC 既由微生物源提供也由植物源提供,不同的是大部分 LMW-DC 来源于体内周转的微生物残体,而小部分来源于体外修饰和植物物理破碎形成的溶解态小分子 C(图 2)。近年来,关于微生物碳泵调控微生物残体贡献 SOC 积累的实证有所增加[32,37,58]。不同源植物残体 C 化学结构和分解程度的差异导致 LMW-DC 化学结构的分异,直接影响微生物残体 C 和植物残体埋藏 C 对 SOC 的

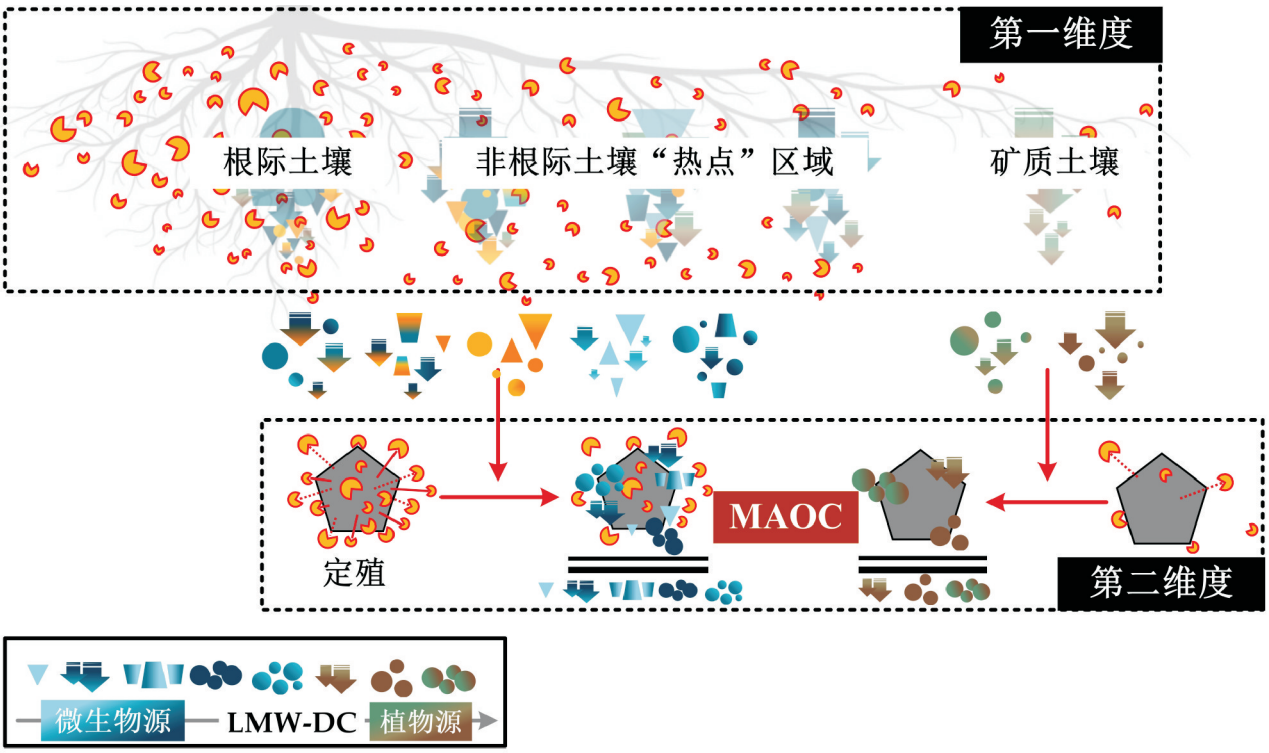
贡献比例[17]。本文将从土壤(宏观环境)和矿物(微观表面)2 个维度对 LMW-DC 的周转过程加以说明。

一般情况下,矿物表面微生物的定殖密度越高,发生同化和合成代谢的可能性越大[27]。但研究[33,85]发现,大多数微生物在土壤矿物表面的定殖率并不高,其发生定殖的概率与土壤微生物群落丰度密切相关[66]。从图 3 可以看出,根际土壤和非根际土壤“热点”区域(生物孔穴和团聚体表面)[86-88],即微生物丰度较高的区域(第 1 维度)土壤矿物表面微生物定殖率相对较高(一般是非根际土壤的 10 倍[89-90])。土壤微生物群落特征(丰度和定殖率)是碳泵发挥作用的先决条件,两者共同调控不同源 LWM-DC 的化学结构和含量。



注:LMW-DC 为溶解态的低分子量碳底物。

图 2　土壤微生物“碳泵”调控的 LMW-DC 的产生过程



注:MAOC 为矿质结合态有机碳。

图 3　2 个维度的土壤微生物群落的特征对 MAOC 形成的影响

2.2　MAOC 形成过程对不同来源 LMW-DC 的吸附选择

MAOC 形成的概念框架认为一旦植物源 LMW-C 以溶解态存在于土壤中(图 4),便能与矿物表面产生位移或被微生物利用,并通过直接吸附作用形成 MAOC[27]。但由于土壤微生物对 LMW-C 的截获远胜于矿物[79,91-92],因此只有小部分 LWM-DC 被转运至土壤与未定殖微生物的矿物表面发生物理化学吸附[77,93]。而大部分 LMW-C 只要对微生物没有严格的代谢限制(温度和氧气)和毒性,均被微生物利用完成同化合成和生长增殖,以微生物源 LMW-DC 的形式(微生物残体、分泌物、胞外聚合物和其他代谢产物等)贡献 MAOC 的形成[16,74]。此时的 LMW-DC 与矿物表面发生物理化学吸附之前首先通过体内周转途径,因此将其定义为直接吸附途径的间接模式,即“间接吸附”。虽然间接吸附主导 MAOC 的形成,但由于土壤中活性黏土矿物的大量存在,直接吸附也不能被忽视。已有研究[94]指出,森林生态系统中地上植物残体 LWM-DC 的大量输入与活性次生矿物(氧氢化物或水铝英石等结晶差的矿物)作用形成强键,贡献 MAOC 形成高达 89%。

3　MAOC 形成和稳定的调控因素

土壤微生物介导的植物残体 C 转化为 MAOC 的形成提供物质基础[27,34],并通过体内周转和体外修饰途径调控进入土壤与矿物表面发生作用的

LMW-DC 组分和含量[3,37]，而 MAOC 的固存完全取决于 LMW-DC 与土壤矿物表面的结合程度[27,95]。

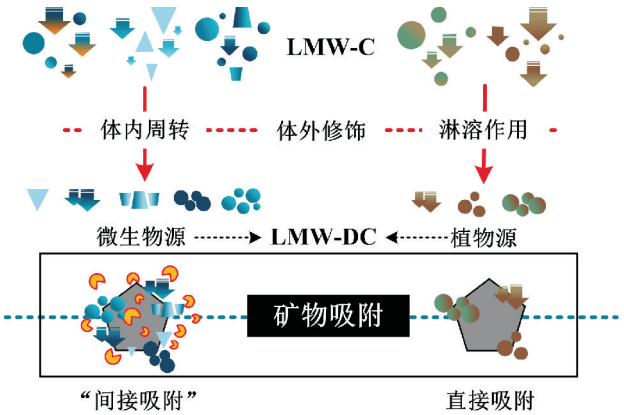
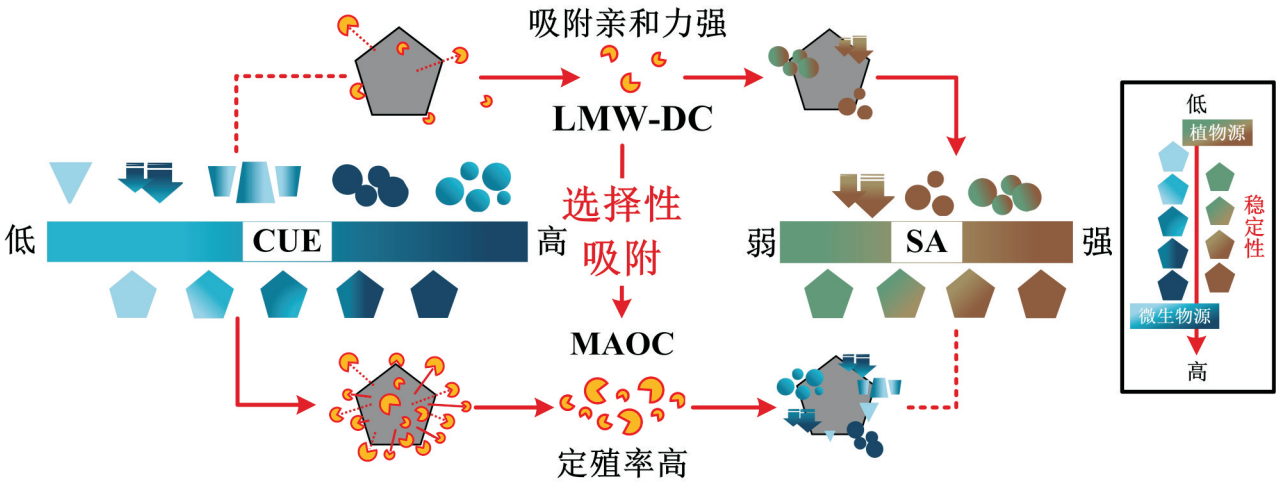


图 4 土壤矿物对 LMW-DC 的选择性吸附途径

3.1 影响 MAOC 形成的主要因素

3.1.1 *土壤微生物 C 利用效率* 由图 5 可知，土壤微生物 C 利用效率(carbon use efficiency，CUE)、矿物的吸附亲和力(sorption affinity，SA)及吸附位点三者共同作用，决定 MAOC 的形成概率[26,96-98]。如单糖和氨基酸等具有高 CUE(40%～80%)的 LMW-C[31,69]，在被微生物矿化过程中消耗(CO_2)的比例相对较少[99-100]，因此，通过体内周转贡献 MAOC 形成的 LMW-DC 比例较多；反之，一些酚酸(水杨酸和对羟基苯甲酸)和多价有机酸(草酸)等低 CUE(0～30%)LMW-C，形成被土壤矿物选择性吸附的 LMW-DC 相对较少(图 5)[31,62,101]。这些影响因素在土壤微生物丰度较高的区域尤为突出，LMW-DC 的绝对数量越多，发生间接吸附的概率越大[58,102]。相比之下，直接吸附的 LMW-DC 规避土壤微生物的同化作用，此时 MAOC 的形成概率更大程度取决于土壤矿物与 LMW-DC 之间的吸附作用力[98,103-104]。



注：CUE 为土壤微生物碳利用效率；SA 为矿物的吸附亲和力。

图 5 土壤微生物碳利用率(CUE)与矿物的吸附亲和力(SA)对 MAOC 形成的影响

3.1.2 *土壤矿物的吸附亲和力* 吸附作用力中，配体交换的成键作用最强，其次是阳离子桥接、氢键或范德华力[97,105]，非极性的芳香环也可以通过阳离子—π 和电子供体—受体作用和矿物表面之间形成较强的吸附作用[106]。不同的吸附作用力表现出不同的吸附亲和力(SA)，高极性和高 SA 的 LMW-DC 与土壤矿物形成强键直接吸附促进 MAOC 的形成。如多价羧酸(柠檬酸和草酸)、一些酚酸和木质素单体(香草醛、水杨酸和对香豆酸)等，一致的官能团和极性使其通过配体交换与矿物表面形成最稳定的有机—矿物键直接并入 MAOC 库[46,62,77,107]。而低极性 LMW-DC 表现出较差的 SA，如单糖(葡萄糖)、一些氨基酸(丙氨酸)和一元羧酸(乙酸)，它们与矿物表面产生的作用力相对较弱，只能通过较弱的缔合作用，但发生的概率微乎其微。一旦没有被定殖在矿物表面的微生物吸收利用，则被动地转移到非根际土壤中[92,108-109]。

3.1.3 *土壤矿物的吸附位点* 并不是所有 LMW-DC 的 CUE 与 SA 都呈正相关关系，它们之间还存在相互制约[29,62]。葡萄糖具有较高的 CUE，但 SA 却很低[31,77]，一些极性酚类化合物(水杨酸和对羟基苯甲酸)表现出强烈的 SA[101]，但 CUE 却不高。此时，CUE 和 SA 无法成为判断 MAOC 形成概率的指标，而此时 LMW-DC 与矿物表面的“吸附位点”成为影响 MAOC 形成的关键[98]。吸附位点即土壤矿物表面可供 LMW-DC 占据的空间位置，空间位置越多形成 MAOC 的概率越大。吸附位点较多的土壤矿物拥有更多的表面正电荷，因此更容易吸附带负电的 LMW-DC 形成 MAOC。Kleber 等[57]提出“矿物表面有机层”的概念，即初始的土壤矿物表面并没有太多吸附有机质的特殊位点，但随着有机质分子形成并逐渐包裹在矿物表面，使矿物表面的吸附位点增多。土壤矿物表面可供有机质选择的吸附点位随着 SOC 含量的增加而相对增多[80,110]，如糖、氨基酸和乙酸

等。LMW-DC 在吸附位点较高的根际土壤中形成 MAOC 的概率较大,尤其是根际周围(2 mm)[108,111],根际沉积 C 的积累有利于矿物表面吸附位点的形成[87,98],而对于低有机质水平的矿物土壤并没有这样的条件。因此,吸附位点理论也为根际土壤和矿质土壤中 MAOC 的形成差异的研究提供新思路。

3.2　影响 MAOC 稳定的主要因素

从 MAOC 积累角度出发,决定土壤 MAOC 库容大小的主要因素是 LMW-DC 与矿物的结合程度[4,112]。矿质吸附受到化学和物理的双重保护是 MAOC 稳定固存的重要机制[113],尤其是无定形矿物吸附形成 MAOC(矿物学保护机制)[52,55,94,114-115],及团聚体结构产生的"分室作用"(物理隔离机制)[38,97,116-117]。

3.2.1　*土壤矿物学保护机制*　一般而言,矿物学保护机制中以缩合反应为基础产生的化学键合的吸附作用最为稳定,其次是可与矿物表面发生直接作用的电子,形成"供体—受体"机制(electron donoracceptor, EDA),它们以配位体置换[105]、络合[118-119]、氢键、高价离子键桥、阳离子桥接与阴离子交换[120]、阳离子—π 键[121]、n—π 电子作用[122-123]、偶极—偶极作用、熵驱动疏水分配[124-125]及其协同作用与 LMW-DC 结合,降低微生物残体 C 的矿化速率,而以范德华力和静电作用力为主的物理吸附相对较弱(表 1)。

在众多的矿物类型中,铁铝氧化物与黏土矿物对 LMW-DC 的吸附能力较强[80,105,126]。其中,配体交换作用是铁铝氧化物吸附有机质(SOM)的主要机制[78],铁铝氧化物表面的羟基与 SOM 中的羟基/酚羟基发生配体交换形成以矿物为核心的内圈(Inner-sphere)[103,105,126-127],这种内络合作用使吸附态的 SOM 难以从矿物表面解吸[128]。与铁铝氧化物相比,黏土矿物主要通过阳离子桥接、阴离子交换、范德华力对 LMW-DC 中的疏水组分进行吸附[125,129],这主要与矿物本身的比表面积有关[130]。比表面积较大的蒙脱石对腐殖酸[131-132]和微生物多糖[120]的吸附量显著高于比表面积相对较小的高岭石[45,132]。土壤中铁铝氧化物和黏土矿物的含量越高,其巨大的比表面积和大量的表面电荷对 LMW-DC 的吸附能力越强,微生物残体生物有效性的降低有利于 MAOC 积累和固存[4,85,126]。

表 1　土壤矿物的吸附作用机制

吸附类型	强度	作用机制
化学吸附	强	缩合反应
		电子"供体—受体"机制
物理吸附	弱	配体交换、络合(内圈)、氢键、离子桥、阳离子—π 键、n—π 电子
		范德华力、静电作用

3.2.2　*土壤团聚体的物理隔离机制*　土壤团聚体的物理隔离机制在以往 SOC 固存的研究中已经被证实[133-134],大团聚体(>250 μm)通常比微团聚体(<250 μm)含有更多的有机碳[135],但微团聚体中的有机碳能更长时间的稳定固持于土壤中。土壤团聚体的保护不仅起到物理屏障作用,使其内部的 SOC 免受微生物和酶的攻击[44]。氧气和养分的循环限制及水分的供给差异,直接影响团聚体内部微生物的活性、丰度及群落结构,导致有机碳循环路径发生改变[136-137],从而有利于 SOC 的固存[134,138]。到目前为止,还没有确切的证据来证明为什么与微团聚体相关的有机碳通常比大团聚体的保存时间更长。但随着 MAOC 研究的不断深入,人们认为 MAOC 的矿物保护机制与团聚体的物理隔离机制对 SOC 稳定性的影响密切相关[139],土壤中 70%以上的有机碳贮存于粉砂和黏粒级的团聚体颗粒中,微团聚体不仅可以将内部可利用的老碳封存与微生物进行物理上的隔离,而且内部的微生物残体还能加强土壤矿物结合形成 MAOC 而相对稳定地存留在土壤中[109,116-117,140]。

但需要强调的是,土壤团聚体的物理固存是存在饱和点的,MAOC 的积累也是有限的[141-142],不会随着土壤黏粒含量的增加呈现持续增加的趋势,而在土壤矿物比表面积达到一定值后出现 C 饱和[49,114]。同样,土壤矿物与 LMW-DC 作用后并不总是保持吸附的状态,MAOC 还可能出现解吸,与竞争有机化合物产生交换,以及生物和非生物降解作用等状况[129,143]。虽然大量单步解吸试验均已证实,吸附在土壤矿物上的 SOM 一般较难解吸[78],可解吸部分仅占吸附量的 6%～14%,但此类单因素吸附解吸试验中未考虑微生物因素。尤其当底物资源出现化学计量失衡时,微生物在养分胁迫情况下对 MAOC 进行分解利用[103,144-145]。如通过阳离子桥作用或范德华力吸附的 SOM 易发生解吸,并作为有效 N 源被活体微生物优先利用[102]。MAOC 的循环利用也是影响其稳定固存的原因之一[10,28,38]。因此,MAOC 的稳定性还取决于土壤微生物异化分解(激发效应)和同化合成(续埋效应)2 个过程之间此消彼长的动态平衡[33,37,74,146]。

4　MAOC 的展望

目前的大多研究将 MAOC 视为土壤有机 C 库的稳定部分,作为土壤碳汇功能的评价指标,并认为

MAOC 含量的稳态增长才是土壤碳汇的终极目标。但针对 MAOC 的形成和稳定机制的研究还相对薄弱。试验分析技术的缓慢发展未能跟上人们对 MAOC 研究的快速认知,因此并没有足够和广泛的研究结果对此加以支持。MAOC 是如何形成、积累并稳定下来,基于 MAOC 的概念构架,以物质基础、形成条件和影响因素为切入点,聚焦土壤微生物群落这个复杂的生态圈,探寻其与土壤矿物颗粒间发生的微妙反应(物理、化学和生化),分析不同源 LMW-DC 对 MAOC 形成的贡献差异,以探究从植物残体 C 分解到 MAOC 形成过程中土壤微生物群落作用为突破,针对未来可能的研究方向和内容作出展望。

4.1 土壤微生物调控的 LMW-DC 形成机制

不同生态系统提供 SOC 形成的植物 C 源存在明显差异。土壤微生物介导的体内周转和体外修饰途径根据差异性植物 C 源提供化学组分和复杂程度不同的 LMW-DC 贡献 MAOC 的形成。探究土壤微生物碳泵对 LMW-DC 的调控差异,揭示土壤微生物残体 C 的续埋效应对 MAOC 的贡献比例,有助于深化不同生态系统土壤微生物残体对 SOC 积累差异的研究。

4.2 从分子水平对 LMW-DC 组分进行细化

土壤矿物究竟优先选择哪些 LWM-DC 进行吸附? LMW-DC 中哪些化学基团贡献 MAOC 的形成? 从分子水平对 LMW-DC 化学组分和复杂程度的认知,建立 LMW-DC 与 MAOC 的相关关系,探究不同组分 LMW-DC 对 MAOC 形成的影响,有助于明晰 MAOC 的形成过程。

4.3 土壤矿物的选择性吸附机理

土壤矿物的选择性吸附是 MAOC 形成的关键。土壤矿物表面和 LMW-DC 吸附叠层在空间上是如何实现的[103]? 与土壤矿物发生直接作用的 LMW-DC 的亲水性和矿物表面的疏水性的关系如何? 影响土壤矿物与 LMW-DC 表面吸附作用力有哪些? 通过土壤矿物对 LWM-DC 吸附选择的研究,探究 MAOC 对土壤稳定碳库的潜在贡献。

4.4 影响 MAOC 形成和稳定的因素

不同生态系统、土壤类型及土层深度在水、热、气、生等要素下差异显著,加之土壤微域环境中生物与非生物因素间的相互作用,共同影响 MAOC 的形成与稳定,针对不同生态系统、土壤和植被类型及土层深度具体分析 LMW-DC(溶解态低分子量 C 底物)的差异及其对 MAOC 形成和稳定的影响。

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