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农田土壤碳循环过程及其量化方法

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摘要: 已有研究表明除了作物碳(根际沉积碳和秸秆碳)对农田土壤有机碳(SOC)的输入外,土壤碳还来源于土壤自养微生物固定SOC的贡献以及土壤无机碳(SIC)的固定(无机化学途径和微生物的生物矿化途径)。农田SOC的高低主要受到外源作物碳输入和原有SOC分解的平衡作用。作物碳输入在短期内通常促进SOC的分解,呈现正(根际)激发效应。通过整合分析主要作物的根际激发效应和秸秆还田的激发效应的研究,发现作物根系生长和秸秆还田引起的(根际)激发效应大小平均值分别为75%和67%。尽管秸秆还田通过激发效应引起SOC分解的额外释放,但是土壤残留秸秆碳通常大于激发效应导致SOC的额外损失,因此秸秆还田可能增加SOC的储量。在农田系统中,秸秆碳和根际沉积碳往往共存,这导致土壤碳输入和输出至少有3个碳源(根际沉积碳、秸秆碳和土壤碳),由于多碳源体系的区分方法存在挑战,目前这两种作物碳(根际沉积碳和秸秆碳)对SOC分解的激发效应影响是不清晰的。最后,提出了新量化方法,可以多源区分根际CO₂排放以及SOC中作物碳输入的碳源,以及区分碱性土壤中无机化学和微生物途径对SIC的贡献。研究有助于提高对农田土壤SOC和SIC输入和输出途径的理解,以及农田土壤碳平衡评估的精确度。

关键词: 土壤碳; 根际沉积碳; 激发效应; 秸秆还田; 多碳源体系

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Carbon Cycling Processes in Croplands and Their Quantification Methods

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Abstract: Recent studies have shown that the source of soil carbon (C) includes not only the input of crop C (rhizodeposit- and residue-C) to soil organic C (SOC) but also the contribution of soil autotrophic microorganisms to SOC and the fixation of soil inorganic C (SIC) from the soil inorganic chemical pathway and microbial biomineralization pathway. The level of SOC in croplands is mainly controlled by the balance between the input of crop C and the loss of SOC via decomposition. In the short term, the input of crop C usually promotes the SOC decomposition, showing a positive (rhizosphere) priming effect. We analyzed the literature on the rhizosphere priming effect of major crops and the priming effect of straw additions and found that they were on average 75% and 67%, respectively. The residual straw C in the soil could completely compensate for the SOC loss caused by the priming effect of straw returning. In croplands, rhizodeposit- and residue-C often coexisted, which resulted in at least three C sources (rhizodeposit-, straw-, and soil-C) for soil C input and output. Finally, we proposed a new method to distinguish the contribution of multiple C sources to the CO₂ emission and the SOC input in rhizosphere soils, as well as the contribution of inorganic chemistry and microbial pathways to the SIC input in calcareous soils. This review is helpful to improve the understanding of the input and output pathways of SOC and SIC in croplands and to improve the accuracy of soil C assessment in croplands.

Key words: soil carbon; rhizodeposit-C; priming effect; straw returning; multi-carbon source system

农田土壤固碳指通过人为和自然作用来提高土壤有机碳(soil organic carbon, SOC)^[1-3]和无机碳(soil inorganic carbon, SIC)^[4-6]储量,将大气CO₂固持在土壤碳库中。以往研究多关注作物光合固碳对SOC的贡献,其他途径较少关注^[7,8]。利用非同位素法研究土壤SOC对不同措施的反应,根本原理还是把土壤看成黑盒子,通过不同时间或处理之间差减来量化,这忽略了各个途径的贡献,进而导致不同农业措施对土壤固碳的调控机制是模糊的^[8-10]。碳同位素法是量化土壤外源碳输入和内外源碳输出的有效手段,包括^{13/14}C标记法和¹³C自然丰度法^[7,8]。外源SOC的输入除了主要源于作物根际沉积碳和作物残体碳外,还部分来源于土壤固碳微生物(光能化和能自养)的贡献^[1,11](表1)。在秸秆还田下的农

田土壤,作物根际沉积碳和秸秆碳输入是同时存在的:①通过^{13/14}CO₂标记作物地上部,区分SOC中源于外源根系和原有土壤的比例,量化根际沉积对SOC的贡献^[2,3,7,8];②^{13/14}C标记作物残体添加到土壤,划分SOC中内外源有机碳的比例,量作物残体对SOC的贡献^[12];③C₃作物长期种植在C₄土壤上(反之亦然,表1)。以往研究利用¹³C自然丰度法来量化C₃作物残体对SOC的贡献,准确地说,这是C₃种植体系的贡献,包括净根际沉积碳部

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分^[7-9,13,14]. SOC 输入的第 2 个途径是土壤微生物对大气 CO₂ 和根际呼吸的固定,以前认为这个贡献很小,然而,最近发现这个贡献超出以往的估测^[1,6,15]. 例如,Ge 等^[1]通过 110 d 的密闭¹⁴C₂ 土壤培养试验,发现土壤光合固碳微生物对旱田和稻田 SOC 的贡献率分别为 0.15% 和 0.65%,推算出全球 0 ~ 20 cm 土壤固碳量为 0.57 ~ 7.3 Pg·a⁻¹^[16],因此,土壤固碳微生物对 SOC 的贡献不

容忽视. 另外,Liu 等^[6]在野外沙地通过注入¹³C₂ 试验,发现部分 SOC 直接源于大气¹³C₂ 进入土壤中的¹³CO₂ 和 H¹³CO₃⁻,其固碳速率为 3.276 μg·(kg·d)⁻¹,结合宏基因组进一步发现,推测由微生物的化能自养和异养途径来固碳. 因此,随着碳同位素方法结合微生物测序技术在固碳研究中的应用,研究者们发掘了更多的土壤有机固碳途径.

表 1 ^{13/14}C 量化土壤有机和无机固碳的方法总结

Table 1 Summary of methods for quantifying soil organic and inorganic carbon fixation by the ^{13/14}C method

不同碳源的贡献途径	方法	原理	优点	缺点	文献
根际沉积碳和作物残体碳对 SOC 的贡献	^{13/14} C 标记	① 通过对作物地上部标记 ^{13/14} C ₂ ,追踪 SOC 中源于根际沉积碳的贡献;② 通过添加 ^{13/14} C 标记作物残体到土壤,追踪 SOC 中源于作物残体碳的贡献	可以精确区分 SOC 源于“作物新碳”和“土壤老碳”的贡献,不需要特定的 C ₃ /C ₄ 土壤条件	① 需要在密闭标记室内进行标记,对于高大的作物(例如玉米)比较难操作;② ¹³ C 标记均匀作物残体比较昂贵;③ ¹⁴ C 标记物有放射性,不适合在田间实施	[2,3,7,8,12]
	¹³ C 自然丰度	通过把 C ₃ 作物种植或 C ₃ 残体添加到 C ₄ 土壤上(反之亦然),根据作物碳和 SOC 之间 δ ¹³ C 差异,借助两源混合模型区分 SOC 中源于作物碳的贡献	① 不需要人工标记,费用低,操作简单;② 不需要标记装置,适合田间原位试验;③ 适合长期试验	① 需要特定的 C ₃ 土壤和 C ₄ 作物组合(反之亦然);② 自然丰度 ¹³ C 分馏降低区分 SOC 中不同碳源比例的准确性;③ 不适合短期试验	[7~9,13,14]
土壤自养微生物对大气和土壤 CO ₂ 的有机固定	^{13/14} C 标记	把土壤暴露在富含 ^{13/14} C ₂ 的密闭空气中, ^{13/14} C ₂ 扩散进入土壤,在光照条件下可以同时发生光合途径(光能自养)和非光合途径(化能自养和异养),在黑暗条件下,微生物主要是通过非光合途径,将土壤中 ^{13/14} C ₂ 的转化为 SOC	适合室内(^{13/14} C ₂ 标记)或者原位(¹³ C ₂ 标记)量化微生物固碳贡献	① 需要密闭的标记装置;② ¹³ C ₂ 标记费用较高;③ ¹⁴ C ₂ 标记有辐射风险	[1,6,11,15]
大气和土壤 CO ₂ 的无机化学固定对 SIC 的贡献	^{13/14} C 标记	① 作物地上部光合固定 ^{13/14} C ₂ ,转运到地下部,土壤溶液钙镁离子固定根源呼吸释放的 ^{13/14} C ₂ 形成 PIC 沉淀;② 钙镁离子直接固定空气的 ^{13/14} C ₂ 形成 PIC 沉淀	在短期内,通过人工标记 ^{13/14} C ₂ 可以量化作物光合碳和大气 CO ₂ 进入 SIC 的碳量,适合研究 SIC 固碳的动态过程	① 由于短期内光合碳和大气 CO ₂ 进入 SIC 含量很小,因此需要高富集度的 ¹³ C ₂ 标记,费用需求比较高;② 如果借助低检测阈值的 ¹⁴ C ₂ 标记,有辐射的风险	[19,20]
	¹³ C 自然丰度	借助 ¹³ C 两源混合模型来划分 PIC 在 SIC 中的比例,结合 SIC 碳量,量化 SIC 通过无机化学途径的固碳量	① 不需要人工标记,适合田间原位和大尺度量化评估研究;② 适合研究长期农业措施对 PIC 固碳的影响	① 由于短期内农业措施对 PIC 影响较小,因此这个方法仅适用于长期措施的影响;② CO ₂ 的扩散和沉淀反应产生分馏导致 PIC 区分的不确定性	[4,5]
大气和土壤 CO ₂ 的微生物固定对 SIC 的贡献	^{13/14} C 标记	通过灭菌和不灭菌处理,结合 ^{13/14} C ₂ 饲喂土壤培养试验,区分无机化学途径和微生物途径对无机固碳的贡献	可以区分生物和非生物途径对土壤无机固碳的贡献	需要灭菌和标记的全因子试验处理,处理和计算相对复杂	[21]

在富含无机碳的碱性土壤上,由于碱性土壤额外增加了无机固碳途径,土壤固碳途径比酸性和中性土壤中的途径更加复杂^[17]. 随着^{13/14}C 技术在研究土壤固碳的深入,有研究发现土壤无机固碳既可以通过无机化学途径(非生物途径)^[4,5],也可通过土壤微生物的生物矿化(biomineralization)途径^[6]. 最

近,丁仲礼等^[18]在《中国“碳中和”框架路线图研究》中指出碱性土壤富含钙离子,通过无机化学途径捕获大气 CO₂ 形成碳酸钙沉淀,即形成次生无机碳(pedogenic carbonate, PIC),对大气 CO₂ 实施封存. 在我国西北和华北碱性农田,由于根际呼吸和作物残体分解释放 CO₂ 为 PIC 形成提供充足碳源,大

量施用含钙镁的化肥、含钙镁盐基离子的秸秆以及灌溉富含钙镁离子的地下水,以上农业措施为土壤额外输入了 Ca^{2+} 和 Mg^{2+} , 这为 PIC 形成提供了充足 Ca^{2+} 和 Mg^{2+} 源,因此,这两个地区农田 PIC 的累积速率甚至约是 SOC 累积速率的 2 倍^[17]. 通过¹³C 两源模型可以划分 PIC 源与 SIC 的比例,结合 SIC 含量,进而量化 PIC 形成量^[4,5]. 由于短期内 PIC 形成量很小,借助¹³C 自然丰度法很难检测到,因此¹³C 自然丰度法适合量化不同农业措施对 PIC 形成的长期影响,不适合研究作物生长和秸秆分解对 PIC 形成的短期影响^[19]. 借助^{13/14}CO₂ 标记注入土壤环境,可以定量分析大气 CO₂ 进入 PIC 的碳量,例如, Gao 等^[20] 发现注入大气 CO₂ 的三分之一形成 PIC,土壤无机固碳速率为 $475.9 \text{ mg} \cdot (\text{m}^2 \cdot \text{d})^{-1}$. 根源呼吸进入 PIC 的碳量是非常低的,可能低于¹³C 的检测阈值 (10^{-7} mol),因此采用低检测阈值的¹⁴C 标记 (10^{-13} mol) 可能是个有效方法^[7]. 此外, Liu 等^[21] 最近通过灭菌和不灭菌处理土壤,结合¹³CO₂ 饲喂土壤培养 75 d,发现土壤无机固碳不仅通过无机化学途径,还包括微生物途径,并且后者远高于前者的贡献(约 2 倍). 以往研究没有考虑微生物的生物矿化途径对无机固碳的贡献,这可能高估了无机化学固碳途径的贡献,今后这方面需要更多生物和非生物途径区分研究,以提高土壤无机固碳评估的精确度^[6].

1 作物光合碳对土壤碳输入的贡献及其对土壤有机碳分解的激发效应

^{13/14}C 法可以区分 SOC 中源于“根系新碳”和“土壤老碳”的比例,定量作物光合碳对 SOC 的输入. 从碳标记物上可以区分为: ①放射性同位素¹⁴C, ②稳定同位素¹³C; 从示踪方法上进一步区分为: ①连续标记(包括人工^{13/14}C 标记和自然¹³C 丰度)^[7,9,22], ②重复脉冲^{13/14}C 标记^[23-25], ③单次脉冲^{13/14}C 标记^[26,27]. 与¹³C 标记相比,¹⁴C 标记具有费用相对便宜和检测阈值低等优点,但是¹⁴C 具有放射性,对环境和人体有辐射风险,不适合在野外原位应用^[7,26]. 在所有碳标记方法中,借助连续人工标记量化 SOC 输入是最精确的,但是长时间人工连续标记需要稳定温度、湿度和 CO₂ 浓度的标记装置,这在国内外少数实验室才能实施,很难在田间做原位标记,只能在田间和室内做盆栽试验^[22,28,29]. ¹³C 自然丰度法是个折中选择,¹³C 自然丰度法实际上是长期¹³C 低丰度自然标记,例如通过把 C₃ 作物长期种植或将 C₃ 残体持续添加到 C₄ 土壤上,根据作物碳和 SOC 之间 $\delta^{13}\text{C}$ 差异,通过¹³C 两源模型来定量作物碳对 SOC 的输入,但是这个方法仅适合研究外源

碳长期累积过程^[9,30]. 如果研究田间单季作物生长对 SOC 的贡献,^{13/14}C 脉冲标记是个有效手段,因为脉冲标记持续几个小时,标记室内的温度、湿度和 CO₂ 浓度要求相对易于满足^[31,32]. 目前在野外和室内广泛应用的有 3 种脉冲标记量化方法(图 1): ①不同植株在不同关键物候期平行标记,然后经过相同天数后(示踪期)收获,这个方法量化的是每个关键生育期的净根际沉积碳的累加^[31,32]; ②不同植株在不同关键物候期平行标记,一部分标记植株经过短示踪期后(几个小时和几天)收获,另一部分标记植株在生育期末收获,这个方法量化不同时期净根际沉积碳到生育期末的残留^[26,27,33]; ③同一个植株在不同时期(例如相隔两周)脉冲标记,到生育期末收获,标记频率覆盖了整个生育期,标记相对均匀,这也是连续人工标记的折中选择^[23,24].

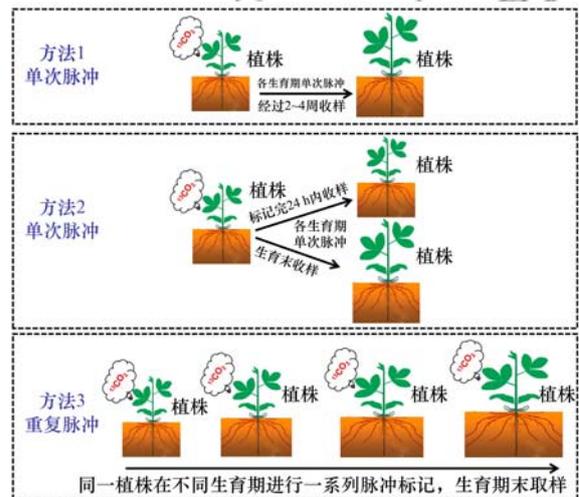


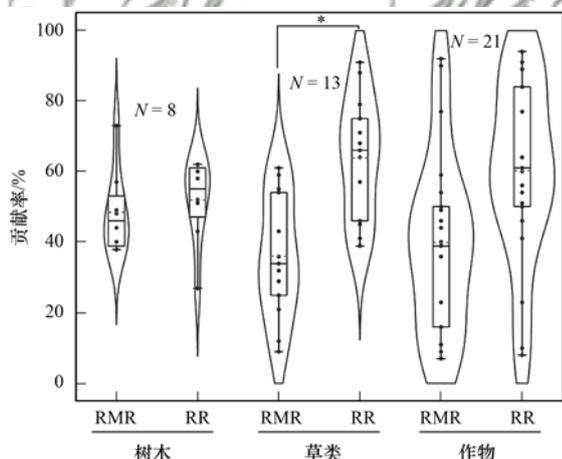
图 1 3 种^{13/14}CO₂ 脉冲标记方法的示意

Fig. 1 Schematic of three ^{13/14}CO₂ pulse labeling methods

1.1 根际沉积碳对土壤碳输入的贡献

植物根系生长对 SOC 输入的贡献主要是以根际沉积碳的形式,植物根际沉积碳在土壤中的驻留时间远高于残体碳,例如水稻根际沉积碳的驻留时间约是其残体碳的 1.5 倍^[34]. 总根际沉积碳包括: ①净根际沉积碳; ②分解的根际沉积碳(根际微生物呼吸)^[2,35,36]. 在全球范围内,三源区分根际呼吸(活根呼吸、根际沉积碳和 SOC 分解)的研究仍然很缺乏,数据源比较少,本文通过整合分析发现作物、草类和树木的根际沉积碳分解占根源呼吸的比例分别为 40%、36% 和 48% (图 2). 结合 Pausch 等^[2] 整合作物、草类和树木的光合^{13/14}C 分配结果(净根际沉积碳占根源呼吸的比例分别为 42%、38% 和 83%),由此间接估算出 3 类植物根际沉积碳的净残留与分解的比值分别为 1:1、1:1 和 1:1.7, 这暗示植物总根际沉积碳大约是净根际沉积碳的 2

~3 倍,因此,如果忽略根际沉积碳的分解,这可能导致大幅低估了根系释放到土壤中的碳量.在绝大多数光合碳分配研究中仅量化前者,而对后者的定量分析极少,这是由于量化后者的技术难度很大,前提是需要把根际呼吸划分为活根呼吸、根际微生物呼吸和 SOC 分解^[36~38].目前,区分这 3 个 CO₂ 组分的同位素方法主要有 6 种:①同位素稀释法;②模拟根际沉积碳法;③根际沉积碳洗脱法;④土壤¹⁴C 动态释放建模法;⑤根源呼吸减去根际微生物呼吸释放的¹⁴CO₂^[39];⑥根分离法结合¹³C 脉冲标记法^[36].以上 6 种方法都是建立在基本假设上进行区分,^{13/14}C 方法很难精确区分这 3 个碳源释放的 CO₂,这是由于活根和根际微生物呼吸均来源于根系,进而导致两者释放 CO₂ 的同位素值信号相似^[36],并且这两个来源的 CO₂ 共存于同一时空.根际激发效应对 SOC 分解的影响主要归因于根际沉积碳输入对根际微生物的激发^[40],本文推测根际微生物呼吸与根际激发效应呈正相关性^[41].由于三源区分根际呼吸的技术限制,导致根际激发效应的生态学机制解析仍不清晰,因此,这亟需进行三源区分根际呼吸以及定量根际微生物呼吸研究.



N 表示数据源的数目,箱式图中的黑色实线和红色虚线分别表示中位数和平均值,顶部和底部边界分别表示所有数据的 75% 和 25%,上部和下部误差线分别表示所有数据的 95% 和 5%,下同;RR (root respiration) 和 RMR (rhizo-microbial respiration) 分别表示活根和根际微生物呼吸对根源呼吸的贡献率;星号表示 RR 和 RMR 贡献率之间的显著性差异 ($P < 0.05$);整合分析三源区分根际呼吸的数据来源于树木^[37,42~45]、草类^[36,42,46~50]和作物^[35,38,39,51~54]

图 2 活根和根际微生物呼吸对根源呼吸的贡献

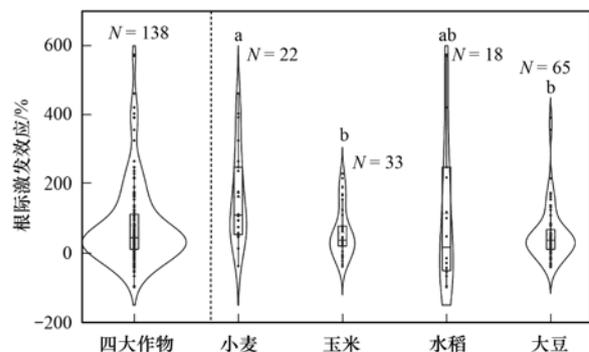
Fig. 2 Contribution of live root respiration and rhizo-microbial respiration to root-derived respiration

以往研究在秸秆还田土壤取样,通过测定¹³C 值来区分 SOC 中源于秸秆的比例,认为这是秸秆还田对 SOC 的贡献^[9,13],但是,这忽略了残留根系和根际沉积碳对 SOC 的贡献,导致秸秆还田对 SOC 贡献

的高估.例如,笔者通过整合分析玉米和小麦光合^{13/14}C 分配的研究^[8],发现玉米和小麦光合碳转移到地下(根系残体碳和净根际沉积碳)占净光合碳(植株残体碳+净根际沉积碳)的比例分别为 19% 和 23%,其中根系残体碳的贡献率分别为 14% 和 18%,净根际沉积碳的贡献率都为 5%.因此,SOC 中的“作物新碳”确切地说是整个种植体系(还田秸秆+残留根系+净根际沉积)对 SOC 输入的贡献.

1.2 作物生长对土壤碳释放的根际效应

根系生长过程中释放根际沉积碳,一部分根际沉积碳被土壤微生物利用,改变根际土壤 SOC 分解的速率,呈现 SOC 分解的“根际激发效应”^[41,55].两源区分根际呼吸(根源呼吸和 SOC 分解)可以用同位素法和非同位素法,非同位素法原理从本质上就是差减法,假设种植物和不种植物处理的 SOC 源 CO₂ 释放相等,这忽略了根际激发效应.因此,仅可以通过碳同位素法来定量分析根际激发效应^[81].Huo 等^[56]整合分析了 31 个根际激发效应的研究,发现根际激发效应增加 SOC 分解的幅度为 59%,其中木本植物、草类植物和作物的根际激发效应分别为 77%、57% 和 38%.本文进一步细化四大作物(小麦、玉米、水稻和大豆)的根际激发效应,整合了 30 个关于四大作物的根际激发效应研究,发现四大作物根系生长显著增加 SOC 的分解,根际激发效应的平均和中位数分别为 75% 和 42% (图 3),其中小麦根际激发效应最高(平均和中位数分别为 162% 和 111%),水稻次之(115% 和 18%),然后是玉米(60% 和 38%)和大豆(36% 和 31%,图 3).尽管作物根际激发效应增加了 SOC 的分解,但是不一定导致 SOC 储量的降低,如果根系释放的碳(包括净根际沉积碳和腐烂根系)腐殖化到 SOC 含量超过正根际激发效应



不同小写字母表示不同作物根际激发效应之间的显著性差异 ($P < 0.05$);整合分析作物根际呼吸的数据来源于四大作物小麦^[60~67]、玉米^[68~76]、水稻^[28,77]和大豆^[29,41,61,62,78~85]

图 3 四大作物生长对 SOC 分解的根际激发效应

Fig. 3 Rhizosphere priming effect of four major crops on the decomposition of soil organic carbon

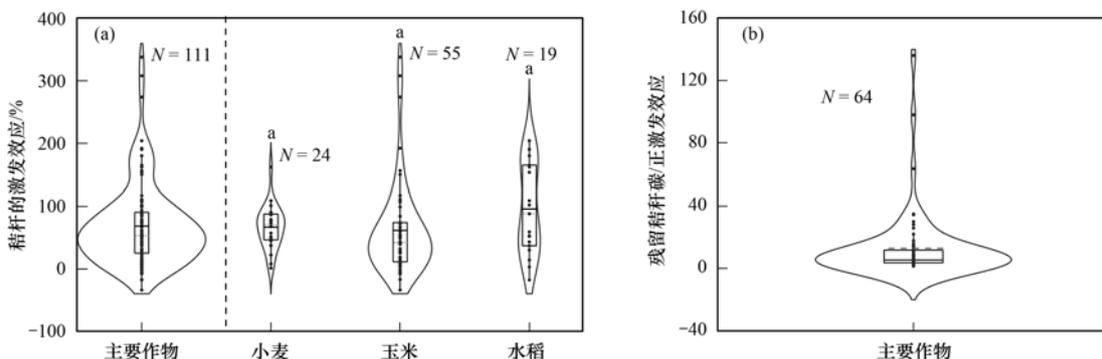
引起的额外 SOC 释放^[33], 根系生长则导致 SOC 储量增加, 反之亦然^[40,57]. 如果量化根际土壤 SOC 的平衡, 这需要同时量化光合碳在植物-土壤系统中的分配和输入, 以及区分根际 CO₂ 释放和根际激发效应^[8]. 但是, 同一个试验同时研究这两个主题的比较少^[48], 因此, 根际土壤碳平衡的精量化基础数据依然很少. 例如, 对小麦和玉米进行¹³C₂ 脉冲标记, 笔者量化了这两个作物根际效应, 发现增加土壤总碳释放分别为 0.26 g·kg⁻¹ 和 0.62 g·kg⁻¹^[32], 而小麦和玉米净根际沉积碳分别为 0.11 g·kg⁻¹^[58] 和 0.25 g·kg⁻¹^[59], 所以净根际沉积碳无法弥补正根际效应导致土壤碳的额外释放. 总之, 根际效应对 SOC 平衡的影响是个双刃剑, 取决于正根际激发碳分解和净根际沉积碳输入的平衡作用^[53].

另外, 碱性土壤包括 SOC 和 SIC 库, 根系生长同时影响 SOC 和 SIC 的释放和输入. 例如, 在整个作物生长季, 本文发现冬小麦根际效应对 SOC 源 CO₂ 额外释放量是 SIC 的 2.5 倍, 而夏玉米生长导致 SOC 和 SIC 源 CO₂ 额外释放量相等, 所以碱性土壤碳循环不能忽略根际效应对 SIC 释放的影响^[52]. 相对于 SIC 含量的背景值, 根系生长对 SIC 的输入量是相对低的, 通过低丰度¹³C₂ 标记很难检测到, 需要高丰度¹³C₂ 标记或者低检测限的¹⁴C 标记来量化(¹³C 和¹⁴C 检测限分别为 10⁻⁷ mol 和 10⁻¹³ mol)^[7,19]. 从目前来看, 根系生长对 SIC 释放和输入的影响研究是非常少的, 这需要更多的研究者来关

注这个问题, 为碱性农田碳中和对策提供基础数据.

1.3 作物残体对土壤有机碳分解的激发效应

在农田系统中, 作物残体还田可以在短期内促进或抑制 SOC 的分解, 这种现象被称作“激发效应”^[86]. 作物残体包括根系和秸秆, 由于根系含结构性碳组分高于秸秆, 因此根系分解速率低于秸秆, 这可能导致根系对 SOC 的贡献更大^[34,87]. 例如, 从作物残体分解角度, Zhu 等^[34] 发现水稻根系和秸秆在土壤中的驻留时间分别为 50.3 d 和 39.5 d; 从作物残体驱动微生物残体对 SOC 输入角度, Xu 等^[88] 发现玉米根系还田通过微生物残体途径对 SOC 积累量高于秸秆还田处理. 目前, 秸秆还田对激发效应的研究相对较多^[86], 较少关注根系还田的激发效应^[89], 两者同时研究的更少^[34,88]. 通过整合分析^{13/14}C 秸秆的土壤培养试验, 本文发现 3 大作物秸秆 (小麦、玉米和水稻) 对 SOC 分解的激发效应, 发现平均和中位数分别为 68% 和 53% [图 4(a)], 其中小麦、玉米和水稻秸秆的激发效应的平均值分别为 67%、61% 和 96%, 中位数分别为 71%、42% 和 88% [图 4(a)]. 因此, 秸秆还田在大部分情况下促进 SOC 的分解. 秸秆还田对 SOC 含量的影响取决于残留秸秆碳和正激发效应大小的平衡^[57,90], 本文进一步量化了残留秸秆碳与正激发效应, 发现平均比值为 13 倍 [中位数为 5 倍, 图 4(b)], 这表明残留秸秆碳可以补偿正激发效应导致 SOC 的额外分解.



不同小写字母表示不同作物秸秆激发效应之间的显著性差异 ($P < 0.05$); 整合分析秸秆还田对激发效应的数据来源于小麦秸秆^[91-96]、玉米秸秆^[10,97-108]、水稻秸秆^[34,89,109-114] 和其他农作物秸秆^[115-117]

图 4 作物秸秆对 SOC 分解的激发效应

Fig. 4 Priming effect of crop residues on the decomposition of soil organic carbon

2 量化土壤有机和无机固碳的新方法

2.1 区分作物生长对土壤内外源碳释放和外源碳输入的影响

在秸秆还田下的根际土壤, 外源有机碳的输入包括根际沉积碳与秸秆碳, 这两种作物碳都可以引起 SOC 分解的激发效应. 在酸性土壤上, 根际土壤

CO₂ 释放源达到 3 个, 包括秸秆碳、根源呼吸和 SOC, 而在碱性土壤, 根际土壤 CO₂ 释放又增加了 SIC 源, 达到 4 个. 区分根际土壤 CO₂ 是量化土壤碳平衡的前提, 而 3/4 源碳体系的存在给根际土壤 CO₂ 的区分带来挑战. 土壤残留秸秆碳的输入量化可以用^{13/14}C 方法直接划分 SOC 来源, 也可间接用^{13/14}C 方法量化土壤 CO₂ 中的秸秆分解碳量, 进而

用总秸秆碳投入减去秸秆分解碳来量化秸秆碳的净输入^[10].

2.1.1 区分秸秆还田下根际土壤 CO₂ 的释放

在酸性土壤上,3 源区分秸秆还田下根际土壤 CO₂ 有两种方法[图 5(a)],第一种方法为平行¹³C 标记秸秆和植株地上部^[118],第二种方法为平行¹³C 标记秸秆^[119].第一种方法标记处理为:①¹³C 秸秆 + 植株 + 土壤;②秸秆 + ¹³C 标记植株 + 土壤;③秸秆 + 植株 + 土壤.通过处理 1 和 2 与处理 3 组合,分别量化秸秆分解量和根源呼吸量,最后剩余为 SOC 的分解碳量.第二种方法标记处理为:①高富集¹³C 作物残体 + 作物 + 土壤;②低富集¹³C 作物残体 + 作物 + 土壤.

物 + 土壤.通过利用秸秆碳、根系碳和 SOC 之间的 $\delta^{13}\text{C}$ 差异,借助¹³C 三元混合模型,3 源拆分秸秆还田下根际土壤 CO₂ 的释放^[103,119,120],从而量化根系生长对土壤内外源 CO₂ 释放的影响.

在碱性土壤上,为了 4 源区分秸秆还田下根际 CO₂ 释放,通过平行¹³C 标记秸秆和植株地上部来实现,具体标记处理为[图 5(b)]:①秸秆 + ¹³C 标记植株 + 土壤;②高富集¹³C 秸秆 + 植株 + 土壤;③低富集¹³C 作物残体 + 作物 + 土壤;④秸秆 + 植株 + 土壤.第一步通过处理 1 和 4 量化根源呼吸的碳量,在第一步基础上,通过处理 2 和 3 构建¹³C 四元混合模型,4 源拆分根际土壤 CO₂ 的释放.

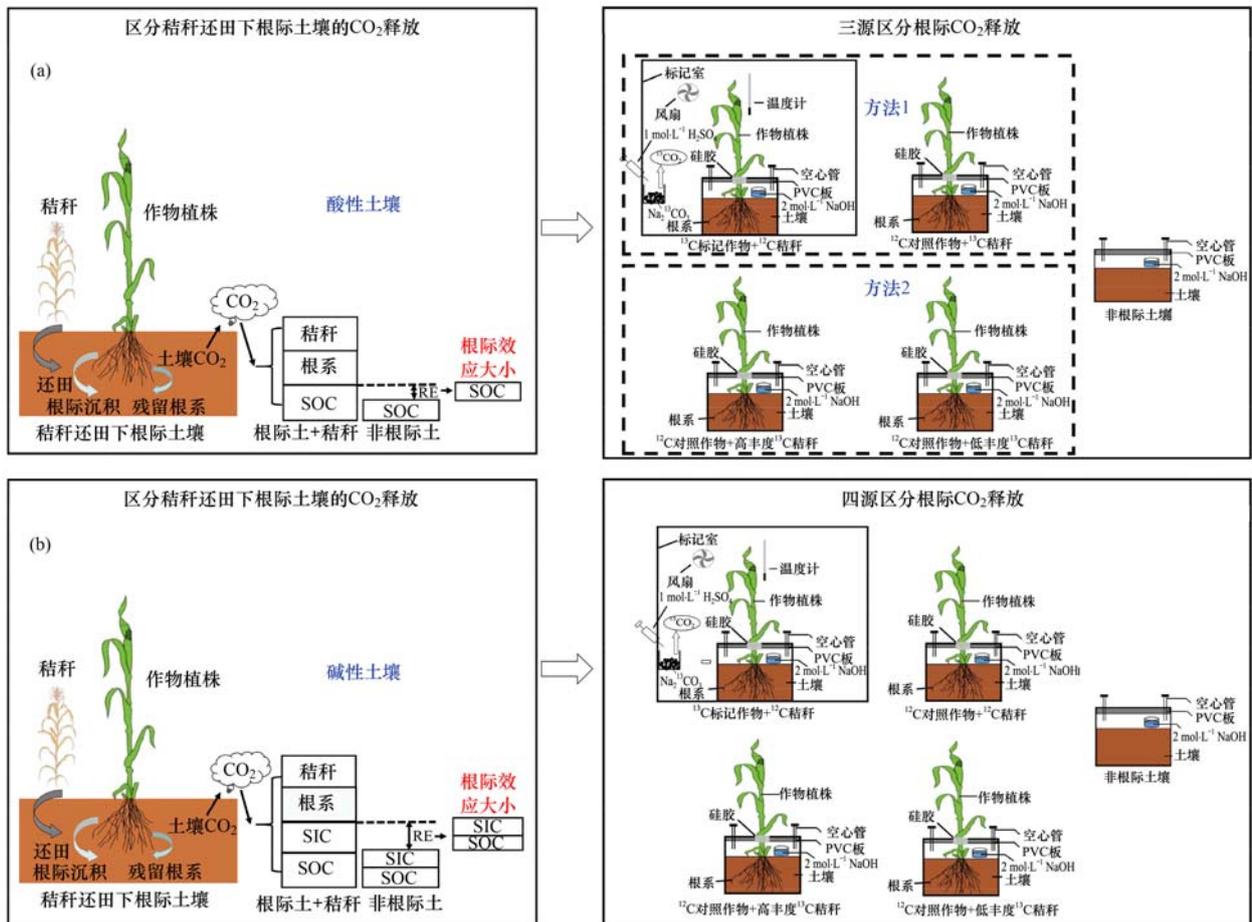


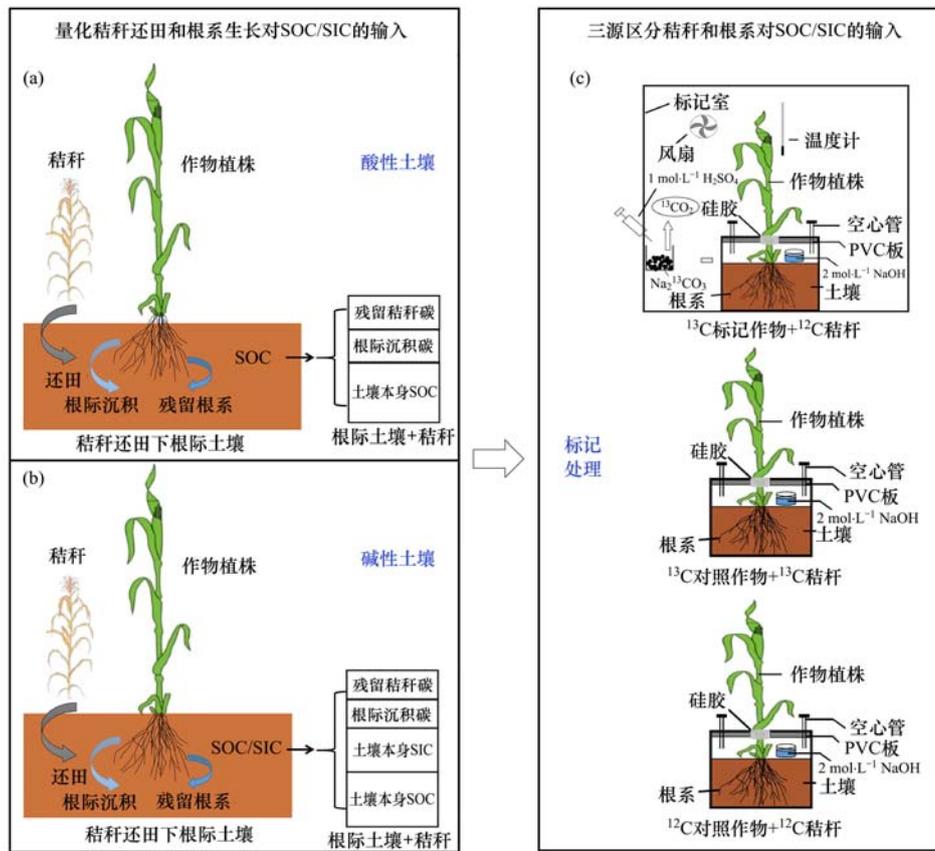
图 5 区分酸性和碱性土壤在秸秆还田下根际 CO₂ 的释放

Fig. 5 Separating CO₂ emission from rhizosphere under straw returning in acidic and calcareous soils

2.1.2 根际沉积碳和秸秆碳对土壤碳输入的贡献

在根际沉积碳和秸秆碳共存下,除了以木质素和微生物残体形式对 SOC 输入外^[121],另外在碱性土壤上,也能以无机化学固碳形式对 SIC 的输入^[4,17].通过平行¹³C 标记秸秆和植株地上部,来量化作物碳对 SOC 和 SIC 的贡献,具体标记处理如下(图 6):①¹³C 秸秆 + 植株 + 土壤;②秸秆 + ¹³C 标记植株 + 土壤;③秸秆 + 植株 + 土壤.根际沉积碳的输入只能用直接方法,秸秆碳的输入

可用直接和间接两种方法来量化(图 6).直接和间接方法都是通过¹³C 平行标记植株地上部和秸秆,两种方法都需要两源区分 SOC(酸性土壤)和 SIC(碱性土壤)中源于根际沉积碳的比例,以及通过称重法来量化残留根系碳,两种方法区别在于残留秸秆碳对 SOC 的贡献,直接方法是通过直接区分 SOC 中源于秸秆碳的贡献^[122],间接方法是通过秸秆碳投入量减去秸秆碳分解量来计算土壤残留秸秆碳量^[10].



(c) 量化根际沉积碳和秸秆碳对土壤碳输入的贡献包括: ①直接方法: 土壤碳的净输入 = SOC/SIC_{秸秆碳(1)} + SOC/SIC_{根际沉积碳(2)} + 残留根系碳₍₃₎; ②间接方法: 土壤碳的净输入 = (总还田秸秆碳 - 秸秆分解₍₁₎) + SOC/SIC_{根际沉积碳(2)} + 残留根系碳₍₃₎, 式中下标(1)~(3)分别表示碳输入分别通过¹³C标记秸秆、¹³C标记作物和根系收获法来量化; 酸性土壤仅包括SOC组分, 而碱性土壤包括SOC和SIC两个组分

图6 量化酸性和碱性土壤中根际沉积碳和秸秆碳对土壤的输入

Fig. 6 Quantifying the input of rhizodeposit-C and straw-C into acidic and calcareous soils

2.2 区分次生无机碳中源于无机化学沉淀和微生物形成途径

在碱性土壤, 目前PIC形成多关注无机化学沉淀途径, 较少关注微生物的生物矿化途径对无机固碳的贡献. 还田秸秆分解和根源呼吸释放的CO₂可能通过无机化学途径^[4,17]和微生物途径^[6]被SIC固定. 为了区分这两个途径, 可以在不灭菌和灭菌土壤条件下, 设置标记处理: ①高丰度¹³C标记作物 + ¹²C秸秆; ②¹²C对照作物 + 高丰度¹³C秸秆; ③¹²C对照作物 + ¹²C秸秆. 在不灭菌条件下, 通过¹³CO₂气体标记作物地上部或者¹³C标记秸秆添加, 量化PIC源于无机化学和微生物途径的总贡献; 在灭菌环境下, 通过平行标记作物地上部和秸秆, 量化PIC源于无机化学途径的贡献. 最后, 不灭菌下PIC中源于根际沉积碳和秸秆碳的贡献减去灭菌下作物碳的贡献, 即得微生物途径的无机固碳贡献(图7).

3 展望

(1) 一部分根际沉积碳被土壤微生物分解, 引起根际激发效应, 量化这部分碳的前提是需要把根

源呼吸进一步区分为活根呼吸和根际沉积碳的分解. 由于区分技术限制, 相关研究仍然较少, 这导致总根际沉积碳量化的不确定性.

(2) 碱性土壤包括SOC和SIC库, 根系生长对SIC溶解也产生影响, 由于碱性土壤增加了SIC源CO₂的释放, 导致根际土壤CO₂释放源达到3个(根系、SOC和SIC). 因此, 在碱性土壤, 三源区分根际土壤CO₂的释放是量化根际效应的前提. 为了提高量化根际土壤碳输出的准确性和模型预测精度, 多源CO₂释放区分研究需要进一步加强.

(3) 大部分秸秆还田对激发效应和碳平衡的影响研究仅考虑秸秆单独添加, 然而, 在秸秆还田下的农田, 作物根际沉积碳和秸秆碳共存, 这导致多源碳体系中作物碳输入和输出的量化仍是一个挑战. 尤其在碱性土壤, 根际土壤CO₂释放源达到4个. 本文初步提出了碱性和酸性土壤中作物碳输入和输出量化的新方法.

(4) 在农田“碳中和”目标下, 碱性土壤无机固碳可能是个生态固碳手段, 以往研究多关注无机化学固碳贡献, 伴随着微生物无机固碳途径的发现, 需

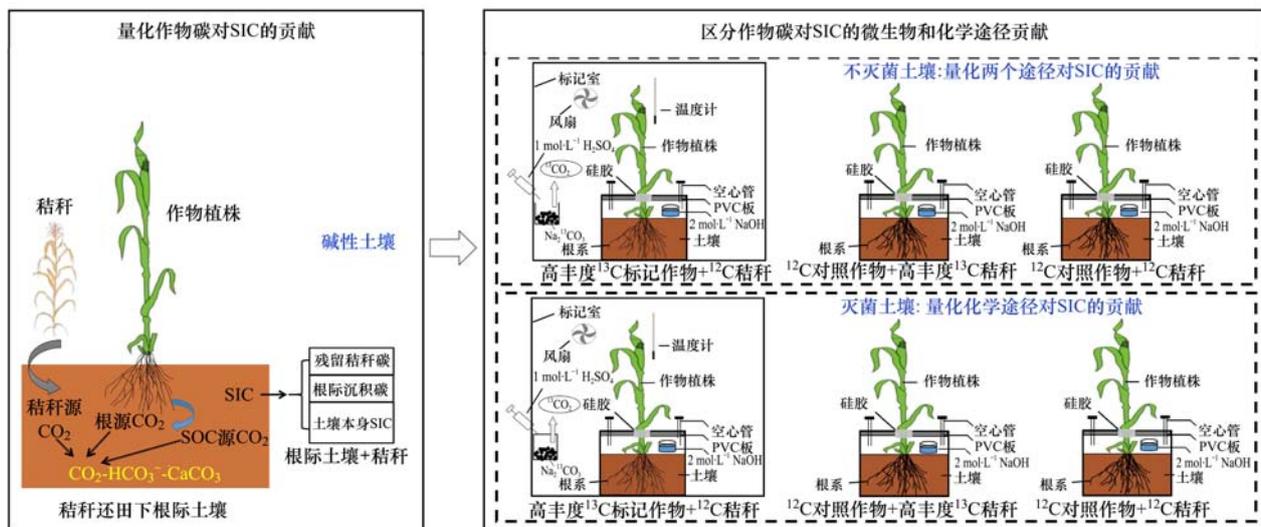


图7 量化在碱性土壤中根际沉积碳和秸秆碳对土壤无机碳的输入

Fig. 7 Quantifying the input of rhizodeposit-C and straw-C into soil inorganic carbon in calcareous soils

要重新思考以往无机化学途径固碳的结果,以往研究是否高估了无机化学固碳的贡献?尤其针对秸秆还田下的根际土壤,本文初步提出了区分生物和非生物途径对无机固碳贡献的新方法。

4 结论

本文通过文献整合分析发现:活根呼吸和根际沉积碳分解比值约为2:3;在大部分情况下,作物根系生长和秸秆碳输入增加了SOC的分解,呈现正(根际)激发效应(平均值分别为75%和67%);尽管秸秆还田激发土壤SOC的额外分解,但是多数情况下土壤残留秸秆碳高于SOC额外分解的损失,因此,秸秆还田可能导致SOC库的净增加。针对秸秆碳和根际碳共同输入的农田土壤,本文提出了新量化方法,这可能有助于提高农田土壤有机和无机碳循环评估的精确度。

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