

氮磷添加对土壤有机碳的影响：进展与展望

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摘要 土壤有机碳库是陆地生态系统最大的碳库, 在调控全球碳循环和气候变化中起着重要的作用。人为活动所导致的氮、磷输入和大气氮、磷沉降提高了陆地生态系统的氮、磷可利用性, 进而会通过调控植物生长和微生物活性对土壤有机碳动态产生重要影响。目前, 在全球范围内已经开展了很多氮磷添加调控土壤有机碳动态的野外控制实验, 并取得了一些突破和进展, 但还缺乏较为系统全面的梳理与总结。该文以氮磷添加对土壤碳输入和输出的影响为切入点, 从土壤有机碳的碳库大小、组分和分子组成3个方面系统阐述了氮磷添加对土壤有机碳的影响及其潜在机制。根据以往的研究结果, 氮添加、磷添加和氮磷共同添加对土壤有机碳库的影响总体上表现为促进作用。其中, 氮添加引起的促进作用是微生物对土壤有机碳的分解输出降低和/或植物碳输入增加所致, 而磷添加引起的促进作用可能主要是由于植物碳输入的增加。对于土壤有机碳组分(粒径分组或密度分组)而言, 氮添加虽然同时促进了活性有机碳组分(颗粒态有机碳或轻组分有机碳)和稳定性有机碳组分(矿物结合态有机碳或重组分有机碳), 但降低了稳定性碳组分占土壤总有机碳的比例。此外, 氮添加对土壤有机碳分子组成的影响较为复杂, 受到土壤氮有效性、氮添加量和氮形态等因素的调节。与氮添加相比, 磷添加和氮磷共同添加对土壤有机碳组分和分子组成影响的研究十分有限, 其影响机制尚不清楚。基于已有研究中存在的不足, 该文提出了未来需要加强的4个方面的研究内容: 磷添加对不同生态系统尤其是热带森林土壤有机碳的影响, 氮磷添加下植物和微生物在调控土壤有机碳及其组分变化中的作用与相对贡献, 长期氮磷添加及其交互作用对土壤有机碳的影响, 氮磷添加对深层土壤有机碳的影响。

关键词 土壤有机碳; 矿物结合态有机碳; 颗粒态有机碳; 分子组成; 微生物群落结构; 密度分组; 氮沉降; 磷沉降

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Effects of nitrogen and phosphorus addition on soil organic carbon: review and prospects

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Abstract

Soil organic carbon (SOC) pool is the largest carbon pool in terrestrial ecosystems and plays an important role in regulating the global carbon cycle and climate change. The inputs of nitrogen (N) and phosphorus (P) induced by anthropogenic activities and atmospheric deposition of N and P increase the availabilities of N and P in terrestrial ecosystems, which in turn will have important impacts on SOC dynamics via regulating plant growth and microbial activity. At present, many field-manipulation experiments regarding the effects of N addition and/or P addition on the dynamics of SOC have been conducted worldwide, and some breakthroughs and progress have been made, but a systematic and comprehensive review and summary of them is still lacking. By taking the effects of N addition and/or P addition on the inputs and outputs of soil carbon as the starting point, we systematically reviewed the effects of N addition and/or P addition on SOC and the potential mechanisms from three aspects: the size, fraction and molecular composition of SOC. According to the results of previous studies, N addition, P addition, and combined N and P (N + P) addition generally stimulate the size of SOC pool. The stimulation effect of N is caused by the decreased carbon outputs from microbial decomposition and/or the enhanced carbon inputs of plant above- and/or below-ground under N addition. However, the stimulation effect of P may be dominated by the enhanced carbon inputs of plant above- and/or below-ground under P addition. As for the fractions of SOC separated by particle-size or density fractionation, N addition promotes both labile fractions (particulate organic carbon or light fraction carbon) and stable fractions (mineral-associated organic carbon or heavy fraction carbon) of SOC, but reduces the proportion of stable carbon fractions to total SOC. In addition, the effects of N addition

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on the molecular composition of SOC are complex and diverse, and are regulated by environmental and experimental factors such as soil N availability, N addition rate, and N fertilizer form. Compared with N addition, studies on the effects of P addition and N + P addition on the fraction and molecular composition of SOC are very limited, and the associated mechanisms for the effects of P addition and N + P addition on these variables are still unclear. To improve our understanding, we propose four aspects of studies that need to be strengthened in the future, including the effects of P addition on SOC in different types of ecosystems (especially tropical forests), the role and relative contribution of plants and microorganisms in regulating the changes of SOC and its fractions under N addition and/or P addition, the effects of long-term N addition and/or P addition and their interactions on SOC, and the effects of N addition and/or P addition on SOC in deep soils (below 20 cm).

Key words soil organic carbon; mineral-associated organic carbon; particulate organic carbon; molecular composition; microbial community structure; density fractionation; nitrogen deposition; phosphorus deposition

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土壤是陆地生态系统最大的碳库, 超过植被和大气的碳库之和, 土壤碳库的微小变化都会对大气CO₂浓度和全球气候变化产生巨大的影响, 在调节全球碳循环和气候变化中起着重要的作用(Lal, 2004)。土壤有机碳及其对全球变化的响应是生物地球化学和全球变化领域的研究热点, 受到国内外学者的广泛关注(Jackson *et al.*, 2017; Lajtha *et al.*, 2018; Lu *et al.*, 2021a)。土壤有机碳库的变化主要取决于植物以地上凋落物和根系分泌物与残体的形式向土壤的碳输入过程和微生物分解土壤有机碳产生的碳输出过程。植物向土壤的碳输入过程受到植物生长与生产力、凋落物生产和地下碳分配等因素的影响, 碳输出过程主要受到土壤微生物的调控, 如微生物生物量、碳利用效率(CUE)、酶活性和群落组成等(Cusack *et al.*, 2011a; 李嵘和常瑞英, 2015; Riggs & Hobbie, 2016)。因此, 在外界干扰下, 植物生长和土壤微生物分解活性等与碳输入和输出密切相关过程的变化会对土壤有机碳库的动态变化产生影响。

土壤有机碳的组成成分复杂, 在全球变化等外界因素的影响下, 其变化不仅体现在碳库大小的变化上, 也体现在其组分和分子组成等物理和化学属性的变化上。土壤有机碳库由代表着不同稳定机制及周转速率的多种功能碳库所构成, 一般而言, 可将其区分为活性有机碳库和稳定性有机碳库(Six *et al.*, 2002; von Lützow *et al.*, 2007; Lavalley *et al.*, 2020)。同样地, 土壤有机碳也是由具有不同化学结构的有机碳分子所构成, 它们具有不同的稳定性和降解速度。全球变化要素如氮(N)、磷(P)沉降等可以通过化学反应作用、改变植物地上和地下凋落物的质量以及改变微生物周转和底物利用偏好等来改

变土壤有机碳的组分和分子组成(Janssens *et al.*, 2010; Mori *et al.*, 2018)。因此, 了解并剖析土壤有机碳的碳库大小、组分和分子组成的变化对于准确预测土壤有机碳动态具有重要作用。

N和P被认为是限制植物生长和生态系统生产力的两种重要元素(Elser *et al.*, 2007; Vitousek *et al.*, 2010)。自工业革命以来, 人为活动如化石燃料燃烧、农田矿质肥料施用以及大气N、P沉降等极大地增加了陆地生态系统的N、P输入(Galloway *et al.*, 2004; Peñuelas *et al.*, 2012)。据估计, 从19世纪60年代到20世纪90年代人类活动导致的N输入量已从15 Tg·a⁻¹上升到156 Tg·a⁻¹, 预计到2050年将增加到270 Tg·a⁻¹(Galloway *et al.*, 2004)。与此类似, 人类活动已经使全球P输入量由工业革命前的0.3 Tg·a⁻¹增加到2005–2010年间的14–16 Tg·a⁻¹, 并将持续增加(Peñuelas *et al.*, 2012)。氮磷输入和沉降及其所导致的养分可利用性增加和养分不平衡对区域和全球陆地生态系统碳循环产生了显著的影响, 如改变植被生长与生产力、微生物活性及其对土壤有机碳的分解作用(Feng & Zhu, 2019; Xu *et al.*, 2021a)。氮磷富集所导致的这些植物和微生物的变化会对土壤有机碳动态产生影响, 如改变其碳库大小、组分和分子组成。

因此, 探究氮磷添加对土壤有机碳动态的影响对于理解碳与养分之间的耦合作用以及准确预测陆地生态系统碳循环动态及其与气候变化之间的反馈至关重要。目前, 在全球范围内已经开展了很多关于氮磷添加对土壤有机碳影响的案例研究, 但是不同研究的结果存在很大的差异, 受到诸多因素的影响与调控。为此, 本文以氮磷添加对土壤碳输入和

输出过程的影响为切入点, 系统综述了氮磷添加(N添加、P添加和氮磷共同(N + P)添加)对土壤有机碳的碳库大小、组分和分子组成的影响模式与调控机理, 指出了当前研究中存在的不足, 并提出了未来的研究建议。

1 氮磷添加对土壤碳输入和输出过程的影响

1.1 氮磷添加对土壤碳输入过程的影响

植物碳输入是土壤有机碳的主要来源, 对土壤有机碳的形成与积累至关重要, 氮磷添加可直接通过影响地上凋落物和地下根系碳输入过程而调控土壤有机碳动态。研究表明, 氮磷添加对森林、草地和农田等各类陆地生态系统的地上生产力具有显著的促进作用, 且N添加引起的促进作用在北方森林更为强烈, 而P添加导致的促进作用在热带气候区的生态系统(主要为热带森林)中更为强烈(Li *et al.*, 2016; Čapek *et al.*, 2018; Schulte-Uebbing & de Vries, 2018; Hou *et al.*, 2020)。这种N、P添加对陆地生态系统生产力的促进结果可能和植被生产力养分限制的纬度格局有关(Du *et al.*, 2020; 冯继广和朱彪, 2020; Hou *et al.*, 2021), 即高纬度地区主要为N限制, 低纬度地区主要为P限制(Vitousek, 1984; Vitousek *et al.*, 2010; Norby *et al.*, 2016)。

地上凋落物及其分解产生的可溶性有机碳输入是土壤有机碳的一个重要来源途径(Cotrufo *et al.*, 2015; Lu *et al.*, 2021b)。研究表明, N、P添加对不同养分状况下的生态系统的凋落物生产具有不同的影响。一般而言, 在N或P限制的生态系统, 相应的N或P添加能够通过提高植被生产力而促进凋落物生产; 而在N或P不受限制的生态系统, N或P添加并不会对植物生产力和凋落物生产产生显著的影响(Janssens *et al.*, 2010; Feng & Zhu, 2019; Wright, 2019; Xu *et al.*, 2021a)。此外, 研究发现, 土壤可溶性有机碳对N添加的响应和凋落物生产对N添加的响应存在显著的正相关关系, 说明凋落物的输入能够显著地提高土壤可溶性有机碳的含量, 进而提高土壤有机碳含量(图1; Xu *et al.*, 2021a, 2021b)。

除地上凋落物外, 根系也是土壤有机碳的重要来源, 而且根系对土壤有机碳形成与积累的贡献远高于地上凋落物(Jackson *et al.*, 2017; Sokol & Bradford, 2019; Villarino *et al.*, 2021)。这主要与3个因素有关: (1)根系能够比地上凋落物向土壤供应更

多的碳; (2)根系死亡后可以立即而直接地与土壤矿物、微生物和团聚体相互作用, 具有较高的有机碳形成效率; (3)根系来源碳(如根际沉积物)比凋落物来源碳更能有效地形成稳定的土壤有机碳(Rasse *et al.*, 2005; Crow *et al.*, 2009; Jackson *et al.*, 2017; Sokol *et al.*, 2019; Sokol & Bradford, 2019)。与地上生产力不同, 氮磷添加对不同类型生态系统地下生产力的影响较为复杂, 可表现为促进作用、没有显著影响或抑制作用(Li *et al.*, 2016; Yue *et al.*, 2017; Jiang *et al.*, 2019; Xing *et al.*, 2022a)。氮磷添加的促进作用可能是由于植物生长受到N、P限制, 或者单一养分的添加会加剧植物对另一种养分的需求, 进而促使植物分配更多的光合产物到地下以获取所缺乏的养分(Li *et al.*, 2016; Čapek *et al.*, 2018); 而没有显著影响或抑制作用的原因可能是植物根系的主要功能之一是用于获取养分, 当植物面对养分可利用性提高之后, 不需要分配更多的光合产物到地下部分来获取养分(Peng *et al.*, 2017; Ning *et al.*, 2021)。虽然氮磷添加对生态系统地下生产力的影响不尽相同, 但目前的大尺度整合分析研究大都表明, 氮磷(N、P和N + P)添加对地下生产力总体上表现为促进作用或没有显著影响(图1; Li *et al.*, 2016; Yue *et al.*, 2017; Jiang *et al.*, 2019)。

1.2 氮磷添加对土壤碳输出过程的影响

土壤呼吸是土壤碳输出的主要形式, 通常包含两个主要过程, 分别为根系自养呼吸和微生物分解土壤有机碳产生的异养呼吸。前者输出的碳来源于植物根系, 其输出与土壤有机碳并无直接关联, 而且对土壤有机碳的影响较小。后者输出的碳占到土壤呼吸总量的60%, 达到60–80 Pg·a⁻¹ (Chen *et al.*, 2014; Hursh *et al.*, 2017); 作为土壤呼吸的重要组成部分, 微生物对土壤有机碳的分解作用对土壤有机碳的动态变化至关重要, 在研究中被广泛关注。土壤有机碳分解受到诸多因素的调控, 其中以土壤微生物生物量、酶活性、CUE和群落结构等属性为主。

研究表明, 在一些N限制的生态系统, N添加能够通过提高微生物活性而促进土壤有机碳的分解(Zhang *et al.*, 2014; Zhong *et al.*, 2016), 但总体上N添加倾向于降低土壤有机碳的分解(Janssens *et al.*, 2010; Ramirez *et al.*, 2012; Zhou *et al.*, 2014; Xu *et al.*, 2021a)。具体而言, N添加主要可通过4条途径抑制土壤有机碳的分解(图1): (1)添加的外源N直接和

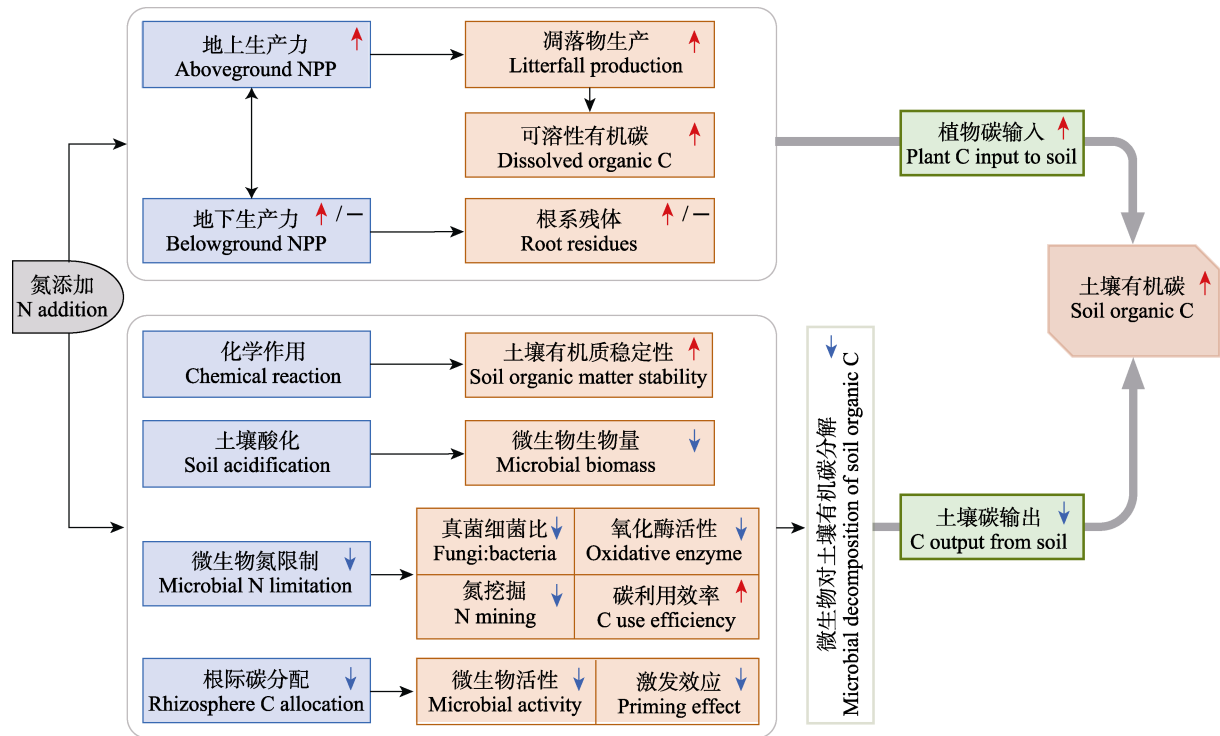


图1 氮添加促进土壤有机碳积累的潜在机制。框内向上箭头表示增加，向下箭头表示降低，横线表示没有响应，这些符号表示不同研究的总体响应情况。

Fig. 1 Potential mechanisms of how nitrogen (N) addition stimulates soil organic carbon (C) accumulation. In the box, upward arrows indicate increase, downward arrows indicate decrease, short horizontal lines indicate no response, and these symbols indicate the overall responses across studies. NPP, net primary productivity.

土壤有机质发生缩合反应(condensation reaction)等化学作用，从而增强土壤有机质的化学稳定性使其难以被微生物分解利用(Fog, 1988; Janssens *et al.*, 2010)。(2) N添加可降低土壤pH，导致土壤酸化和铝离子的活化而产生毒害(Treseder, 2008; Tian & Niu, 2015; Chen *et al.*, 2020b)，从而抑制微生物生物量及其分解作用(Ye *et al.*, 2018; Zhang *et al.*, 2018)。(3) N添加减缓微生物N限制程度，这既可直接提高微生物CUE、降低氧化酶活性和微生物对土壤有机质的“氮挖掘”(Manzoni *et al.*, 2012; Ramirez *et al.*, 2012; Spohn *et al.*, 2016; Liu *et al.*, 2018)，也可改变微生物群落结构(即降低真菌细菌比)和功能，降低对稳定性有机碳的分解，进而导致异养呼吸降低(Frey *et al.*, 2004; Janssens *et al.*, 2010; Kamble *et al.*, 2013)。(4) N添加提高土壤养分可利用性后，植物会调整其资源获取策略而减少向地下部分尤其是根际的碳分配，导致微生物活性下降和激发效应降低，进而抑制根际微生物呼吸(Janssens *et al.*, 2010; Feng & Zhu, 2021; Ning *et al.*, 2021)。

与N添加可通过土壤酸化等途径抑制微生物对土壤碳的分解输出不同，P添加对土壤有机碳分解的影响较为复杂(Cleveland *et al.*, 2002; Camenzind *et al.*, 2018; Mori *et al.*, 2018; Feng & Zhu, 2019)。研究表明，在P限制的热带森林中，P添加可通过缓解微生物P限制而促进微生物的生长和活性，从而提高其对土壤有机碳的分解(Johnston *et al.*, 2019; Hui *et al.*, 2020)。此外，P添加也可通过非生物途径促进土壤有机碳的分解，其机制是：与有机化合物相比，磷酸盐与土壤矿物表面的吸附位点具有更高的亲和力，加入的无机P会使得被土壤矿物吸附的有机化合物(如可溶性有机碳)发生解吸，从而使这些碳底物能够被微生物利用分解(Spohn & Schleuss, 2019; Spohn *et al.*, 2022)。也有研究指出，P添加可通过多种途径降低土壤有机碳分解，如降低植物向地下的碳分配(Wang *et al.*, 2017)，降低微生物“磷挖掘”(Mori *et al.*, 2015)，提高微生物CUE (Manzoni *et al.*, 2012)，以及增强植物N限制及其对N的吸收而抑制微生物分解活性(Feng & Zhu, 2019)。尽管不同研究得到的

结果不尽相同, 但综合各类生态系统而言, P添加总体上对微生物活性及其对土壤有机碳的分解表现为无显著影响或促进作用(Camenzind *et al.*, 2018; 范珍珍等, 2018; Feng & Zhu, 2019; Jiang *et al.*, 2021)。

2 氮磷添加对土壤有机碳的影响与潜在机制

2.1 氮磷添加对土壤总有机碳库的影响

目前, 全球或区域尺度的整合分析结果大都表明, 氮磷添加总体上有显著增加土壤有机碳库的趋势, N添加的促进程度为4%–11%, P添加的促进程度为5%左右, N + P添加的促进程度为8% (Janssens *et al.*, 2010; Liu & Greaver, 2010; Yue *et al.*, 2017; Chen *et al.*, 2018b; Xu *et al.*, 2021a)。氮磷添加(尤其是单独的N添加)下, 土壤有机碳库的增加通常被归因于植物向土壤中的碳输入(通常以植被生产力为表征)增加和土壤有机碳分解输出降低两个方面(图1), 而且这两个方面可以耦合发生或单独发生而起作用(Ye *et al.*, 2018; Xu *et al.*, 2021a)。与单独的N或P添加相比, N + P添加总体上对土壤有机碳的促进作用更强, 可能与N + P添加对植物碳输入的促进程度更大有关(Elser *et al.*, 2007; Yue *et al.*, 2017; Jiang *et al.*, 2019)。就N、P添加的交互作用(N × P)而言, 其对土壤总有机碳库的影响可能取决于生态系统中植物和微生物的养分限制状况。有研究发现, N × P在苔原和农田中表现为拮抗作用, 但就不同生态系统来说, N × P通常不显著, 而是更多地表现为加和效应(即N + P添加的效果相当于单独N添加和单独P添加效果的叠加)(Sundqvist *et al.*, 2014; Yue *et al.*, 2017; Luo *et al.*, 2019; Jiang *et al.*, 2021)。就调控因素而言, 研究表明, N添加对土壤有机碳库的促进作用受到实验处理时间和N添加量的调控, 表现为随实验处理时间和N添加量的增加促进作用增强(Xu *et al.*, 2021a; Lu *et al.*, 2022); 而P添加和N + P添加并没有类似的规律, 但案例研究有限, 还存在较大的不确定性。

植物碳输入的增加和微生物分解输出的降低是氮磷添加促进土壤有机碳积累的两个潜在机制, 但它们的主导作用在N添加和P添加下存在差异。基于热带森林实验和数据整合分析, 最近的一项研究提出了土壤碳吸存假说, 该假说认为: 在“氮限制”的生态系统(如北方森林)中, N添加促进植被净初级生产力, 地上凋落物输入增加和土壤碳排放降低导致

土壤碳吸存增加; 而在“氮富集”的生态系统(如热带森林)中, 长期N添加对净初级生产力无显著影响, 即植物向土壤中的碳输入没有增加, 土壤碳吸存增加的主要驱动因素是土壤碳排放和可溶性有机碳淋溶降低(Lu *et al.*, 2021b)。此外, 也有研究指出, N添加下土壤有机碳的增加主要与微生物对有机碳的分解输出减弱有关, 而与植物碳输入的增加无密切关系(Crowther *et al.*, 2019; Lu *et al.*, 2022)。综合不同研究而言, N添加下土壤有机碳积累的主要驱动力可能是微生物对土壤有机碳分解输出的降低(Crowther *et al.*, 2019; Lu *et al.*, 2021b, 2022)。鉴于P添加对微生物分解总体表现为无显著影响或促进作用, P添加对土壤有机碳的促进作用可能主要与植物碳输入的增加有关(Yue *et al.*, 2017; Feng & Zhu, 2019; Hou *et al.*, 2020)。由于N添加和P添加促进土壤有机碳增加的主要原因不同, N + P添加对土壤有机碳的促进作用可能是微生物分解输出降低和植物碳输入增加共同作用的结果。然而, P添加和N + P添加对土壤有机碳的影响仍缺乏较为系统和定量化的研究, 仍需要进一步探讨。

虽然氮磷(N、P和N + P)添加提高土壤有机碳库的现象在全球尺度上普遍存在, 但是氮磷添加对土壤有机碳的负效应也经常在被观测到(Waldrop *et al.*, 2004; Keeler *et al.*, 2009; Crowther *et al.*, 2019; Huang *et al.*, 2019; Luo *et al.*, 2020)。这种负效应可能与以下原因有关: (1)在N和/或P限制的生态系统, 氮磷添加提高了微生物活性(如生物量和酶活性增加)、降低了微生物CUE, 促进了微生物对土壤碳的分解输出, 而且对碳分解输出的促进作用强于对碳输入的促进作用(Waldrop *et al.*, 2004; Keeler *et al.*, 2009; Luo *et al.*, 2019)。(2)氮磷添加提高了植物地上部分的碳输入, 但没有改变或降低了植物地下部分生产力, 而植物地下部分碳输入对土壤有机碳的形成与积累更为重要(Jackson *et al.*, 2017; Sokol & Bradford, 2019; Villarino *et al.*, 2021)。换言之, 地上碳输入增加对土壤有机碳的促进作用不足以弥补地下碳输入减少和微生物分解作用所带来的土壤有机碳降低(Song *et al.*, 2013; Keller *et al.*, 2022)。(3)加入对植物生长非限制性的养分会加剧微生物与植物之间对另一种养分的需求与竞争(Čapek *et al.*, 2018); 一方面会导致植物生产力和其向土壤碳输入的降低, 另一方面也会导致微生物从土壤有

机质中挖掘养分而促进土壤碳的分解输出。(4)不平衡的或过量的氮磷添加超过了植物和微生物对养分的需求,导致养分失衡或产生毒害(Harpole *et al.*, 2011),对植物生长和微生物活性产生抑制,降低植物碳输入、限制微生物对植物来源碳转化成稳定的土壤有机碳,进而导致土壤有机碳净损失。

2.2 氮磷添加对土壤有机碳组分的影响

2.2.1 土壤有机碳分组方法

区分土壤有机碳组分的方法主要包括物理分组法(如粒径分组和密度分组)、化学分组法(如KMnO₄氧化法和酸水解法)和生物分组法等(Six *et al.*, 2000; von Lützow *et al.*, 2007; 张国等, 2011)。粒径分组和密度分组等物理方法因能较好区分不同来源、不同稳定性的有机碳组分,在实践中操作方便,对土壤的破坏性小,而成为最常用的土壤有机碳分组方法(von Lützow *et al.*, 2007; Cotrufo *et al.*, 2019; Chen *et al.*, 2021)。

粒径分组是指根据粒径大小将土壤有机碳分为不同的组分,一般划分为颗粒态有机碳(POC, >53 μm)和矿物结合态有机碳(MAOC, <53 μm)两个组分(von Lützow *et al.*, 2007; Chen *et al.*, 2020b, 2021)。如果将土壤有机碳分为大团聚体有机碳(>250 μm)、微团聚体有机碳(53–250 μm)和黏粉粒有机碳(<53 μm, 即MAOC) 3个组分,该分组方法也可以称为团聚体分组(Six *et al.*, 2000; Huang *et al.*, 2019)。密度分组是指根据土壤颗粒在一定密度(通常为1.60–1.85 g·cm⁻³)溶液中的沉降情况,将土壤有机碳分为轻组分有机碳和重组分有机碳两部分,轻组分有机碳可进一步分为游离态的轻组分有机碳和包裹态的轻组分有机碳(von Lützow *et al.*, 2007;

Cusack *et al.*, 2011b; Ye *et al.*, 2018; Lavalley *et al.*, 2020)。尽管两种分组方法的操作不同,但它们所得到的碳组分的性质具有一定的相似性(表1; Six *et al.*, 2002; von Lützow *et al.*, 2007; Lavalley *et al.*, 2020)。一般认为,轻组分有机碳和POC类似,主要来源于新输入的、分解不完全的凋落物和根系残体,由于缺少矿物或物理化学保护较容易被微生物分解利用,被认为是活性碳组分;重组分有机碳和MAOC类似,由于与矿物结合受到保护而比较稳定,难以被微生物分解利用,被认为是稳定性碳组分(Six *et al.*, 2002; von Lützow *et al.*, 2007; Lavalley *et al.*, 2020)。此外,游离态的轻组分有机碳和大团聚体有机碳类似,包裹态的轻组分有机碳和微团聚体有机碳类似(von Lützow *et al.*, 2007; Cusack *et al.*, 2011a, 2011b)。目前,采用粒径分组、密度分组或者二者结合起来的方法将土壤有机碳分为POC (>53 μm或<1.60–1.85 g·cm⁻³)和MAOC (<53 μm或>1.60–1.85 g·cm⁻³)被认为是一种行之有效的有机碳组分区分方法,有助于更好地理解土壤有机碳的形成和稳定以及预测土壤有机碳对环境变化的响应(Lavalley *et al.*, 2020; Rocci *et al.*, 2021; Feng *et al.*, 2022)。

2.2.2 氮磷添加对土壤有机碳组分的影响

氮磷添加对土壤有机碳不同组分的影响比较复杂,在不同研究中存在很大的差别。研究发现,氮磷(N、P和N+P)添加促进了土壤活性碳组分(POC, 指碳库大小),主要原因是氮磷添加促进了植物碳输入、抑制了微生物活性及其对该碳组分的分解(Ye *et al.*, 2018; Chen *et al.*, 2020b; Yuan *et al.*, 2020)。与活性碳组分不同,这些研究表明, N添加降低了稳定性碳组分(MAOC), 主要原因是N添加所导致的土壤

表1 土壤有机碳的分组方法及其组分特性

Table 1 Fractionation methods and characteristics of soil organic carbon fractions

粒径分组 Size fractionation	密度分组 Density fractionation	特性 Characteristic	文献 Reference
大团聚体有机碳 Macroaggregate OC (>250 μm)	游离态的轻组分有机碳 Free light-fraction OC	来源于新输入的植物残体,最容易被微生物分解,周转速率最快 Originated from newly-inputted plant residues, most easily to be decomposed by microbes, and with the fastest turnover rate	Six <i>et al.</i> , 2002; Marin-Spiotta <i>et al.</i> , 2008
微团聚体有机碳 Microaggregate OC (53–250 μm)	包裹态的轻组分有机碳 Occluded light-fraction OC	来源于半分解的植物残体,但在团聚体内部受到了物理保护,较易分解,周转速率较快 Originated from partly-decomposed plant residues, but physically protected within aggregates, easier to be decomposed, and with a faster turnover rate	Trumbore, 1993; von Lützow <i>et al.</i> , 2007
黏粉粒/矿物结合态有机碳 Silt-clay/mineral-associated OC (<53 μm)	重组分有机碳 Heavy-fraction OC	与土壤矿物紧密结合,较难被分解,周转速率较慢 Closely bound to soil minerals, difficult to be decomposed, and with a slow turnover rate	John <i>et al.</i> , 2005; Lavalley <i>et al.</i> , 2020

括号内指的是土壤粒径大小。

The notes in parenthesis indicate the particle-size of soil fractions. OC, organic carbon.

酸化降低了微生物生物量碳和钙结合态有机碳(Ye *et al.*, 2018; Chen *et al.*, 2020b); 而P添加和N + P添加没有显著改变稳定性碳组分(Yuan *et al.*, 2020)。然而, 也有一些研究发现, N添加促进了高山苔原和热带森林土壤中的稳定性碳组分(Neff *et al.*, 2002; Cusack *et al.*, 2011b)。这可能是因为, N添加能够促进植物残体来源的有机质与矿质N进行缩合反应而使其进入矿物结合态的土壤组分中, 或者通过微生物对植物残体的转化而将其以微生物残体的形式进入稳定性碳组分中(Moran *et al.*, 2005; Cusack *et al.*, 2011b; Mori *et al.*, 2018)。与N和土壤有机质的缩合反应不同, 有研究发现, P添加和N + P添加降低了稳定性碳组分(Liu *et al.*, 2013; Luo *et al.*, 2020), 这可能与添加的P使矿物吸附的可溶性有机碳解吸附有关(Spohn *et al.*, 2022)。也有研究发现, 活性碳组分在单独的N或P添加下降低, 而在N + P添加下增加, 即N × P表现为拮抗作用; 这可能是单一养分添加加剧了养分不平衡, 促使微生物对活性碳组分的分解, 而N + P添加促进了植物碳输入(Luo *et al.*, 2019, 2020)。然而, 也有很多研究表明, N + P添加对

土壤碳组分的影响与单独的N或P添加类似, 即N和P之间不存在交互作用(Liu *et al.*, 2013; Huang *et al.*, 2019; Luo *et al.*, 2020; Yuan *et al.*, 2020)。

综合以往的研究(Averill & Waring, 2018; Ye *et al.*, 2018; Chen *et al.*, 2020b, 2021), 氮磷添加主要通过提高土壤N、P可利用性和/或导致土壤酸化对植物残体与根际沉积物输入、土壤微生物生物量与残体积累以及金属离子的淋失(如 Ca^{2+})或释放(如 Fe^{3+} 和 Al^{3+})产生影响, 进而对土壤有机碳组分产生影响(图2)。然而, N添加和P添加对土壤有机碳组分影响的途径可能不同。N添加可通过导致土壤酸化和增加土壤N可利用性而对碳组分产生影响, 而P添加应该是更多地通过增加土壤P可利用性而对碳组分产生影响(图2), 这是因为P添加对土壤pH的影响一般比较小, 不易导致土壤酸化(Feng & Zhu, 2019)。

虽然N添加对土壤有机碳组分的影响在不同的案例研究中存在差异, 但总体而言, N添加对活性碳组分(游离态的轻组分有机碳、大团聚体有机碳和POC)和稳定性碳组分(重组分有机碳和MAOC)都表现为促进作用(Chen *et al.*, 2018a; Lu *et al.*, 2021a;

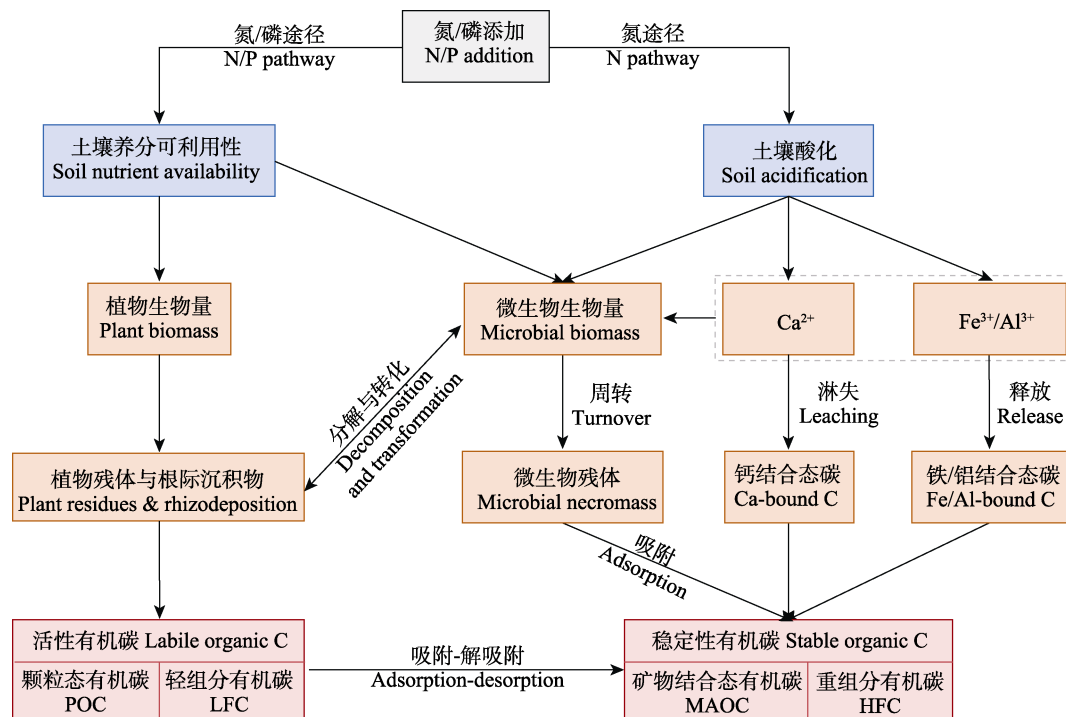


图2 氮磷添加对土壤有机碳组分影响的潜在机制。颗粒态有机碳和矿物结合态有机碳为粒径分组得到的组分, 轻组分有机碳和重组分有机碳为密度分组得到的组分, 它们的性质分别类似。

Fig. 2 Potential mechanisms of how nitrogen (N) and/or phosphorus (P) addition affect the fractions of soil organic carbon (C). Particulate organic C (POC) and mineral-associated organic C (MAOC) are the fractions separated by size fractionation, light-fraction organic C (LFC) and heavy-fraction organic C (HFC) are the fractions separated by density fractionation, and the characteristics of POC vs. LFC and MAOC vs. HFC are similar, respectively.

Rocci *et al.*, 2021)。具体来说, N添加对活性碳组分的促进程度(15%–18%)强于对稳定性碳组分的促进程度(3%–9%); 因此, N添加提高了活性碳组分在土壤总有机碳中的比例, 降低了稳定性碳组分的比例(Chen *et al.*, 2018a; Lu *et al.*, 2021a; Rocci *et al.*, 2021)。N添加对活性碳组分的影响受到土壤pH和植物碳输入的调控, N添加促进活性碳组分的机理是: 促进碳输入和/或通过土壤酸化抑制微生物活性(如生物量)及其对活性碳组分的分解作用(Averill & Waring, 2018; Chen *et al.*, 2018a; Ye *et al.*, 2018; Lu *et al.*, 2021a)。然而, N添加对稳定性碳组分的影响还存在一定的争议。一方面, N添加可能会通过抑制氧化酶活性而降低微生物对稳定性有机碳的分解而提高稳定性碳组分(Janssens *et al.*, 2010; Chen *et al.*, 2018b)。另一方面, N添加也可能会通过抑制微生物生长与残体积累及其对土壤有机碳的贡献而使稳定性碳组分减少(Averill & Waring, 2018; Chen *et al.*, 2018a, 2020b; Ye *et al.*, 2018)。因此, N添加对土壤稳定性碳组分的影响可能取决于两个过程在实验持续时间上的平衡, N添加在短期内即可对微生物的分解活性产生影响, 但需要较长的时间才能对微生物残体积累及其对土壤有机碳的贡献产生作用(Ye *et al.*, 2018; Ma *et al.*, 2021)。因此, 未来还需要研究长期N添加对土壤稳定性碳组分的影响与机制。

2.3 氮磷添加对土壤有机碳分子组成的影响

2.3.1 土壤有机碳分子组成测定方法

土壤有机碳分子组成比较复杂, 不同的有机碳分子由于其化学结构和分子属性不同而具有不同的稳定性和降解速度。分子结构相对简单而活性较高

的有机碳组分通常稳定性较低, 很容易被微生物分解利用; 而分子结构复杂的有机碳组分稳定性较高, 很难被微生物分解利用。研究表明, 土壤有机碳的分子组成与其被微生物分解的难易程度和微生物呼吸速率密切相关(Guo *et al.*, 2017; 叶成龙等, 2018; Hou *et al.*, 2019)。因此, 土壤有机碳的分子组成在很大程度上决定了土壤有机碳的稳定性及其周转速率(Guo *et al.*, 2017; 张仲胜等, 2018)。

在以往的研究中, 固态¹³C核磁共振波谱技术(¹³C-NMR)和傅里叶变换红外光谱分析常被用于研究土壤有机碳的分子组成, 这两种方法都是基于所测定的含碳官能团来表征土壤有机碳的分子组成(Baldock *et al.*, 1992; Demyan *et al.*, 2012; Hou *et al.*, 2019)。相比而言, ¹³C-NMR因其对土壤有机碳分子组成的解析更加贴近真实状态而被广泛应用(叶成龙等, 2018; 李娜等, 2019; Yuan *et al.*, 2020)。按照¹³C-NMR测定结果, 一般将土壤有机碳分为4个含碳功能团(Baldock *et al.*, 1992), 分别为烷基碳(alkyl C)、烷氧碳(O-alkyl C)、芳香碳(aromatic C)和羰基碳(carbonyl C), 不同含碳功能团的性质如表2所示。烷基碳和芳香碳较难被微生物分解利用, 是难以降解的较稳定的有机碳成分; 烷氧碳和羰基碳较易被微生物分解利用, 是不稳定的活性有机碳成分。通常采用各含碳功能团含量的百分比表征土壤有机碳的分子组成, 采用芳香度(芳香碳/烷氧碳)、脂化度(烷基碳/烷氧碳)和总指数(芳香度与脂化度之和) 3个指数来表征土壤有机碳的总体分子组成和难降解性, 指数越大表明土壤有机碳越难被降解(Baldock *et al.*, 1997; Wagai *et al.*, 2013; 叶成龙等, 2018)。

表2 固态¹³C核磁共振波谱技术测定的土壤有机碳功能团及其主要形式与特性

Table 2 Functional carbon (C) groups measured by solid-state ¹³C nuclear magnetic resonance spectroscopy and their dominant C forms and characteristics

碳功能团 Functional group	化学位移 Chemical shift (δ)	碳的主要形式 Dominant forms of carbon	特性 Characteristic
烷基碳 Alkyl C	0–45	主要为脂肪族化合物等, 来自于植物角质、蜡质、木栓质 Mainly aliphatic compounds, originating from plant cutin, waxes, suberin	较稳定, 不易被分解, 为难分解碳 Relatively stable, not easy to be decomposed, and categorized as the recalcitrant C
烷氧碳 O-alkyl C	45–110	主要为碳水化合物, 如纤维素、半纤维素等 Mainly carbohydrates, such as cellulose, hemicellulose, etc.	容易被分解, 为易分解碳 Easy to be decomposed, and categorized as the easily-decomposed C
芳香碳 Aromatic C	110–165	主要为单宁、木质素等 Mainly tannin, lignin, etc.	难以被分解, 为难分解碳 Difficult to be decomposed, and categorized as the recalcitrant C
羰基碳 Carbonyl C	165–210	大多为脂肪酸、氨基酸、酰胺、酯、酮醛类物质 Mostly fatty acids, amino acids, amide, esters, ketones and aldehydes	容易被分解, 为易分解碳 Easy to be decomposed, and categorized as the easily-decomposed C

根据Baldock等(1992, 2004)和Kögel-Knabner (2002)总结而成。

Generated according to Baldock *et al.* (1992, 2004) and Kögel-Knabner (2002).

2.3.2 氮磷添加对土壤有机碳分子组成的影响

养分添加对土壤有机碳分子组成的影响复杂多样, 并没有一致性的规律。研究表明, N添加对土壤有机碳分子组成的影响受到土壤N有效性、N添加量和N形态等多种因素的调节。在土壤N有效性方面, 有研究发现, 在N有效性较高的热带低地森林中, N添加对烷基碳占比无影响, 但降低了烷氧碳占比; 而在N有效性较低的热带山地森林中, N添加提高了烷氧碳占比, 但降低了烷基碳占比(Cusack *et al.*, 2011a)。在N添加量方面, 有研究表明, 土壤有机碳分子组成随N添加量的增加呈现非线性响应(Li *et al.*, 2019; Man *et al.*, 2021)。一项在温带草原的研究表明, 不同剂量的N添加均提高了烷基碳占比, 但对芳香碳占比存在不同的影响, 即随N添加量的增加芳香碳占比呈现先降低后增加的趋势(Li *et al.*, 2019)。与此相反, 一项在农田生态系统的研究发现, 烷基碳占比随N添加量的增加呈现先降低后升高的趋势, 而芳香碳占比呈现先升高后降低的趋势(Man *et al.*, 2021)。在N形态方面, 有研究发现, 硝态氮和铵态氮添加对土壤有机碳分子组成具有相异性的影响; 具体而言, 铵态氮添加降低了北方森林土壤轻组分中的烷基碳占比, 但硝态氮添加对其无显著影响; 与此相反, 硝态氮添加降低了芳香度, 但铵态氮添加对其没有显著影响(Cheng *et al.*, 2017)。与N添加相比, P添加、N + P添加和N × P交互作用对土壤有机碳分子组成影响的研究还很少(Guo *et al.*, 2017; Yuan *et al.*, 2020; Li *et al.*, 2021)。一项在高寒草甸的研究发现, N + P添加改变了土壤有机碳的分子组成, 提高了烷基碳占比、降低了烷氧碳占比, 使得土壤有机碳的难降解性增强(Guo *et al.*, 2017)。然而, 在高寒草甸的另一项研究发现, 为期10年的P添加和N + P添加没有改变各类含碳功能团的占比, 也没有改变脂化度和芳香度等表征有机碳可降解性的指数, 而且N × P不显著(Yuan *et al.*, 2020)。与此类似, 为期35年的P添加和N + P添加也没有改变农田土壤有机碳的分子组成(Li *et al.*, 2021)。在这些研究中, P添加对土壤有机碳的分子组成没有显著影响, 这可能与P添加没有改变土壤微生物群落结构有关。虽然在不同的研究中, 氮磷添加对各类含碳功能团占比的影响不尽相同, 但总体上影响比较小, 这可能与土壤有机碳的分子组成相对稳定, 需要在长期养分添加下才能发生较大的变化有关(Wang *et*

al., 2019; Lu *et al.*, 2021b; van den Enden *et al.*, 2021)。

在氮磷添加调控土壤有机碳分子组成的机制方面, 有研究指出土壤有机碳分子组成与微生物群落结构存在一定的关联(Cusack *et al.*, 2011a; Xing *et al.*, 2022b), 这表明氮磷添加可通过改变微生物群落结构而对土壤有机碳的分子组成产生影响。两项在高寒草甸的研究表明, 10年的N添加和15年的N + P添加显著降低了土壤烷氧碳占比, 其占比的降低可能是由于N添加改变了微生物群落结构、使其由真菌向细菌转变, 进而使微生物对包含烷氧碳在内的不稳定碳底物的分解利用增加(Guo *et al.*, 2017; Yuan *et al.*, 2020)。此外, 基于土壤密度分组的一项研究发现, 土壤轻组分中的烷氧碳占比与革兰氏阳性细菌生物量呈负相关关系, 而烷基碳占比与真菌相对丰度呈负相关关系; 同时, N添加提高了真菌丰度但降低了烷氧碳占比(Cusack *et al.*, 2011a)。这些研究表明, 氮磷添加可通过改变微生物群落结构及其对土壤碳底物的利用偏好而改变土壤有机碳的分子组成, 但目前这方面的研究案例十分有限, 限制了我们对于养分添加如何调控土壤有机碳分子组成的深层认识与理解, 未来仍需要进一步探讨。

3 总结和展望

土壤有机碳库的变化取决于碳输入和输出两个过程之间的动态变化, 而这两个过程都受到土壤氮磷可利用性的调节, 因此, 外源氮磷的输入会通过改变碳输入和输出过程而对土壤有机碳的碳库大小、组分和分子组成等产生影响。整合目前的研究结果, N添加和P添加整体上对土壤总有机碳表现为促进作用(Yue *et al.*, 2017; Chen *et al.*, 2018b; Feng & Zhu, 2019; Xu *et al.*, 2021a), 但二者的促进机制可能存在差异。N添加对土壤有机碳的促进作用是由于N添加增加了碳输入并同时降低了碳输出(图1; Lu *et al.*, 2011; Zhang *et al.*, 2018; Xu *et al.*, 2021a), 而P添加对土壤有机碳的促进作用可能主要是由于P添加促进了碳输入(Yue *et al.*, 2017; Feng & Zhu, 2019)。在土壤有机碳组分方面, N添加对活性和稳定性有机碳组分均表现为促进作用, 但对活性有机碳组分的促进作用更大; 但P添加对土壤有机碳组分的影响尚不清楚。此外, N添加和P添加对土壤有机碳分子组成的影响并没有一致性的结果, 而且相

关的研究案例也很少,氮磷添加调控土壤有机碳分子组成的机制还有待进一步探讨。

总体而言,以往的研究为我们认识养分富集如何调控土壤有机碳的碳库大小、组分和分子组成提供了思路与借鉴,有利于准确预测未来氮磷沉降背景下土壤有机碳的动态变化。然而,目前关于氮磷添加如何影响土壤有机碳仍然存在一些尚不清楚的方面,需要在未来的研究中进行加强。

(1)加强P添加对土壤有机碳影响的研究。与N添加相比,P添加对不同类型生态系统土壤有机碳的影响无论是在其碳库大小还是在其组分和分子组成上都十分欠缺,导致我们对相关的机制认知非常有限。热带森林的净初级生产力占全球净初级生产力的38%,总碳库占到全球陆地生态系统碳库的40%,在全球陆地碳循环中具有重要作用(Pan *et al.*, 2011; Townsend *et al.*, 2011)。热带森林作为P限制的生态系统,在全球变化背景下备受关注,但P添加对其土壤有机碳的影响与机制也尚不清楚。一方面,P添加可通过缓解植物P限制而促进热带森林的树木生长和生产力,进而促进植物对土壤的碳输入(Wright *et al.*, 2018; Wright, 2019)。另一方面,P添加也可通过缓解微生物P限制而促进其生长和对土壤有机碳的分解,进而使土壤碳输出增加(Cleveland *et al.*, 2002; Camenzind *et al.*, 2018; Hui *et al.*, 2020)。然而,长期P添加能否持续促进微生物活性,以及植物的碳输入和微生物的碳分解输出两个过程在调控热带森林土壤有机碳动态中的相对重要性尚不清楚,使得P添加对土壤有机碳的影响仍存在较大的不确定性。因此,未来需要加强P添加对不同类型生态系统(尤其是热带森林)土壤有机碳影响的研究,并在已有的P添加实验平台上持续开展研究并进行系统测定,这将有利于揭示P富集对土壤有机碳的碳库大小、组分和分子组成影响的潜在机制。

(2)加强氮磷添加下植物和微生物在调控土壤有机碳及其组分变化中的作用和相对贡献的研究。根据以往的研究,植物来源的活性碳组分可通过两种途径转化为稳定性碳组分:一是土壤矿物的吸附和团聚体的物理保护等非生物途径,二是微生物对植物来源碳的“体内周转”与转化的生物途径(Lehmann & Kleber, 2015; Liang *et al.*, 2017)。微生物对植物来源碳的转化及其周转而形成的残体是稳定性碳组分的重要来源(Cotrufo *et al.*, 2013; Chen *et*

al., 2020a; Wang *et al.*, 2021),而微生物残体与活体微生物生物量密切相关(Yang *et al.*, 2020; Wang *et al.*, 2021)。大部分研究表明,N添加总体上对土壤微生物生物量具有抑制趋势(Xiao *et al.*, 2018; Zhang *et al.*, 2018; Xu *et al.*, 2021a);因此,从这一角度而言,N添加可能会通过降低微生物对植物来源碳的“体内周转”而减少稳定性碳的形成与积累。然而,目前的研究表明,N添加促进了土壤稳定性碳组分(Chen *et al.*, 2018b; Rocci *et al.*, 2021),这表明土壤物理化学过程参与的非生物途径在N添加调控土壤稳定性碳组分中可能比微生物参与的生物途径更加重要。土壤微生物不仅可以作为贡献者调控土壤有机碳库中微生物来源碳的动态,也可作为分解者调控植物来源碳的动态(Liang *et al.*, 2017)。然而,目前的研究主要是从植物碳输入和微生物对土壤碳的分解输出两个过程探讨了N、P添加对土壤有机碳动态的影响,但并未对他们的相对贡献进行量化。因此,未来的研究可结合生物标志物和碳同位素标记等方法和技术来定量碳输入和输出过程对土壤有机碳及其组分的调控作用,以及植物和微生物来源碳对土壤有机碳及其组分的贡献。

(3)加强长期氮磷添加及其交互作用对土壤有机碳影响的研究。目前,在全球范围内开展的氮磷添加对土壤有机碳影响的研究中,一半以上(55%)的实验其处理持续时间不超过5年,仅有12%的实验其处理持续时间超过20年(Feng & Zhu, 2019; Xu *et al.*, 2021a)。研究表明,氮磷添加对土壤总有机碳的促进强度随实验持续时间延长而增加(Lu *et al.*, 2021a; Xu *et al.*, 2021a)。然而,土壤的固碳能力是有限的,会发生饱和(Jackson *et al.*, 2017),这意味着在长期氮磷添加下土壤有机碳可能不会持续增加。因此,未来的研究需要关注土壤的碳饱和能力,并结合模型进行模拟预测,这有助于理解土壤有机碳在较长时间尺度上的变化趋势。与土壤总有机碳类似,在短期内,氮磷添加通常对土壤有机碳的稳定性组分和分子组成没有显著的影响(Cheng *et al.*, 2017; Yuan *et al.*, 2020; Xu *et al.*, 2021a)。然而,有机碳组分和分子组成对土壤有机碳能够长期稳定存储至关重要,而且往往需要在较长的时间后才能观测到其变化。此外,在全球变化背景下,N沉降和P沉降是相伴发生的,而且其沉降速率的不同会导致养分之间的不平衡(Peñuelas *et al.*, 2013; Zhu *et al.*,

2016), 会对植物碳输入和微生物分解作用产生影响, 并进而影响土壤有机碳的碳库大小、组分和分子组成。然而, 以往的研究主要关注单一养分添加(尤其是N添加)对土壤有机碳的影响, 忽视了N + P添加及其交互作用的影响。研究表明, N + P添加对土壤总有机碳的促进作用强于单独的N或P添加(Yue *et al.*, 2017), 这表明当前的单独的N或P添加实验结果可能总体上会低估未来氮磷沉降背景下土壤有机碳的增加幅度。因此, 未来需要利用已有的氮磷添加实验平台并增加N × P双因子实验的开展, 加强长期的N添加、P添加、N + P添加及N × P对土壤有机碳的碳库大小、组分和分子组成影响的研究, 这将有利于提高对未来氮磷沉降背景下土壤有机碳动态的准确预测。

(4)加强氮磷添加对深层土壤有机碳影响的研究。目前, 大部分的研究主要关注氮磷添加对表层土壤有机碳的影响, 而忽视了深层土壤(Rocci *et al.*, 2021; Xu *et al.*, 2021a)。研究表明, 氮磷添加对深层(20 cm以下)土壤有机碳大小、组分和分子组成的影响与表层(主要为0–20 cm)土壤在强度与方向上并不一致(Yu *et al.*, 2020; Rocci *et al.*, 2021; Xu *et al.*, 2021a)。这一结果启示我们, 忽视深层土壤将会高估或低估氮磷添加对土壤有机碳的影响, 进而使得氮磷沉降背景下对土壤有机碳动态的预测具有不确定性。因此, 未来需要加强对深层土壤有机碳的关注, 系统研究氮磷添加对其碳库大小、组分和分子组成的影响。

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