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农田氧化亚氮减排技术及其与绿肥协同应用分析

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摘要: 氧化亚氮(N₂O)是导致全球气候变暖的主要温室气体之一, 农业活动是N₂O的重要排放源。土壤N₂O排放主要源于硝化和反硝化过程, 受土壤pH值、氧气浓度、二氧化碳浓度、水分、质地、温度和外来碳氮投入等因素的影响。近年来, 中国在利用绿肥实现化肥减施、驱动土壤健康方面取得了明显成效。但关于绿肥参与N₂O排放的研究尚处在起步阶段。种植利用绿肥对N₂O排放的影响受绿肥种类、土壤理化性状等多方面因素共同作用, 绿肥主要通过调控土壤无机氮含量影响N₂O排放, 绿肥生长期能够吸收土壤盈余的无机氮, 翻压后能够替代部分氮肥, 通过减少硝化和反硝化底物减少农田土壤N₂O排放, 但同时存在由于绿肥腐解引发的有机氮矿化导致的N₂O排放风险。可根据绿肥种植制度、作物种类、气候条件和土壤类型等, 采用适宜的N₂O减排技术。南方水稻与绿肥轮作区, 可减施氮肥40%, 添加生物炭等碱性调理剂; 华北地区主作物与绿肥轮作区, 可减施氮肥15%~20%, 添加化学抑制剂、结合氮肥机械化深施; 东北和西北地区的主作物复种、间作绿肥制度中, 可减施氮肥13%~48%, 结合添加硝化抑制剂、结合水肥一体化和免耕; 西南地区主作物与绿肥轮作制度中, 可减施氮肥15%~20%, 配合缓控释肥一次性施肥和添加化学抑制剂等。重点探讨了N₂O减排技术在绿肥制度中应用的可行性, 以期为更好发挥绿肥作用, 进一步减缓N₂O排放提供参考。

关键词: 绿肥; 氧化亚氮; 影响因素; 减排技术

Techniques of N₂O emission reduction in farmland and their synergistic application with green manure

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Abstract: Nitrous oxide (N₂O) is one of four the main gases linked to global warming, and agricultural production is the largest anthropogenic source of N₂O emissions. N₂O mainly originates from nitrification and denitrification processes in soil and is predominantly influenced by soil pH value, O₂ concentration, CO₂ concentration, moisture,

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texture, temperature, and exogenous carbon (C) and nitrogen (N) input. In recent years, China has achieved remarkable results in using green manure to reduce chemical N fertilizer application and drive soil health. However, study of the role of green manure in N_2O emission is still in the early stages. The impact of planting and incorporating green manure on soil N_2O emission depends on factors such as the varieties of green manure and the physicochemical properties of the soil. Among them, the influence on soil mineral N is the greatest factor. Generally, green manure can efficiently absorb soil mineral N in the fallow period, and its incorporation into the soil can reduce chemical N fertilizer application, thus decreasing N_2O emission. However, green manure releases large amounts of N during its decomposition, which may increase soil N_2O emissions. Combined with appropriate N_2O emission reduction approaches, N_2O emission in green manure-based systems can be reduced according to planting systems, crop varieties, climate conditions and soil types. In southern China's rice-green manure rotation area, chemical N could be reduced by 40%, when adding alkaline amendments such as biochar. In northern China's main crop-green manure rotation area, chemical N could be reduced by 15%–20%, through adding chemical inhibitors and combining mechanical deep application of chemical N fertilizers. For main crops rotated or intercropped with green manure systems in Northeast and Northwest China, chemical N could be reduced by 13%–48%, by adding nitrification inhibitors, with integrated water-fertilizer management practices and no-tillage. In main crops rotated with green manure systems of Southwest China, chemical N could be reduced by 15%–20%, through techniques such as slow-release fertilization, use of chemical inhibitors, and others. In this study we have focused on the feasibility of N_2O emission reduction by combining green manure practices and exogenous reduction approaches to N_2O emission, to provide practical guidance for reducing N_2O emission in green manure-based systems.

Key words: green manure; nitrous oxide; influencing factors; emission reduction technology

氧化亚氮(nitrous oxide, N_2O)是第三大温室气体,在大气中的留存时间可达 120 年之久,其百年尺度的增温潜势是二氧化碳(carbon dioxide, CO_2)的 298 倍,对全球气候变暖有深远影响^[1],是破坏臭氧层的重要影响因素^[2]。农业活动是 N_2O 最大的人为排放源^[3],2020 年全球农田土壤 N_2O 排放量估计为 $1.2 \text{ Tg N} \cdot \text{yr}^{-1}$,我国农业活动中的 N_2O 排放情况也不容乐观, N_2O 排放量约为 $198.6 \text{ Gg N} \cdot \text{yr}^{-1}$,约占全世界的 $1/6$ ^[4]。我国 N_2O 排放中的 49%~78% 来源于氮肥^[5-6]。推动农田 N_2O 减排,对助推我国农业绿色高质量发展,实现“碳达峰、碳中和”双碳目标具有重要意义。

农田 N_2O 减排技术主要包括调整肥料用量及种类、优化种植制度、利用硝化和脲酶抑制剂、添加生物炭和黏土矿等土壤改良剂、水肥一体化等,这些技术的主要目标就是提高氮素的利用效率、减少氮肥的投入及其在土壤中的累积,进而降低 N_2O 的排放。土壤 N_2O 的产生主要是土壤微生物作用的过程,微生物受环境因素影响极大,因此通过调控手段改变土壤的硝化和反硝化作用过程,也是抑制 N_2O 排放的研究热点。多年来,全球在氮肥减量或替代、调控 N_2O 产生的机理机制等方面,取得了系统的研究进展。绿肥是我国传统农业的精华,是培养地力的重要物质基础,在化肥减量、耕地质量提升、农田固碳减排中发挥着重要作用^[7]。近年来,中国在利用绿肥实现化肥减施、驱动土壤健康方面取得了明显成效。但关于绿肥参与 N_2O 排放的研究尚处在起步阶段。如何既发展好绿肥的土壤培肥与有机替代效应,又利用科学的手段管控好其可能的 N_2O 排放增加的风险,是当前亟需解决的科学和技术问题。为此,本研究梳理了土壤 N_2O 产生途径及其影响因素、减排技术,分析了绿肥种植利用对 N_2O 排放的影响和农田 N_2O 减排技术在绿肥种植制度中应用的可行性,以期优化绿肥种植制度中的管理技术,在保障绿肥节肥养地的同时实现 N_2O 减排。

1 农田 N_2O 产生途径及其影响因素

1.1 农田 N_2O 产生途径

土壤 N_2O 产生的过程有生物学过程和非生物学过程。生物学过程是 N_2O 产生和排放的主要过程,包括硝化作用、反硝化作用、耦合硝化-反硝化作用、化学反硝化作用和硝酸盐的异化还原作用等(图 1)。

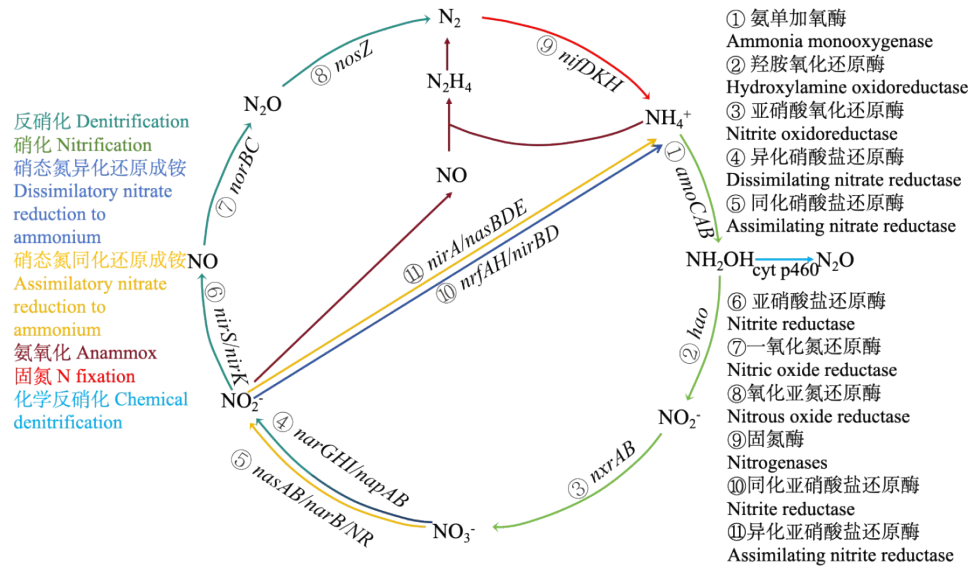


图1 土壤中 N_2O 产生途径及相关的酶

Fig. 1 Pathways and corresponding enzymes of soil N_2O emission

硝化作用是在有氧条件下,氨(ammonia, NH_3)或铵盐(ammonium, NH_4^+)被硝化微生物氧化成硝酸盐的过程, N_2O 作为副产物释放^[8]。硝化作用是碱性和中性土壤中 N_2O 产生的主要途径^[9-11],此环境下硝化作用由氨氧化细菌(ammonia-oxidizing bacteria, AOB)主导^[12],而在酸性土壤中氨氧化古菌(ammonia-oxidizing archaea, AOA)通常起主导作用^[13]。另外,近年有研究发现能将 NH_3 完全氧化为硝态氮(nitrate, NO_3^-)的完全氨氧化菌,可通过其中间产物羟胺的非生物反应产生 N_2O ^[14]。

反硝化作用是在兼性厌氧条件下,反硝化微生物逐步将土壤中的 NO_3^- 还原成 NO 、 N_2O 、 N_2 的过程^[15]。完全的反硝化作用最终产物是 N_2 ,然而,约1/3的反硝化细菌和具有反硝化能力的真菌缺少 N_2O 还原酶(N_2OR , 编码基因 *nosZ*),无法将 N_2O 还原为 N_2 ^[16-17]。 N_2O 还原细菌有两种不同的类群,分别为典型的反硝化细菌(Clade I)和非典型的反硝化细菌(Clade II)。土壤 N_2O 还原主要由Clade II决定,Clade II丰度增加或群落结构改变,可能会促进 N_2O 还原从而降低 N_2O 排放量^[18]。耦合硝化-反硝化作用是由硝化过程产生的 NO_3^- 为反硝化作用提供底物,从而生成 N_2O 的过程^[19]。化学反硝化作用是指 NO_2^- 化学分解或与其他物质的化学反应过程,主要产物为 N_2O 、 NO_x 和 N_2 ^[20]。仅在土壤pH较低时化学反硝化才被视为 N_2O 的一个产生源,而在碱性条件下 NO_2^- 能够短暂积累,从而减少 N_2O 的排放^[21]。硝态氮异化还原成铵作用是一类以 NH_4^+ 为主要产物的硝态氮异化还原过程,此过程伴有 NO_2^- 的短暂积累和 N_2O 的排放^[22]。

1.2 农田 N_2O 排放的影响因素

1.2.1 影响农田 N_2O 排放的环境因素

农田土壤 N_2O 排放主要受土壤pH、氧气(oxygen, O_2)浓度、 CO_2 浓度、水分、质地、温度和外来碳氮投入等因素的影响(表1)。土壤pH是影响土壤硝化、反硝化作用的关键因子。硝化反应强度一般与土壤pH值呈正相关,pH值增加通过提高硝化反应底物(NH_3)浓度^[33-34],增加 N_2O 排放。在pH<6.0时反硝化群落可获得的有机质和无机氮较少, N_2OR 的形成受到抑制^[24], N_2O 向 N_2 还原的过程受阻,反硝化产物主要为 N_2O ,而在pH>7时,反硝化产物主要为 N_2 ^[23,35]。 O_2 和 CO_2 浓度通过影响硝化和反硝化作用相对贡献调控 N_2O 排放。当土壤 O_2 含量低于5%时,土壤 N_2O 排放量急剧增加,并且硝化作用对 N_2O 排放的贡献明显下降^[25]。 N_2OR 受到 O_2 的抑制,但反硝化过程中其他的还原酶仍可发挥作用,导致 N_2O 的积累^[36]。高浓度 CO_2 主要通过增强反硝化作用提高土壤 N_2O 排放。高浓度 CO_2 减少了植物蒸腾作用,从而增加了土壤含水量,为反硝化作用提供了厌氧环境,另外高浓度的 CO_2 促进植物释放根系分泌物^[1],为反硝化作用提供了底物。相比于环境 CO_2 浓度,土壤中高浓度的 CO_2 导致 N_2O 排放量增加了21%~36%^[26]。土壤含水量通过调控土壤通气性和有效

氮分布,影响硝化、反硝化过程^[27]。土壤含水量在30%~60%时硝化作用是产生N₂O的主要来源,高于70%时反硝化作用是N₂O的主要来源^[37]。土壤质地通过影响土壤通气性和水分状况,导致硝化、反硝化过程存在差异^[38-39]。一般而言,N₂O的排放量为壤质>砂质>粘质土壤^[40]。土壤温度通过影响微生物活性,改变土壤氧气和有效碳的含量^[41-42],间接影响了N₂O的排放,35~40℃时N₂O排放量达到峰值^[29]。

1.2.2 影响农田N₂O排放的底物因素 作为硝化和反硝化作用的底物,土壤中无机氮(NH₄⁺、NO₃⁻)和有机质的浓度直接影响N₂O排放^[43]。施氮不仅通过增加硝化、反硝化作用底物浓度,促进N₂O排放,施氮增加的NO₃⁻还可作为末端电子受体被优先利用,N₂OR活性被抑制^[44-45],降低了N₂O向N₂的转化比例。有机质是土壤中异养微生物的碳源和能量来源,添加有机物料对土壤N₂O排放的影响尚无一致定论。“水稻(*Oryza sativa*)—小麦(*Triticum aestivum*)”种植制度中麦秸还田减少了1%~78%的N₂O排放^[46]，“水稻—紫云英(*Astragalus sinicus*)”种植制度中稻秸还田减少了12%的N₂O排放^[47],而Zhou等^[32]在培养试验中发现添加麦秸、豆科绿肥均增加了N₂O排放,是未添加有机物料处理的1.2~1.9倍。

表1 土壤N₂O排放的主要影响因素

Table 1 Main influencing factors of soil N₂O emission

影响因素 Influencing factor	N ₂ O排放适宜条件 Suitable conditions for N ₂ O emission	作用机理 Functional mechanism	参考文献 Reference
pH值 pH value	中性/微碱性 Neutral/slightly alkaline	控制N ₂ OR结构表达 Control the expression of N ₂ OR structure	[23-24]
氧气浓度 O ₂ concentration	厌氧环境 Anaerobic environment	反硝化作用主导N ₂ O排放 Denitrification dominated N ₂ O emission	[25]
二氧化碳浓度 CO ₂ concentration	高浓度 High concentration	增加土壤含水量;植物生长量和根系分泌物增加,进而影响微生物活性 Increase soil moisture content; Plant growth and root exudates increase, which affects microbial activity	[1, 26]
水分含量 Moisture content	>70%	厌氧环境促进反硝化作用 Anaerobic environment promotes denitrification	[27]
土壤质地 Soil texture	粘土 Clay	保持土壤含水量,影响氧气含量 Maintain soil moisture content and affect O ₂ content	[28]
土壤温度 Soil temperature	35~40℃	改变微生物活性;保持土壤含水量、氧气含量 Change microbial activity; Maintain soil moisture and O ₂ content	[29]
氮投入 N input	添加尿素、有机肥等 Add urea, organic fertilizer, etc.	提高硝化势和N ₂ O/N ₂ Improve nitrification potential and N ₂ O/N ₂	[30-31]
碳投入 C input	有机肥投入、根系分泌物等 Organic fertilizer input, root exudates, etc.	增加了土壤异养微生物的呼吸,有机物料中有效性碳为反硝化微生物提供了电子供体,促进了反硝化作用 Increase soil heterotrophic microbial respiration, and the available C in organic materials provide electron donors for denitrifier which promoted denitrification	[32]

2 种植利用绿肥影响农田N₂O排放的效应与机制

2.1 种植利用绿肥对农田N₂O排放的影响

我国当前绿肥面积稳定在每年约413万hm²,仅占绿肥潜力面积不足12%,发展空间和节氮减排潜力巨大^[48]。种植利用绿肥能够促进土壤碳氮等养分循环、改善土壤的物理化学性质、改变土壤的温度及湿度、影响土壤的微生物群落结构,进而影响土壤N₂O的排放。一项包含106个观测值的荟萃分析表明,40%的观测结果显示绿肥减少了土壤N₂O排放,60%的观测结果则显示增加了土壤N₂O排放,综合全年观测结果来看,绿肥增加和减少的N₂O排放量基本持平^[49]。种植绿肥对N₂O排放的影响取决于绿肥种类、土壤理化性状、气候等多方面因素共同作用^[50-51]。一般而言,种植利用禾本科绿肥造成的N₂O排放低于豆科绿肥^[52]。绿肥作物地上及地下部的生物量和化学性质均影响N₂O排放^[53-54]。土壤无机氮含量是影响绿肥制度中N₂O排放的主要因素,绿肥种植期间能够吸

收土壤盈余的无机氮,通过减少硝化、反硝化作用底物降低土壤 N_2O 排放^[55],当绿肥吸氮量高时, N_2O 排放量较吸氮量少时显著降低了5倍^[56]。绿肥还田后,大量的有机物料投入不仅增加了土壤中无机氮、活性炭和氮含量,还促进了硝化、反硝化微生物活性^[57-58]。此时,土壤 N_2O 排放主要受绿肥碳/氮和生物量影响。研究认为低碳/氮的豆科绿肥还田比高碳/氮的非豆科绿肥土壤排放了更多的 N_2O ^[32,59]。而相比于绿肥碳/氮, N_2O 排放受生物量的影响更大。研究表明,翻压燕麦(*Avena sativa*,高碳氮比、高生物量)比豌豆(*Pisum sativum*,低碳氮比、低生物量)的 N_2O 排放量更高^[60]。绿肥不同还田方式中,相比于覆盖还田,翻压还田土壤 N_2O 排放量更高^[60]。绿肥翻压还田增加了土壤通气性和微生物与有机物料的接触面积,进一步增加了土壤微生物活性^[61-63],提高了 N_2O 排放量。相比于冬闲,秋冬绿肥覆盖能够提高土壤温度,这可能增加种植利用绿肥时的土壤 N_2O 排放风险^[64]。土壤质地也会影响绿肥种植制度中的 N_2O 排放,随着土壤粒径从粘土、壤土向沙壤土的增加, N_2O 排放量逐步减少^[43]。

种植利用绿肥从多方面影响 N_2O 排放,不同地区、不同种植制度中绿肥对 N_2O 排放存在正负效应^[65-66](表2)。国外研究表明,经济园林中,相比于未种植绿肥,种植绿肥增加了地中海葡萄(*Vitis vinifera*)园周年 N_2O 排放11.5%^[78];而柑橘(*Citrus reticulata*)园中豆科和非豆科绿肥混播覆盖,促进了 N_2O 转化为 N_2 ,使得全年 N_2O 排放量显著降低了12.6%^[77]。我国部分绿肥制度中 N_2O 排放已有报道,但还缺少区域性系统性的绿肥种植和翻压期间 N_2O 排放周年监测。南方绿肥水稻轮作系统中,冬季种植翻压油菜(*Brassica campestris*)较冬闲全年 N_2O 累积排放量显著增加了53.1%^[74],翻压黑麦草(*Lolium perenne*)、紫云英增加了37.5%、43.7%^[79]。北方旱地玉米(*Zea mays*)间作系统中,与玉米单作相比,玉米间作大豆(*Glycine max*)处理 N_2O 年平均排放通量降低了25.6%~48.8%^[67-68]。华北的绿肥—棉花(*Gossypium* spp.)轮作系统中,相比于冬闲处理,棉花轮作二月兰(*Orychophragmus violaceus*)全年 N_2O 累积排放量显著减少了58.0%^[80]。西北的夏绿肥冬小麦轮作系统中,与夏休闲相比,黑豆(*Glycine max*)—冬小麦轮作在绿肥填闲期和冬小麦生长期土壤 N_2O 排放量分别显著增加了26.8%~44.2%和6.2%~52.3%^[71]。

表2 不同制度中种植利用绿肥对 N_2O 排放的影响

Table 2 Effects of green manure on N_2O emission under different planting systems

种植制度 Planting system	试验地点 Experimental site	施氮量 Chemical N application rate ($kg \cdot hm^{-2}$)	绿肥替代氮肥 比例 Proportion of green manure instead of chemical N	N_2O 排放变化 N_2O emission change	参考文献 Reference
玉米前期间套作 Inter-cropping with maize during the pre-growth period	中国北京市 Beijing, China	300~360	0	-25.5%~-48.8%	[67]
	中国河南省新乡市 Xinxiang City, Henan Province, China	120	0	-31.98%	[68]
	中国甘肃省武威市 Wuwei City, Gansu Province, China	360	0	-17.7%	[69]
	埃塞俄比亚南方各族州 Ethnic states of southern Ethiopia	32	0	-15.0%~+5.0%	[70]
麦后复种绿肥 Rotated with wheat	中国甘肃省平凉市 Pingliang City, Gansu Province, China	0~270	0	+6.2%~+52.3%	[71]
旱地冬绿肥 Winter green manure in dry land	中国河南省安阳市 Anyang City, Henan Province, China	225	25%~50%	-13%~-58%	[58,72]
	西班牙马德里 Madrid, Spain	190	26%	-25.6%	[50]
稻田冬绿肥 Winter green manure in paddy soil	中国江西省丰城市 Fengcheng City, Jiangxi Province, China	356.9	0	-45.2%~-73.4%	[73]
	中国江苏省苏州市 Suzhou City, Jiangsu Province, China	300	0	-2.1%~+53.1%	[74]
	中国湖南省祁阳市 Qiyang City, Hunan Province, China	153	0	-26.9%~-48.8%	[75]
经济林园绿肥 Green manure covers the economic forest	中国湖北省当阳市 Dangyang City, Hubei Province, China	260~371	15%~30%	-16.1%~-32.2%	[76]
	美国佛罗里达州 Florida, US	260	0	-17.0%~+12.6%	[77]

“+”表示增加 Indicated increase;“-”表示降低 Indicated decrease.

2.2 种植利用绿肥影响N₂O排放的微生物机制

种植利用绿肥会通过影响底物(NO₃⁻, NH₄⁺等)浓度和土壤通气性等,调控土壤硝化和反硝化微生物群落丰度和多样性进而影响土壤N₂O排放^[77,81-82]。绿肥生长期间,土壤硝化(AOB-*amoA*、AOA-*amoA*)和反硝化功能基因(*nirK*、*norB*、*nosZI*和*nosZII*)丰度均显著增加,N₂O减排的主要原因为覆盖绿肥增加了氧化亚氮还原功能微生物基因(*nosZI*和*nosZII*)相对丰度^[83]。同时,绿肥覆盖改变了氨氧化古菌(*Candidatus Nitrososphaera evergladensis*和*Candidatus Nitrososphaera gargensis*)、亚硝酸还原细菌(*Bosea robiniae*, *Bradyrhizobium paxllaeri*, *Bradyrhizobium* sp., *Chelatococcus daeguensis*, *Chetalococcus* sp., *Rhodobacter sphaeroides*和*Rhodopseudomonas palustris*)和氧化亚氮还原细菌(*Achromobacter cycloclastes*, *Azospirillum* sp., *Bradyrhizobium diazoefficiens*, *daeguensi*, *Chetalococcus* sp., *Microvirga* sp., *Rhizobium etli*和*Shinella* sp.)关键群落组成,从而降低N₂O排放^[77]。

绿肥还田后,向土壤中输入大量有机氮,有机氮矿化逐渐释放NH₄⁺,由于氨氧化微生物大多为自养型微生物,土壤NH₄⁺的增加能够提高土壤硝化潜势^[84-85]。在南方酸性红壤中的研究表明,翻压绿肥增加了土壤硝化潜势,提高了AOA和AOB的*amoA*基因丰度,并且对AOA群落结构的影响高于AOB^[86],硝化潜势的增加提高了N₂O排放风险。另外,硝化微生物通过增加硝化潜势,加速了氧气的消耗,引起反硝化过程的增强。翻压豆科绿肥,显著增加了土壤反硝化微生物功能基因*narG*和*nirK*丰度^[87],翻压禾本科绿肥土壤反硝化微生物功能基因*narG*、*napA*、*nirK*、*nirS*和*nosZI*丰度同样显著增加,这提高了反硝化过程的完成度,降低了土壤N₂O排放^[88]。同时,翻压绿肥促进了微生物活动,提高了微生物对氮素的固定^[89],减少了硝化和反硝化底物,有降低N₂O排放的潜力。有机氮的矿化速率取决于土壤水分含量、温度、绿肥碳氮比等,总的来说绿肥还田后一周为快速腐解期^[90],由于旱地土壤N₂O排放以硝化反应为主^[91],此时容易造成N₂O的排放高峰,研究人员应重点关注此段时间减排N₂O的可行性技术。

3 N₂O减排技术在绿肥制度中的应用现状

农业生产中主要的N₂O减排技术包括优化施肥制度(减肥、有机肥替代和控释肥替代等)、优化种植制度、配施土壤改良剂(化学抑制剂、生物炭和矿物类材料)、少耕或免耕和滴灌等,通过调控环境因素减排N₂O。近年来,这些措施在绿肥制度中开展了相关研究应用。

3.1 优化施肥制度

1980—2014年,我国氮肥使用量增加了两倍,但粮食产量仅增加了83%^[92],氮素利用效率明显下降。氮肥不合理施用是我国农业生产中N₂O排放的主要来源,77%的农田土壤N₂O排放来源于氮肥^[93]。我国氮肥减施潜力高达15%~19%,优化施氮后小麦、玉米和水稻的产量可增加10%~19%,氮盈余减少40%^[94]。荟萃分析表明,优化施氮量相对于传统施氮量,可以在降低25%的氮素投入、18%的N₂O排放量的同时,保持目标产量^[95]。由于硝化、反硝化底物的减少,减量施氮能够有效降低N₂O的排放^[95-96]。种植利用绿肥可减施化学氮肥20%~40%^[48],能够进一步减少外源氮的投入。南方水稻轮作绿肥系统中,减少化肥用量能降低N₂O排放,随紫云英替代化肥比例(25%~100%)的增加,N₂O减排比例随之增加(44.0%~83.7%)^[97];柑橘间作豆科绿肥可减施氮肥10%~30%,N₂O排放量降低了11.2%~32.2%^[76]。

联合国粮农组织和国际肥料工业协会发布的报告表明,氯化铵和有机肥N₂O排放系数较低^[98]。有机肥替代化肥是最为常见的农业施肥措施之一,不同有机肥的N₂O减排效果存在差异。油菜粕替代化肥,N₂O可减排16.1%~32.2%^[98]。而家禽粪肥替代化肥全年N₂O排放量显著增加了78.9%^[99]。这可能与有机肥种类、管理措施和环境因素等相关^[100-101]。另外,荟萃分析发现施用缓释氮肥N₂O排放量可降低38.3%^[102]。Liu等^[103]证实缓释尿素的N₂O排放系数显著低于普通尿素、硫酸铵和硝酸钙。绿肥制度中,可根据绿肥腐解后养分释放规律和主作物养分需求特征,选择适宜的缓释肥料,充分发挥缓释肥的N₂O减排效能。

种植利用绿肥作物一般无须增施氮肥,氮素供应时间应与主作物的需肥时期同步。在主作物播种后较播种前施肥增加了氮肥被作物吸收的概率,从而减少了N₂O排放^[104]。例如,在旱地玉米拔节期的侧施氮肥较播种前施

氮 N_2O 排放量降低了16.1%~52.4%^[104],在稻田“早稻—晚稻—紫云英”制度中,相比氮肥全部基施,按照基肥:粪肥:穗肥=5:3:2施用氮肥显著提高了氮肥利用率^[105]。并且,应注意绿肥的翻压时间,宜在绿肥最大生物量时翻压,不宜过早或过迟,在绿肥营养生长时翻压较绿肥生殖生长时 N_2O 排放量降低了11.3%~16.2%^[106]。

3.2 优化作物类型及种植制度

适宜的作物类型及种植制度能够改变土壤物理化学特性和微生物群落多样性,降低土壤 N_2O 排放^[68,77,107]。选择适宜的绿肥作物与粮食作物轮作或间作,能够提高氮肥利用效率,降低 N_2O 排放^[108-110]。在加拿大的研究表明,相比玉米连作,玉米轮作大豆 N_2O 排放显著降低了50%^[111],但在我国的一项研究表明,玉米轮作大豆对 N_2O 排放无显著影响^[112]。间作制度中,玉米间作大豆较玉米单作土壤 N_2O 排放量降低了25.6%~48.8%^[67-68],玉米间作猪屎豆(*Crotalaria pallida*)土壤 N_2O 排放量降低了15.0%^[70]。而玉米间作拉巴豆(*Physoctigma venenosum*)、紫花苜蓿(*Medicago sativa*)、草木樨(*Melilotus officinalis*)较玉米单作 N_2O 排放通量无显著变化^[67,70]。由此可见,种植制度和绿肥种类均显著影响 N_2O 排放,应因地制宜,选择适宜的绿肥种类及种植制度,实现 N_2O 减排的目标。

3.3 添加土壤改良剂

3.3.1 化学抑制剂 化学抑制剂主要包括硝化抑制剂和脲酶抑制剂。硝化抑制剂常见类型有双氰胺(dicyandiamide, DCD)、硝基吡啶(nitrapyrin)和3,4-二甲基吡唑磷酸(3,4-dimethylpyrazole phosphate, DMPP),能够降低土壤中硝化强度、减少 NO_3^- 积累,进而减少硝化和反硝化过程中产生的 N_2O ^[113]。高丹草(*Sorghum sudanense*)—小麦轮作系统中,添加硝化抑制剂可使 N_2O 排放量降低86.5%^[113]。

常见的脲酶抑制剂有N-丁基硫代磷酰三胺[N-(n-Butyl)thiophosphoric triamide, NBPT],通过抑制尿素向 NH_4^+ 转化,延缓尿素水解速率,降低土壤中 NH_4^+ 含量,减少硝化底物进而减少 N_2O 排放^[114]。培养试验显示,相较于对照,添加脲酶抑制剂可使 N_2O 排放量降低17.1%^[115]。等量添加条件下,硝化抑制剂往往较脲酶抑制剂 N_2O 减排效果更好^[115-116]。也可将二者混合使用,降低 N_2O 排放^[117]。

3.3.2 生物炭 生物炭是生物质在高温和厌氧条件下生成的一类结构及性质稳定、碳氮比高的富碳材料,在农业系统中常用作土壤改良剂^[118]。在物理性质上,生物炭具有较高的比表面积、孔隙度、表面电荷和持水性^[119]。在化学性质上,生物炭表面具有大量的官能团、盐基离子,且本身具有较高的灰分含量^[120]。添加生物炭可降低土壤 N_2O 排放的原因有:1)改善土壤通气状况,降低土壤反硝化作用^[121];2)生物炭输入增加了微生物对氮的固定,减少了硝化和反硝化底物^[122];3)生物炭可以吸附土壤硝化作用的底物(NH_4^+)^[122];4)生物炭提高了土壤pH,从而降低反硝化作用^[123];5)生物炭具有浓缩的芳香结构,允许电子在共轭pi电子系统之间转移,促进 N_2O 还原为 N_2 ^[124]。全球荟萃分析表明,施用生物炭可使 N_2O 排放量降低32%~54%^[125], N_2O 减排量与生物炭施用量呈正相关^[126]。小麦—黑麦(*Secale cereale*,用作绿肥)—高粱(*Sorghum bicolor*)轮作系统中,小麦播种前添加生物炭 N_2O 排放平均降低15%^[123]。

3.3.3 矿物类材料 沸石和膨润土等黏土矿能够缓慢地吸附和释放氮,施用黏土矿是土壤 N_2O 减排策略之一。沸石的晶体空间结构赋予了其较高的阳离子吸附和保水性能^[127-128],可以吸附土壤中 NH_4^+ 降低硝化作用^[129],减少 N_2O 排放。稻田的研究表明,添加沸石可使 N_2O 排放量降低9%^[130]。培养试验中也发现,翻压黑麦草处理中,相比于单独添加硫酸镁和硼处理,在此基础上添加沸石可使 N_2O 排放量显著降低30.4%^[131]。与沸石类似,膨润土能够固定土壤中游离的 NH_4^+ ,抑制了 N_2O 排放^[132],旱地的研究发现,添加膨润土可使 N_2O 排放量降低37.3%^[132]。

部分研究表明添加碱性矿石能够减少 N_2O 排放,主要原因是碱性矿石能够通过增加土壤pH,提高氧化亚氮还原微生物丰度^[133]。添加(煅烧)石灰石、白云石可使 N_2O 排放量显著降低21.7%~39.0%^[134-135]。种植绿肥会影响碱性矿石的 N_2O 减排效果,轮作豆科绿肥后,石灰失去小麦种植过程中减排 N_2O 的效果,原因为轮作豆科绿肥缓解了土壤微生物量碳、氮限制,掩盖了添加石灰增加土壤微生物量带来的 N_2O 减排效应^[136]。

黏土矿物及含钙类碱性矿石这些天然材料便宜易得,但施用不便,可利用物理法现代造粒工艺等技术,创制

绿色、环保、易用的增效新产品,达到节肥、减排的目的。施用矿物类材料应该注意因地制宜,碱性黏土矿类材料较适宜南方酸性土壤;北方旱地应选择偏中性的材料,避免土壤碱性过强,影响土壤中氨挥发及作物生长发育。

3.4 其他

保护性耕作条件下 N_2O 排放量一般低于常规耕作,这主要是由于免耕有助于改善土壤结构、增加土壤碳储量^[137],降低土壤中硝化、反硝化还原酶功能微生物丰度,增加氧化亚氮还原微生物丰度^[18,138]。相比于常规耕作,免耕使 N_2O 排放量减少了28%,且干旱条件下 N_2O 减排效果更明显^[117]。地中海葡萄园种植绿肥结合少耕使 N_2O 排放量减少了17.2%^[78],在肥田萝卜(*Raphanus sativus*)—燕麦—蚕豆(*Vicia faba*)轮作系统中,免耕使 N_2O 排放量较常规耕作显著降低了37.5%~47.4%^[64],耕作条件下绿肥翻压分解消耗氧气形成局部厌氧环境,反硝化过程驱动更多的 N_2O 排放^[64]。

滴灌通过改变土壤湿度、温度、氧气含量影响反硝化过程,促进完全反硝化作用的发生,更多的 N_2O 转变成了 N_2 ^[45]。Sánchez-Martín等^[139]通过田间试验,比较了不同灌溉系统 N_2O 排放的差异,结果表明,与沟灌相比,滴灌的 N_2O 排放总量减少了70%。与常规沟灌相比,滴灌菜地 N_2O 排放量降低了16.4%~60.9%^[140]。番茄(*Solanum lycopersicum*)轮作毛叶苕子(*Vicia villosa*)系统中,膜下滴灌较犁沟滴灌作物生长季 N_2O 排放降低了74%^[141]。采用滴灌技术时需要注意根据不同作物适宜的生长环境,调控滴灌强度、频率等控制土壤水分,达到 N_2O 减排的目的。

4 结论与展望

综上,农田土壤 N_2O 排放是土壤pH值、氧气及二氧化碳浓度、水分、质地、温度和外源碳氮投入等因素综合影响的结果。绿肥生长期间能够吸收土壤盈余的矿质氮,翻压后能够替代部分氮肥,有减少农田土壤 N_2O 排放的潜势,但同时存在由于腐解引发的增加土壤活性炭和有机氮含量导致的 N_2O 排放风险。可结合适宜的 N_2O 减排技术,降低绿肥制度中 N_2O 排放,具体包括优化施肥制度、优化种植制度、配施土壤改良剂、采用少耕或免耕等减排技术。

我国生态类型多样、种植制度多元,可根据绿肥种植制度、作物种类、气候条件、土壤类型等,结合适宜的 N_2O 减排技术,降低绿肥制度中 N_2O 排放风险。种植利用绿肥在保证作物稳产的同时,在南方水稻与绿肥轮作区,可减施氮肥40%^[142],采用绿肥稻秸共同还田,添加生物炭等碱性调理剂。在华北地区主作物(如玉米、棉花)与绿肥轮作区,可减施氮肥15%~20%^[58,72],翻压绿肥时添加化学抑制剂、结合氮肥机械化深施。在东北地区的麦后复种绿肥、薯类麻类复种绿肥及玉米、高粱、油葵(*Helianthus annuus*)前期间作绿肥等制度中,可减施氮肥10%~15%^[48],结合免耕模式根茬还田,地上部饲用,减少土壤扰动及翻压腐解带来的增排效应。在西北地区的麦后复种绿肥、玉米前期间作绿肥等制度中,可减施氮肥13%~48%^[72,143-144],添加硝化抑制剂,结合水肥一体化、免耕等技术。在西南地区玉米、烟草(*Nicotiana tabacum*)等与绿肥轮作的制度中,可减施氮肥15%~20%,配合缓控释肥一次性施肥、添加化学抑制剂等技术。

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