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水旱轮作系统中土壤CH_4和N_2O排放研究进展

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摘　要: 农田是温室气体的重要排放源之一,而水旱轮作是显著影响稻田温室气体排放的重要因素之一。本文分析了水旱轮作对甲烷(CH_4)和氧化亚氮(N_2O)两种主要温室气体产排的影响,从水肥管理和不同轮作方式等方面论述其对水旱轮作系统中土壤CH_4和N_2O排放的影响,并根据温室效应等因素,综合性地提出了推行稻季节水灌溉、规范作物施肥管理和优化轮作模式3种减排措施,以期为水旱轮作稻田温室气体减排提供参考。

关键词: 水旱轮作;甲烷;氧化亚氮

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A review on soil CH_4 and N_2O emissions from paddy-upland rotation systems

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Abstract: Farmlands are one of the most important sources of greenhouse gas emissions. Paddy-upland rotation is significant factor affecting greenhouse gas emissions in paddy soils. This paper discusses the effects of paddy-upland rotation on emissions of two main greenhouse gases, methane(CH_4) and nitrous oxide(N_2O), including the impact of water-saving irrigation, fertilizer management and rotation method on soil CH_4 and N_2O emissions from paddy-upland rotation system . Three kinds of greenhouse emission reduction measures are also proposed, including rice season water-saving irrigation, crop fertilization management and rotation mode optimization.

Keywords: paddy-upland rotation; methane; nitrous oxide

温室气体排放导致全球气候变暖等一系列生态环境问题引起了当今社会的广泛关注。甲烷(CH_4)和氧化亚氮(N_2O)是两种重要温室气体,其单位分子的增温潜能分别是二氧化碳(CO_2)的25倍和298倍[1-3]。据IPCC第五次评估报告,全球大气中CH_4和N_2O浓度已由工业革命前的715 $\mu L\cdot m^{-3}$和270 $\mu L\cdot m^{-3}$

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增至2011年的1803 μL·m^{-3}和324 μL·m^{-3}[4]。农业源是大气CH_4和N_2O的主要排放源，分别占全球人为排放CH_4和N_2O的50%和43%以上，我国农业源释放的温室气体总量占中国总温室气体的比例已超过17.0%[5-8]，因此，采用有效的农田管理措施缓解农田温室气体排放具有十分重要的意义。

水旱轮作是我国的重要耕作模式之一，指在同一田块上，按季节有序地交替种植水稻和旱地作物（小麦、油菜、蔬菜、蚕豆、棉花等）的一种种植模式，主要分布在长江和淮海流域，种植面积约470万hm^2[9]。水旱轮作系统农田温室气体排放受水肥管理、耕作栽培等农艺措施的影响[10-12]。因此，采用合适的农田管理措施对减缓农田温室气体排放具有重要的现实意义。本文通过探讨水稻-小麦、水稻-油菜、水稻-紫云英等水旱轮作模式下农田CH_4和N_2O的排放差异，分析其影响因素，并提出相应的减排对策，旨在为水旱轮作模式下土壤温室气体减排提供科学参考。

1 水旱轮作对农田CH_4和N_2O排放的影响

1.1 CH_4排放

与水稻-冬水休闲相比，水稻-干旱休闲更有利于降低CH_4排放。张广斌等[13]研究发现水稻-冬水休闲系统的稻季CH_4排放通量比水稻-干旱休闲高118.5%。相比稻-闲、稻-稻，农田采取稻-油、稻-麦或玉米-水稻等水旱轮作模式能有效减少CH_4排放[6,14-16]。稻-麦轮作的CH_4平均排放通量仅为水稻-冬水田的1/3[17]；稻-麦和稻-油菜轮作周年CH_4排放量比稻-淹水休闲显著降低24.0%~90.5%和89.4%[18-19]。双季稻田改为水旱轮作，土壤CH_4排放量明显降低[20-22]，与双季稻种植模式相比，早稻-玉米、玉米-晚稻CH_4排放量分别降低53.6%~88.0%和54.6%~85.4%[21-23]；油菜-早稻-甘薯‖晚大豆相比油菜-双季稻CH_4周年排放显著降低47.0%、紫云英-早稻-甘薯‖晚大豆相比紫云英-双季稻CH_4周年排放显著降低94.0%[24]。

1.2 N_2O排放

水旱轮作系统的N_2O排放量显著高于持续淹水农田系统。与冬闲水田相比，冬季旱作处理的土壤N_2O的排放量明显升高，与水稻-冬水田相比，江长胜等[19]研究中稻麦轮作增加3.7倍，莫永亮等[25]研究中增加6.2倍，宿敏敏[26]研究中增加48.7%~56.5%、稻-油增加4.5倍[19]。与双季稻相比，稻-玉、玉-稻分别增加50.6%和21.9%~86.1%[16,21,23]。稻-紫云英N_2O平均排放通量比冬闲土壤的N_2O排放通量低，主要与紫云英利用土壤氮素转变为有机氮有关[27]。

1.3 综合温室效应

水旱轮作虽增加农田土壤N_2O排放，但显著降低了CH_4的排放，降低了农田系统的综合净增温潜势（表1）。与双季稻种植相比，稻-玉米、玉米-稻均显著降低农田系统综合增温潜势。稻-麦轮作、稻-油轮作和稻-儿菜轮作比稻-冬水休闲综合增温潜势分别减少73.1%、24.7%和40.7%。

2 水旱轮作系统CH_4和N_2O排放影响因素

2.1 水分管理

2.1.1 水分管理对CH_4排放的影响

水旱轮作模式下CH_4排放通量和排放量随灌水量的减少而降低[29-30]。由于稻季节水灌溉增加了土

表1 不同轮作模式CH_4和N_2O周年排放总量及增温潜势

Table 1 Green warming potential of CH_4 and N_2O during crop growing season in whole year

轮作模式 Rotation pattern	增温潜势GWP/kg $CO_2\cdot hm^{-2}$			增温潜势减少 Decrease in GWP/%	参考文献 Reference
	CH_4	N_2O	CH_4+N_2O		
双季稻	8 607.2	248.0	8 855.2		[22]
水稻-玉米	3 996.0	885.5	4 881.5	81.4	
玉米-水稻	1 260.1	856.2	2 116.3	318.4	
双季稻	—	—	17 848.0		[23]
玉米-水稻	—	—	11 123.0	37.7	
水稻-冬水休闲	—	—	7 800.0		[26]
水稻-小麦	—	—	2 100.0	73.1	
水稻-冬水田	11 840.0	1 20.0	11 960.0		[28]
水稻-油菜	3 700.0	5 300.0	9 000.0	24.7	
水稻-儿菜	1 420.0	5 670.0	7 090.0	40.7	

壤通透性，破坏了产CH_4菌生命活动所需要的极严格厌氧条件，导致CH_4排放量降低[31-34]，因此，稻季节水灌溉对稻季和旱作季CH_4排放均有抑制作用[33-34]。徐莹[35]研究表明，稻-油模式下稻季实行湿润式间歇灌溉、干旱式间歇灌溉和旱作栽培的CH_4周年累积排放量比常规灌溉分别减少了17.0%~66.0%、39.0%~85.0%和60.0%~91.0%；杭玉浩等[36]采用水稻季控制灌溉的稻季和小麦季CH_4排放通量较传统灌溉分别减少了79.9%和26.5%。

2.1.2 水分管理对N_2O排放的影响

稻季水分管理对稻季和非稻季N_2O排放均有影响。持续淹水稻田N_2O排放量很低[37-38]，稻季晒田及干湿交替可以促进水旱轮作系统稻季和非稻季周年N_2O排放[39-40]。邹建文[41]研究表明持续淹水处理的N_2O-N季节排放总量相当于0.01%~0.02%化肥氮，而淹水-烤田-淹水处理的为0.11%~0.56%；杭玉浩等[36]研究表明在稻-麦轮作系统中，水稻季控制灌溉的N_2O排放比传统灌溉增加22.0%~35.5%，小麦季增加11.3%~25.0%。徐莹[35]监测稻-油模式下稻季湿润式、干旱式间歇灌溉和旱作栽培，油菜季N_2O累积排放量比传统灌溉分别增加了7.6%~17.5%、18.5%~19.3%和23.6%~36.2%。由于淹水灌溉降低了土壤Eh，反硝化过程彻底将NO_3^-还原为N_2，减少了N_2O的产生，而稻季干湿交替为氮素硝化与反硝化反应创造了良好环境，促进了土壤N_2O的产生与排放[37, 42-43]。

2.2 施肥管理

2.2.1 施肥管理对CH_4排放的影响

化肥施用对水旱轮作系统中CH_4排放量的影响尚未明确。普遍认为，适当增施氮、磷等肥料，有利于产CH_4菌生命体的构建，但随着施肥量的增加，加快了根际CH_4的氧化，从而降低CH_4排放[44]。左怀峰[45]和杨波[46]研究发现，稻-麦轮作施用205.1 kg N·hm^{-2}和240.0 kg N·hm^{-2}的CH_4累积排放量比不施肥分别增加41.1%和29.5%；有研究表明，随着施肥量增加，早稻-马铃薯和水稻-蚕豆轮作的CH_4周年累计排放量分别增加2.3~3.8倍和1.3~1.4倍[45-46]；宿敏敏等[18,26]研究表明，低于传统施肥量的水稻-小麦轮作系统CH_4排放比不施肥增加11.3%，而传统施肥处理减少48.9%；刘少文等[47]和胡安永等[48]也表明紫云英-水稻轮作模式下施用化肥比不施肥对照较大幅度减少CH_4排放。

水旱轮作系统施用缓释化肥CH_4排放量明显低于普通化肥，主要由于缓释肥含复合增效剂，铵态氮始终处于较高的水平，加剧了CH_4在土壤大气界面的氧化，使CH_4排放降低[49]。左怀峰[45]研究发现施用脲酶抑制剂和控释肥，农田CH_4排放总量比化肥处理分别减少了13.0%和45.5%。胡玉麟等[50]研究缓控肥替代化肥对水稻-豇豆轮作系统温室气体减排效果显著。

不同有机肥影响水旱轮作系统CH_4排放。郭腾飞等[51]研究显示，稻-麦轮作施用秸秆比单施尿素的CH_4周年排放量分别增加14.0%和98.7%；单季稻-小麦和双季稻-油菜轮作模式，随着秸秆施入量增加，CH_4周年累计排放量分别增加1.4~6.0倍[6,14,52]和2.1~3.3倍[6,14]，邹建文[41]研究表明，稻麦轮作施用菜饼、秸秆或牛粪与化肥配施处理比单施化肥CH_4季节排放总量分别增加252.3%、249.7%和45.0%，一方面有机物质是生成产CH_4前体的基质来源，另一方面，有机物质的分解降低土壤Eh，从而促进CH_4产排[53-54]；施用的有机肥中，沼渣肥、菌肥等腐熟的有机肥CH_4排放量最低。有研究表明猪厩肥处理与化肥处理几乎无差异。主要是腐熟后的有机肥可供利用的有机质前体被消耗，因而对CH_4排放的促进作用不明显。

2.2.2 施肥管理对N_2O排放的影响

施用化肥显著增加水旱轮作系统N_2O的排放。化肥氮是N_2O产生的主要前体，为N_2O的产生提供了基质，因此化肥施用通常会促进N_2O排放[55-60]。邹建文[41]认为稻-麦轮作系统中，随着氮肥施用量的增加，N_2O排放量增加；徐鹏等[61]也证实稻-油轮作模式下施化肥处理N_2O排放量显著高于不施氮肥处理。与不施肥相比，稻-麦轮作模式下施入化肥，稻季和旱季N_2O排放通量分别增加71.4%~111.5%和41.7%~61.2%[26,46]，周年排放量增加1.5~27.1倍[6,14,62]，双季稻-油菜周年排放量则增加6.2~12.3倍[6,14]。

缓控释氮肥的氮素释放速率较慢，释放时间长，降低土壤N_2O的排放。尹高飞[63]证实了与化肥相比，等氮量缓释肥料施入后稻季和蚕豆季N_2O累积排放分别减少13.0%和20.4% 。

施用有机肥对水旱轮作系统N_2O排放影响比较复杂。有研究表明，在稻麦轮作系统下，水稻季节小麦秸秆还田显著减少了稻季N_2O的排放，同时稻秆残留对后季非水稻季节的排放也有抑制作用[64]；Zou等[65]和柴凯斌[52]研究发现稻季麦秸还田较麦秸不还田能显著降低N_2O排放达18.0%~38.0%；水稻-蚕豆轮作系统施用156 kg N·hm^{-2}的有机肥，稻季和蚕豆季N_2O排放较不施肥分别增加87.1%和191.7%，但其

增长幅度小于等量的化肥施入[63]；李喜喜[66]研究表明增施50.0%~100.0%猪粪有机肥，稻-麦轮作整个生育期N_2O累积排放量升高66.4%~121.6%；牛厩肥、猪厩肥和菜饼处理稻麦生长季N_2O排放总量比常规化肥处理分别增加17.0%、7.0%、6.0%，而秸秆施用稻季N_2O季节排放总量较无秸秆处理减少了8.0%~88.0%，全轮作周期内N_2O减排16.0%[41]。有机肥对稻-旱轮作模式下N_2O排放影响不一，可能的原因是秸秆还田提高了土壤中C/N，降低了N_2O排放；施用量、C/N、氮含量和形态不同，影响其在土壤中氮形态转化和农作物吸收利用的差异，导致了N_2O排放结果的差异[67-68]。

2.3 轮作模式

2.3.1 不同轮作模式对CH_4排放的影响

不同轮作模式对CH_4排放的影响不同，双季稻-冬季作物轮作模式普遍高于单季稻-旱作模式。黄太庆[14]研究表明双季稻-油菜轮作的CH_4排放量比单季稻-小麦轮作系统高出12.7%~97.7%；伍思平等[69]显示紫云英-双季稻和冬闲-双季稻模式的CH_4累积排放比油菜-中稻分别增加了127.0%和118.0%。前茬不同旱季作物对稻季CH_4排放影响达极显著水平，CH_4排放量表现为紫云英-水稻>休闲-水稻>小麦-水稻>油菜-水稻>黑麦草-水稻[70]。

2.3.2 不同轮作模式对N_2O排放的影响

水旱轮作系统N_2O排放因不同作物的轮作方式而不同。有研究表明，在不同轮作系统中，N_2O周年排放量表现为：双季稻-油菜轮作>单季稻-小麦轮作[6,14]。张岳芳等[71]发现水旱轮作系统旱作季种植不同作物N_2O平均排放通量表现为：油菜>冬小麦>黑麦草>休闲>紫云英。钟川等[24]研究发现，不同水旱轮作模式的N_2O周年排放量为紫云英－早稻－甘薯‖晚大豆>油菜－早稻－甘薯‖晚大豆>紫云英－早稻－晚稻>油菜－早稻－晚稻>马铃薯－早稻－晚稻。由于不同作物的水肥利用效率和农田管理措施的差异，作物对碳氮循环的影响各不相同，导致N_2O的产排不同[72]。

3 水旱轮作系统CH_4和N_2O减排措施建议

3.1 推行稻季节水灌溉，减少CH_4排放

由于CH_4与N_2O两者存在互为消长的关系，因此优化农田水分管理应该在考虑这两种温室气体综合排放的基础上制定合理措施。在水旱轮作系统内，稻季温室气体主要贡献因子为CH_4，与常规灌溉相比，节水灌溉方式虽可增加土壤N_2O排放，但显著降低了CH_4的排放，降低了全球增温潜势(表2)。因此，采用稻季节水、中期烤田，能有效降低综合温室效应。

3.2 规范施肥管理，减少N_2O排放

化肥施用量增加，N_2O排放增加，因此在不影响水稻产量的前提下，考虑减少氮肥的施用。(1)提倡测土配方施肥。在实际的田间管理中，稻-麦轮作系统氮肥的施用也可遵循余庆福等[73]推荐施氮量(麦季210 kg·hm^{-2}+稻季90 kg·hm^{-2})，降低N_2O排放。(2)选用缓释化肥替代普通化肥或分次施肥方式有利于提高氮肥利用效率，减少氮肥损失，抑制N_2O排放。随着农业技术的进步，通过使用N_2O抑制剂来减少温室气体的排放，也逐渐得到了广泛的认可，脲酶抑制剂和硝化抑制剂等氮肥抑制剂可在不减少作物产量的前提下有效减少N_2O的排放。

3.3 优化轮作模式，减少周年增温潜势

加强不同轮作系统作物搭配方式对温室气体排放量的对比研究，探索合理的轮作模式。在保证作物产量的同时，因地制宜地搭配选用根系大、活力强、温室气体排放量低的作物品种。稻-麦轮作、稻-油轮作和水稻-紫云英是我国主要的水旱轮作种植模式。研究表明稻-麦模式周年平均产量比油稻模式高4018 kg·hm^{-2}，经济效益高出6246元·hm^{-2}[74]，旱作季CH_4和N_2O的总增温潜势减少14.2%[71]，单位产量的GWP比双季稻-油菜低0.1~3.0 kg CO_2·kg^{-1}(表3)。

表2 与常规灌溉相比不同水分管理农田温室气体排放

Table 2 Greenhouse gas emissions under different water management patterns compared to conventional irrigation

轮作模式 Rotation pattern	水分管理方式 Water management	CH_4排放量 CH_4 emissions/%	N_2O排放量 N_2O emissions	净增温潜势 Net warming potential/%	参考文献 Reference
稻-油轮作	湿润式间歇灌溉	−62.0	无显著差异	−20.0	[35]
稻-油轮作	干旱式间歇灌溉	−80.0	无显著差异	−17.0	[35]
稻-油轮作	旱作栽培	−90.0	无显著差异	−21.0	[35]
稻-麦轮作	控制灌溉	−79.6	+27.0%	−60.3	[36]

注：表格中"+"表示增加，"－"表示减少。

Note:"+" in the table indicates increase,"－" indicates decrease .

不施氮的条件下，水稻-紫云英和水稻-休闲处理间CH_4和N_2O总增温潜势无显著差异，但水稻-紫云英更有利于作物增产[71]。因此在施氮条件下选用水稻-冬小麦种植模式、不施氮条件下选用水稻-紫云英种植模式有利于减少水旱轮作系统旱作季的温室效应。

4 展望

大量的研究表明农田N_2O和CH_4的排放互为消长。加强农田水肥管理是控制CH_4排放的主导因素，加大研发和推广CH_4抑制剂力度是减缓水旱轮作系统CH_4排放的有力手段。对N_2O而言，提高缓释肥、控释肥料的使用对缓解其大量排放具有更重要的科学意义和实践价值。在今后研究过程中，应综合考虑农作过程对农田土壤CH_4和N_2O排放的影响，积极研究探索有效的CH_4和N_2O综合减排措施，减轻因农业活动产生的温室气体对全球气候变暖及其所带来的环境问题的影响。

近年来，许多学者对水旱轮作不同种植模式下农田温室气体排放进行了研究，大量研究结果表明，合理的水旱轮作有助于增加作物产量，维持土壤肥力。因此，如何在平衡其正面作用的同时减少温室气体排放是今后研究的趋势。不同水稻品种间温室气体排放存在明显差异，深入研究水稻品种改良对温室气体排放的影响及其机理，可在增加作物产量的同时实现温室气体减排。肥料的种类和用量等对水旱轮作系统土壤温室气体排放产生影响，肥料管理对土壤性状造成的变化会直接影响根际土壤微生物如产CH_4菌、硝化细菌和反硝化细菌的种群丰度与活性。但目前我国针对这方面的研究还相对较少，因此，在今后的研究中可以考虑从轮作体系中作物的根际微生态效应等方面展开研究，了解水旱轮作系统养分状况的周期性变化规律，深入地揭示肥料氮素的去向，为土壤固氮和温室气体减排提供理论依据。

目前，我国虽然在温室气体综合减排方面也取得了一些成果，但是没有形成系统的全面的减排措施，目前公认的、广泛应用的、效果明显且持久的水旱轮作系统温室气体减排措施相对较少，缺少科学系统的评估。因此，在以后的研究中，可从整个水旱轮作系统的角度出发，利用碳足迹的评价方法，综合考虑多种影响温室气体排放并在此基础上制定合理的减排措施。

参考文献：

[1] Vitale D, Bilancia M. Role of the natural and anthropogenic radiative forcings on global warming: Evidence from cointegration-VECM analysis[J]. *Environmental and Ecological Statistics*, 2013, 20(3): 413-444.

[2] 吴家梅, 纪雄辉, 刘 勇. 不同施肥处理稻田甲烷排放研究进展[J]. 农业资源与环境学报, 2010, 27(2): 19-24.
WU Jia-mei, JI Xiong-hui, LIU Yong. Research progress of methane emission from paddy field under different fertilizer treatments[J]. *Journal of Agricultural Resources and Environment*, 2010, 27(2): 19-24.

[3] Liu J, Hou H, Sheng R, et al. Denitrifying communities differentially respond to flooding drying cycles in paddy soils[J]. *Applied Soil Ecology*, 2012, 62(Complete):155-162.

[4] IPCC. Climate change: The physical science basis: contribution of working group contribution to the fifth assessment report of the intergovernment panel on climate change[R]. Cambridge: Cambridge University Press, 2013.

[5] Wang F, Yue Z Z, Zhao D Y, et al. Improving energy and GHG performance of the rice-wheat rotation system: A life-cycle analysis based on a large-scale behavior investigation[J]. *Journal of Cleaner Produc-*

表3 不同轮作模式下CH_4和N_2O全球增温潜势及排放强度

Table 3 GWP and greenhouse gas intensity of CH_4 and N_2O for different rotation patterns

轮作模式 Rotation pattern	全年周期内增温潜势 GWPS /kg $CO_2 \cdot hm^{-2}$			贡献率 Contribution rate/%		单位产量增温潜势 GWP per unit yield/kg $CO_2 \cdot kg^{-1}$grain	参考文献 Reference
	CH_4	N_2O	CH_4+N_2O	CH_4	N_2O		
水稻-紫云英	2549	68	2617	97	3	0.3	[49]
双季稻-紫云英	5673	423	6096~7400	93	7	0.4	[24,72]
紫云英－早稻－甘薯‖晚大豆	3318	2085	5403	61	39	0.33	[24]
水稻-小麦	1634~8418	68~1830	1956~9468	61~98	2~39	0.40~1.60	[6,14,49]
双季稻-油菜	2359~141 25	156~2674	2506~168 00	66~95	5~34	0.50~5.60	[6,14,24]
油菜－早稻－甘薯‖晚大豆	3215	1913	5128	63	37	0.27	[24]
早稻-玉米	3996	886	4882	82	18	—	[22]
玉米-早稻	1260	856	2116	60	40	—	[22]
马铃薯-双季稻	5351	378	5729	93	7	0.34	[24]
单季稻-油菜	—	—	3254	—	—	0..02	[70]

tion, doi:10.1016/j.jclepro.2020.120319.

[6] 张啸林. 不同稻田轮作体系下温室气体排放及温室气体强度研究[D]. 南京: 南京农业大学, 2013.
ZHANG Xiao-lin. Greenhouse gases emissions and greenhouse gas intensity from different rice-based cropping[D]. Nanjing: Nanjing Agricultural University, 2013.

[7] Carlson, Kimberly M, Gerber, et al. Greenhouse gas emissions intensity of global croplands[J]. *Nature Climate Change*, 2017,7(1): 63-68

[8] Benbi D K. Greenhouse gas emissions from agricultural soils: Sources and mitigation potential[J]. *Journal of Crop Improvement*, 2013, 27(6): 752-772.

[9] 陈书涛, 黄 耀, 郑循华, 等. 轮作制度对农田氧化亚氮排放的影响及驱动因子[J]. 中国农业科学, 2005, 38(10): 2053-2060.
CHEN Shu-tao, HUANG Yao, ZHENG Xun-hua, et al. Nitrous oxide emission from cropland and its driving factors under different crop rotations [J]. *Scientia Agricultura Sinica*, 2005, 38(10): 2053-2060.

[10] 杨滨娟, 孙 松, 陈洪俊, 等. 稻田水旱轮作系统的能值分析和可持续性评价[J]. 生态科学, 2017, 36(1): 123-131.
YANG Bin-juan, SUN Song, CHEN Hong-jun, et al. Research on emergy analysis and sustainability evaluation under paddy-upland rotation systems[J]. *Ecological Science*, 2017, 36(1): 123-131.

[11] 邓丽萍. 稻田复种轮作对作物产量、土壤肥力及农田温室气体排放的影响[D]. 南昌: 江西农业大学, 2017.
DENG Li-ping. Effects of multiple cropping rotation on crop yield, soil fertility and farmland greenhouse gas emissions[D]. Nanchang: Jiangxi Agricultural University, 2017.

[12] Choudhary M, Panday S C, Meena V S, et al. Long-term effects of organicmanure and inorganic fertilization on sustainability and chemical soil quality indicators of soybean-wheat cropping system in the Indian mid-Himalayas[J]. *Agriculture Ecosystems & Environment*, 2018, 257: 38-46.

[13] 张广斌, 张晓艳, 马二登, 等. 冬季土地管理对稻季 CH_4 产生、氧化和排放的影响[J]. 生态与农村环境学报, 2010, 26(2): 97-102.
ZHANG Guang-bin, ZHANG Xiao-yan, MA Er-deng, et al. Effects of land management in winter on production, oxidation and emission of CH_4 during the rice-growing season[J]. *Journal of Ecology and Rural Environment*, 2010, 26(2): 97-102.

[14] 黄太庆. 不同轮作制度稻田生态系统温室气体排放研究[D]. 南京: 南京农业大学, 2011.
HUANG Tai-qing. Greenhouse gases emissions from different rotation systems in paddy fields[D]. Nanjing: Nanjing Agricultural University, 2011.

[15] 许国春. 不同轮作系统和稻作模式对稻田温室气体排放及氮素平衡的影响[D]. 南京: 南京农业大学, 2017.
XU Guo-chun. Effects of different rotation systems and rice cropping models on greenhouse gas emissions and nitrogen balance in paddy fields[D]. Nanjing: Nanjing Agricultural University, 2017.

[16] 周自强, 李 露, 张 恒, 等. 氮肥配施小麦秸秆生物炭对稻麦轮作土壤剖面 CH_4 和 N_2O 浓度的影响[J]. 南京农业大学学报, 2015, 38(3): 85-92.
ZHOU Zi-qiang, LI Lu, ZHANG Heng, et al. Effects of wheat straw biochar and nitrogen amendment on methane and nitrous oxide distribution characteristics within soil profile in rice-wheat annual rotations [J]. *Journal of Nanjing Agricultural University* , 2015, 38(3): 85-92.

[17] 黄 勤, 魏朝富, 谢德体, 等. 不同耕作制对稻田甲烷排放通量的影响[J]. 西南大学学报(自然科学版), 1996(5): 436-439.
HUANG Qin, WEI Chao-fu, XIE De-ti, et al. Effects of different cropping systems on the emission of methane from paddy field[J]. *Journal of Southwest University*(*Natural Science Edition*), 1996(5): 436-439.

[18] 宿敏敏, 况福虹, 吕 阳, 等. 不同轮作体系不同施氮量甲烷排放比较研究[J]. 植物营养与肥料学报, 2016, 22(4): 913-920.
SU Min-min, KUANG Fu-hong, LÜ Yang, et al. Impact of N fertilization on CH_4 emission from paddy field under different rotation systems [J]. *Journal of Plant Nutrition and Fertilizer*, 2016, 22(4): 913-920.

[19] 江长胜, 王跃思, 郑循华, 等. 耕作制度对川中丘陵区冬灌田 CH_4 和 N_2O 排放的影响[J]. 环境科学, 2006(2): 207-213.
JIANG Chang-sheng, WANG Yue-si, ZHENG Xun-hua, et al. Effects of tillage-cropping systems on methane and nitrous oxide emissions from permanently flooded rice fields in a central Sichuan hilly area of southwest China[J]. *Environmental Sciences*, 2006(2): 207-213.

[20] Xu P, Zhou W, Jiang M D, et al. Conversion of winter flooded rice paddy planting to rice-wheat rotation decreased methane emissions during the rice-growing seasons[J]. *Soil & Tillage Research*, 2020, 198: 104490. doi:10.1016/j.still.2019.104490.

[21] Weller S, Janz B, Jorg, L, et al. Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems[J]. *Global Change Biology*, 2016, 22(1): 432-448.

[22] 彭 华, 纪雄辉, 吴家梅, 等. 双季稻田不同种植模式对 CH_4 和 N_2O 排放的影响研究[J]. 生态环境学报, 2015, 24(2): 190-195.
PENG Hua, JI Xiong-hui, WU Jia-mei, et al. CH_4 and N_2O emission reduction under different cropping systems in double-cropping paddy fields[J]. *Ecology and Environmental Sciences*, 2015, 24(2): 190-195.

[23] 姜振辉, 杨 旭, 刘益珍, 等. 春玉米-晚稻与早稻-晚稻种植模式碳足迹比较[J]. 生态学报, 2019, 39(21): 8091-8099.
JIANG Zhen-hui, YANG Xu, LIU Yi-zhen, et al. Comparison of carbon footprint between spring maize-late rice and early rice-late rice cropping system[J]. *Acta Ecologica Sinica*, 2019, 39 (21): 8091-8099.

[24] 钟 川, 杨滨娟, 张 鹏, 等. 基于冬种不同作物的水旱轮作模式对水稻产量及稻田 CH_4、N_2O 排放的影响[J]. 核农学报, 2019, 33(2): 379-388.
ZHONG Chuan, YANG Bin-juan, ZHANG Peng, et al. Effect of paddy-upland rotation with different winter crops on rice yield and CH_4, N_2O emission in paddy fields[J]. *Journal of Nuclear Agricultural Sciencese*, 2019, 33(2): 379-388.

[25] 莫永亮, 胡荣桂, 赵劲松, 等. 冬水田转稻麦轮作对小麦生长季温室气体排放的影响[J]. 环境科学学报, 2014, 34(10): 2675-2683.
MO Yong-liang, HU Rong-gui, ZHAO Jin-song, et al. Effects of altering winter flooded paddy field to rice-wheat rotation on greenhouse gases emission during wheat growing season[J]. *Acta Scientiae Circum-*

stantiae, 2014, 34(10): 2675-2683.

[26] 宿敏敏. 四川盆地不同轮作方式和氮素管理对农田温室气体排放及净温室效应的影响[D]. 北京: 中国农业大学, 2016.
SU Min-min. Greenhouse gas emission and net global warming potential in croplands as affected by different rotation systems and nitrogen management in Sichuan Basin[D]. Beijing: China Agricultural University, 2016.

[27] 杨滨娟, 黄国勤. 双季稻田冬种紫云英"双减双增"绿色高效循环农业模式[J]. 江苏农业科学, 2018, 46(16): 51-56.
YANG Bin-juan, HUANG Guo-qin. A green and efficiency recycling agriculture mode of winter-planting milk vetch with "Double-Reduction and Double-Increment" in double-season rice fields[J]. *Jiangsu Agricultural Science*, 2018, 46(16): 51-56.

[28] 冯 夕, 江长胜, 彭小乐, 等. 轮作方式对冬水田温室气体排放的影响[J]. 环境科学, 2019, 40(1): 394-402.
FENG Xi, JIANG Chang-sheng, PENG Xiao-le, et al. Effects of crop rotation on greenhouse gas from flooded paddy fields[J]. *Environmental Science*, 2019, 40(1): 394-402.

[29] Hu R G, Cheng W G, Tang S R, et al. Simulating the effects of soil temperature and moisture in the off-rice season on rice straw decomposition and subsequent CH_4 production during the growth season in a paddy soil[J]. *Biology and Fertility of Soils*, 2016, 52: 739-748.

[30] Su M M, Kuang F H, Lv Y, et al. Nitrous oxide and methane emissions from paddy soils in southwest China[J]. *Geoderma Reg*, 2017, 8: 1-11.

[31] Kang G, Cai Z , Feng X . Importance of water regime during the non-rice growing period in winter in regional variation of CH_4 emissions from rice fields during following rice growing period in China[J]. *Nutrient Cycling in Agroecosystems*, 2002, 64(1/2): 95-100.

[32] Dong H , Yao Z , Zheng X , et al. Effect of ammonium-based, non-sulfate fertilizers on CH_4 emissions from a paddy field with a typical Chinese water management regime[J]. *Atmospheric Environment*, 2011, 45(5): 1095-1101.

[33] Qin H L, Tang Y F, Shen J L, et al. Abundance of transcripts of functional gene reflects the inverse relationship between CH_4 and N_2O emission during mid-season drainage in acidic paddy soil[J]. *Biology and Fertility of Soils*, 2018, 54(8): 885-895.

[34] Sacco D, Cremon C, Zavattaro L, et al. Seasonal variation of soil physical properties under different water managements in irrigated rice[J]. *Soil & Tillage Research*, 2012, 118: 22-31.

[35] 徐 莹. 稻田节水灌溉对稻—油轮作温室气体排放及土壤有机碳的影响机制[D]. 武汉: 华中农业大学, 2016.
XU Ying. Mechanisms of greenhouse gas emissions and soil organic carbon dynamics from rice-rapeseed rotation in water-saving irrigation paddy fields[D]. Wuhan: Huazhong Agricultural University, 2016.

[36] 杭玉浩, 王强盛, 许国春, 等. 水分管理和秸秆还田对稻麦轮作系统温室气体排放的综合效应[J]. 生态环境学报, 2017, 26(11): 1844-1855.
HANG Yu-hao, WANG Qiang-sheng, XU Guo-chun, et al. Effects of water regimes and straw incorporation on greenhouse gas emissions in a rice-wheat cropping system[J]. *Ecology and Environmental Sciences*, 2017, 26(11): 1844-1855.

[37] Ahn J H , Choi M Y , Kim B Y , et al. Effects of water-saving irrigation on emissions of greenhouse gases and prokaryotic communities in rice paddy soil[J]. *Microbial Ecology*, 2014, 68(2): 271-283.

[38] Mazza G, Agnelli A E, Orasen G, et al. Reduction of global warming potential from rice under alternate wetting and drying practice in a sandy soil of northern Italy[J]. *Italian Journal of Agrometeorology*, 2016, 2(2): 35-44.

[39] Wei Q, Xu J Z, Yang S H. et al. Partial wetting irrigation resulted in non-uniformly low nitrous oxide emissions from soil[J]. *Atmospheric Environment* , 2017, 161(5): 200-209.

[40] Tariq A, Jensen L, Tourdonnet S, et al. Early drainage mitigates methane and nitrous oxide emissions from organically amended paddy soils [J]. *Geoderma*, 2017, 304: 49-58.

[41] 邹建文. 稻麦轮作生态系统温室气体(CO_2、CH_4和N_2O)排放研究[D]. 南京: 南京农业大学, 2005.
ZOU Jian-wen. A study on greenhouse gases (CO_2, CH_4 and N_2O) emission from rice-winter rotations in southeast China[D]. Nanjing: Nanjing Agricultural University, 2005.

[42] Baruah A, Baruah K K, Gorh D, et al. Effect of organic residues with varied carbon-nitrogen ratios on grain yield, soil health, and nitrous oxide emission from a rice agroecosystem[J]. *Communications in Soil Science and Plant Analysis*, 2016, 47(11):1417-1429.

[43] Liu G, Yu H, Zhang G, et al. Combination of wet irrigation and nitrification inhibitor reduced nitrous oxide and methane emissions from a rice cropping system[J]. *Environmental Science and Pollution Research*, 2016, 23(17): 17426-17436.

[44] Linquist B A , Adviento-Borbe M A , Pittelkow C M , et al. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis[J]. *Field Crops Research*, 2012, 135: 10-21.

[45] 左怀峰. 不同施肥技术对巢湖流域稻麦轮作农田CH_4和N_2O排放影响的研究[D]. 合肥: 安徽农业大学, 2014.
ZUO Huai-feng. Effects of different fertilizing techniques on the emissions of methane and nitrous oxide from rice-wheat rotation cropland of Chao Lake Basin [D]. Hefei: Anhui Agricultural University, 2014.

[46] 杨 波. 不同氮肥管理模式对稻麦轮作系统净温室效应的观测研究[D]. 南京: 南京农业大学, 2015.
YANG Bo. Observation of net globle warming potential under different nitrogen fertilizer management in annual rice-wheat rotation system[D]. Nanjing: Nanjing Agricultural University, 2015.

[47] 刘少文, 殷 敏, 褚 光, 等. 长江中下游稻区不同水旱轮作模式和氮肥水平对稻田CH_4排放的影响[J]. 中国农业科学, 2019, 52(14): 2484-2499.
LIU Shao-wen, YIN Min, CHU Guang, et al. Effects of various paddy-upland crop rotations and nitrogen fertilizer levels on CH_4 emission in the middle and lower reaches of the Yangtze River[J]. *Chinese Journal of Applied Ecology*, 2019, 52(14): 2484-2499.

[48] 胡安永, 孙 星, 刘 勤. 太湖地区不同轮作模式对稻田温室气体(CH_4和N_2O)排放的影响[J]. 应用生态学报, 2016, 27(1): 99-106.

HU An-yong, SUN Xing, LIU Qin. Effects of different rotation systems on greenhouse gas (CH_4 and N_2O) emissions in the Taihu Lake region,China[J]. *Chinese Journal of Applied Ecology*, 2016, 27(1): 99-106.

[49] Mukesh K A, Yumin D, Sanjeev K A, et al. Influence of bamboo biochar on mitigating greenhouse gas emissions and nitrogen loss during poultry manure composting[J]. *Bioresource Technology*, doi:10.1016/j.biortech.2020.122952.

[50] 胡玉麟, 汤水荣, 陶 凯, 等. 优化施肥模式对我国热带地区水稻-豇豆轮作系统N_2O和CH_4排放的影响[J]. 环境科学, 2019, 40(11): 5182-5190.

HU Yu-lin, TANG Shu-rong, TAO Kai, et al. Effect of optimizing fertilization on N_2O and CH_4 emission in a paddy-cowpea rotation system in the tropical regions of China[J]. *Environmental Sciences*, 2019, 40 (11): 5182-5190.

[51] 郭腾飞, 梁国庆, 周 卫, 等. 施肥对稻田温室气体排放及土壤养分的影响[J]. 植物营养与肥料学报, 2016, 22(2): 337-345.

GUO Teng-fei, LIANG Guo-qing, ZHOU Wei, et al. Effects of fertilizer management on greenhouse gas emissions and nutrient status in paddy soil[J]. *Journal of Plant Nutrition and Fertilizers*, 2016, 22(2): 337-345.

[52] 柴凯斌. 秸秆还田对稻麦系统作物产量及温室气体排放的影响[D]. 武汉: 华中农业大学, 2018.

CHAI Kai-bin. The effect of straw incorporation on crop yield and greenhouse gas emission under rice-wheat cropping system[D]. Wuhan: Huazhong Agricultural University, 2018.

[53] Yang X, Shang Q, Wu P, et al. Methane emissions from double rice agriculture under long-term fertilizing systems in Hunan, China[J]. *Agriculture Ecosystems & Environment*, 2010, 137(3): 308-316.

[54] Ye R, Doane T A, Morris J, et al. The effect of rice straw on the priming of soil organic matter and methane production in peat soils[J]. *Soil Biology and Biochemistry*, 2015, 81: 98-107.

[55] 刘晓雨, 李志鹏, 潘根兴, 等. 长期不同施肥下太湖地区稻田净温室效应和温室气体排放强度的变化[J]. 农业环境科学学报, 2011, 30(9): 1783-1790.

LIU Xiao-yu, LI Zhi-peng, PAN Gen-xing, et al. Greenhouse gas emission and Cintensity for a long-term fertilization rice paddy in Tai Lake Region,China[J]. *Journal of Agro-Environment Science*, 2011, 30 (9): 1783-1790.

[56] Li J, Liu H, Wang H, et al. Managing irrigation and fertilization for the sustainable cultivation of greenhouse vegetables[J]. *Agricultural Water Management*, 2018, 210: 354-363.

[57] Zhang X, Davidson E A, Mauzerall D L, et al. Managing nitrogen for sustainable development[J]. *Nature*, 2015, 528: 51-59.

[58] Castellano M J, Schmidt J P, Kaye J P, et al. Hydrological and biogeochemical controls on the timing and magnitude of nitrous oxide flux across an agricultural landscape[J]. *Global Change Biology*, 2010, 16 (10): 2711-2720.

[59] Wang M, Xia X, Zhang Q, et al. Life cycle assessment of a rice production system in Taihu region, China[J]. *International Journal of Sustainable Development & World Ecology*, 2010, 17(2): 157-161.

[60] Jiang J Y, Jiang S S , Xu J Y, et al. Lowering nitrogen inputs and optimizing fertilizer types can reduce direct and indirect greenhouse gas emissions from rice-wheat rotation systems[J]. *European Journal of Soil Biology*, doi:10.1016/j.ejsobi.2020.103152.

[61] 徐 鹏, 蒋梦蝶, 邬 磊, 等. 华中地区水旱轮作模式下水稻季施氮肥对油菜季施氮肥土壤N_2O排放的影响[J]. 环境科学学报, 2018, 38(2): 365-371.

XU Peng, JIANG Meng-die, WU Lei, et al. Effect of nitrogen fertilizer during rice growing season on N_2O emission from the subsequent rapeseed season in central China[J]. *Acta Scientiae Circumstantiae,* 2018, 38(2): 365-371.

[62] Zheng X, Yao Z, Wang R, et al. A 3-year record of N_2O and CH_4 emissions from a sandy loam paddy during rice seasons as affected by different nitrogen application rates[J]. *Agriculture Ecosystems & Environment*, 2012, 152(3):1-9.

[63] 尹高飞. 有机肥替代对不同作物轮作模式下农田温室气体排放的影响[D]. 南京: 南京农业大学, 2019.

YIN Gao-fei. Effect of organic fertilizer substitution on greenhouse gas emissions from farmland in different crop rotation systems[D]. Nanjing: Nanjing Agricultural University, 2019.

[64] Yao Z, Zhou Z, Zheng X, et al. Effects of organic matter incorporation on nitrous oxide emissions from rice-wheat rotation ecosystems in China[J]. *Plant and Soil*, 2010, 327(1/2): 315-330.

[65] Zou J W, Huang Y, Jiang J Y, et al. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application[J]. *Global Biogeochemical Cycles*, 2005, 19(2): 1-9.

[66] 李喜喜. 猪粪施用对稻麦轮作系统温室气体排放的影响研究[D]. 雅安: 四川农业大学, 2016.

LI Xi-xi. Effect of pig manure application on greenhouse gas emissions from rice and wheat rotation system[D]. Ya′an: Sichuan Agricultural University, 2016.

[67] Li M, Xue L H, Zhou B B, et al. Effects of domestic sewage from different sources on greenhouse gas emission and related microorganisms in straw-returning paddy fields[J]. *Science of the Total Environment*, doi:10.1016/j.scitotenv.2020.137407.

[68] 吴家梅, 纪雄辉, 彭 华, 等. 不同有机肥对稻田温室气体排放及产量的影响[J]. 农业工程学报, 2018, 34(4): 162-169.

WU Jia-mei, JI Xiong-hui, PENG Hua, et al. Effects of different organic fertilizers on greenhouse gas emissions and yields in paddy soils [J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2018, 34(4): 162-169.

[69] 伍思平, 眭 锋, 肖小军, 等. 南方双季稻区不同复种方式对稻田综合温室效应的影响[J]. 核农学报, 2020,34(2): 376~382.

WU Si-ping, SUI Feng, XIAO Xiao-jun, et al. Effect in different multiple cropping pattern on the globle warming potential in southern double cropping rice fields[J]. *Journal of Nuclear Agricultural Sciences*, 2020, 34(2): 376-382 .

[70] 张岳芳, 周 炜, 陈留根, 等. 太湖地区不同水旱轮作方式下稻季甲烷和氧化亚氮排放研究[J]. 中国生态农业学报, 2013, 21(3): 290-296.

ZHANG Yue-fang, ZHOU Wei, CHEN Liu-gen, et al. Methane and nitrous oxide emission under different paddy-upland crop rotation systems during rice growth season in Taihu Lake Region[J]. *Chinese Journal of Eco-Agriculture*, 2013, 21(3): 290-296.

[71] 张岳芳, 郑建初, 陈留根, 等. 水旱轮作稻田旱作季种植不同作物对CH_4和N_2O排放的影响[J]. 生态环境学报, 2012, 21(9): 1521-1526.

ZHANG Yue-fang, ZHENG Jian-chu, CHEN Liu-gen, et al. Effects of different upland crops cultivation on CH_4 and N_2O emissions during upland-growing season from paddy rice-upland crop rotation field[J]. *Ecology and Environmental Sciences*, 2012, 21(9): 1521-1526.

[72] 杨 璐. 农田管理措施对稻田温室气体排放的影响分析[D]. 武汉: 华中农业大学, 2016.

YANG Lu. Management measures in paddy field and their effects on greenhouse gases emission[D]. Wuhan: Huazhong Agricultural University, 2016.

[73] 余庆福, 聂立孝. 麦—稻轮作系统中小麦施氮水平对后季直播水稻产量和氮肥利用效率的影响[J]. 南方农业学报, 2016(9):1488-1494.

YU Qing-fu, NIE Li-xiao. Effect of N application rates on grain yield and N-fertilizer utilization efficiency of succeeding direct-seeded rice in wheat-rice rotation systems[J]. *Journal of Southern Agriculture*, 2016, 47(9): 1488-1494.

[74] 孟宇辉, 金文俊, 董召荣, 等. 江淮地区不同水旱轮作模式的资源利用效率与经济效益比较[J]. 生态学杂志, 2019, 38(11): 3357-3365.

MENG Yu-hui, JIN Wen-jun, DONG Zhao-rong, et al. Comparison of resource utilization efficiency and economic benefits of different paddy-upland rotation systems in Jianghuai region[J]. *Chinese Journal of Ecology*, 2019, 38(11): 3357-3365.