农业环境科学学报
JOURNAL OF AGRO-ENVIRONMENT SCIENCE
中文核心期刊/CSCD
请通过网上投稿系统投稿
网址：http://www.aes.org.cn

集约化菜地N_2O排放及减排——基于文献整合分析

吴震，陈安枫，朱爽阁，熊正琴

引用本文:
吴震, 陈安枫, 朱爽阁, 等. 集约化菜地N_2O排放及减排——基于文献整合分析[J]. 农业环境科学学报, 2020, 39(4): 707-714.

在线阅读 View online: https://doi.org/10.11654/jaes.2020-0018

吴　震,陈安枫,朱爽阁,等.集约化菜地N_2O排放及减排——基于文献整合分析[J].农业环境科学学报,2020,39(4):707-714.
WU Zhen, CHEN An-feng, ZHU Shuang-ge, et al. Assessing nitrous oxide emissions and mitigation potentials from intensive vegetable ecosystems in China: Meta-analysis[J]. *Journal of Agro-Environment Science*, 2020, 39(4): 707-714.

集约化菜地N_2O排放及减排
——基于文献整合分析

吴　震,陈安枫,朱爽阁,熊正琴*

(南京农业大学资源与环境科学学院,江苏省低碳农业和温室气体减排重点实验室,南京 210095)

摘　要:为了评估中国菜地生态系统N_2O排放及其减排潜力,通过搜集已发表的露天及温室菜地N_2O减排田间原位观测数据,利用整合分析方法,评估了减施氮肥、配施硝化抑制剂、有机肥替代、施用生物质炭和优化灌溉等几种措施在蔬菜生产中减排N_2O的潜力。结果表明:菜地中大量施用氮肥虽然增加蔬菜产量,但也显著增加了菜地N_2O排放。在高施氮下,与露天菜地相比,温室菜地降低N_2O排放系数和单位产量N_2O排放量。与当地常规管理措施相比,各种优化措施均可在不同程度上降低菜地N_2O排放,幅度分别为49.4%(减施氮肥)、33.2%(配施硝化抑制剂)、26.6%(有机肥替代)、29.1%(施用生物质炭)和34.3%(优化灌溉),平均达36.6%。在高施氮下,有机肥替代化肥能更有效地降低N_2O排放系数和单位产量N_2O排放量。菜地N_2O排放量随着氮肥减施率的增加而降低,在低施氮土壤中N_2O减排效果更好。优化灌溉在不同施氮量下对N_2O的减排效果相当,配施硝化抑制剂和施用生物质炭则在低施氮条件下N_2O减排效果更好。中国露天和温室菜地生态系统N_2O减排潜力大,减施氮肥、配施硝化抑制剂、有机肥替代、施用生物质炭和优化灌溉等几种措施均能有效降低N_2O排放。由于温室菜地集约化程度更高,N_2O减排效果明显。

关键词:菜地;氧化亚氮;氮肥;减排潜力;整合分析

中图分类号:X71;S181　　**文献标志码:**A　　**文章编号:**1672-2043(2020)04-0707-08　　doi:10.11654/jaes.2020-0018

Assessing nitrous oxide emissions and mitigation potentials from intensive vegetable ecosystems in China ——Meta-analysis

WU Zhen, CHEN An-feng, ZHU Shuang-ge, XIONG Zheng-qin*

(Jiangsu Key Laboratory of Low Carbon Agriculture and GHGs Mitigation, College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, China)

Abstract: In order to identify the contribution of vegetable production to nitrous oxide(N_2O) emissions and mitigation potentials in China, we assessed N_2O emissions from both fertilized open-field and greenhouse systems by integrating *in-situ* field observations from published literatures. A meta-analysis was conducted to investigate the effects of optimization measures such as nitrogen(N) reduction, nitrification inhibitor application, organic fertilizer substitution, biochar amendment and optimized irrigation on N_2O mitigation potentials for vegetable ecosystems. Results indicated that N fertilizer application significantly increased N_2O emissions though improved vegetable yield. Greenhouse production systems greatly decreased N_2O emission factors and yield-scaled N_2O emissions under high N amendment as compared to the open-field production system. Relative to the local farmer's practices, various optimization measures significantly decreased N_2O emissions to varying degrees, such as 49.4% for reduced N fertilization, 33.2% for nitrification inhibitor, 26.6% for organic fertilizer substitution, 29.1% for biochar amendment and 34.3% for optimized irrigation, being 36.6% by average. Organic fertilizer substitution decreased

收稿日期:2020-01-06　　**录用日期:**2020-03-24
作者简介:吴　震(1992—),男,山东枣庄人,博士研究生,从事碳氮循环与气候变化研究。E-mail:2017203050@njau.edu.cn
***通信作者:**熊正琴　E-mail:zqxiong@njau.edu.cn
基金项目:公益性行业科研专项(201503106);国家自然科学基金项目(41977078)
Project supported: The Special Fund for Scientific Research on Public Causes(201503106); The National Natural Science Foundation of China(41977078)

both N_2O emission factor and yield-scaled N_2O emissions, especially under high N application inputs. N_2O emissions decreased with the reduction of N fertilizer application rate while the N_2O mitigating effects showed greater potentials under low N inputs. Optimized irrigation decreased N_2O emissions across all N inputs, while nitrification inhibitor and biochar amendment had greater mitigation potentials under low N inputs. Various optimization measures such as nitrogen(N) reduction, nitrification inhibitor application, organic fertilizer substitution, biochar amendment and optimized irrigation manifested great potentials in mitigating N_2O emissions from both open-field and greenhouse vegetable ecosystems while maintaining yields in China. Due to the higher intensification, greenhouse vegetable ecosystems presented greater mitigation consequences.

Keywords: vegetable field; N_2O; nitrogen fertilization; mitigation potential; meta-analysis

我国蔬菜种植产业发展迅速,种植面积由1980年的316万 hm^2(占农作物总播种面积的2.2%)发展到2018年的2044万 hm^2(占农作物总播种面积的12.5%)[1]。我国蔬菜播种面积和产量均占世界总量的40%以上[2]。与传统露天菜地不同,温室蔬菜生产模式能够延长蔬菜生长季节,提高经济效益,解决蔬菜生产时空分布不均的矛盾,其经济产值已占蔬菜产业总产值的60%以上[1]。原农业部《全国种植业结构调整规划(2016—2020年)》提出,到2020年我国蔬菜面积要稳定在2100万 hm^2 左右,其中温室蔬菜要达到420万 hm^2 [3]。

作为当前低碳农业的评估指标,综合净温室效应是基于生命周期评价方法,计算农产品生产系统内各种温室气体排放与消纳之和,并以 CO_2 当量形式表达,评价对气候变化的单一影响[4]。通过田间实测计算,综合分析4种不同叶菜类蔬菜大棚复种体系下的综合净温室效应均以 N_2O 田间直接排放为主,净碳收支、CH_4 排放甚至农业措施碳排放所占比例均较低[5]。Zhou等[6]综合分析不同有机无机替代的蔬菜种植体系碳足迹、氮足迹及生态系统净经济效益后,提出氮肥等肥料生产和 N_2O 田间直接排放是蔬菜生产中碳足迹的主要环节。考虑到现有田间观测测定数据十分有限,本文关于菜地生态系统固碳减排的研究集中为对其 N_2O 田间直接排放及减排的整合分析。

我国2018年的农田氮肥总用量(不包括复合肥)已达2065万 t N[1],而菜地的氮肥投入量和复种指数远高于一般农田。据估计,露天和温室菜地每季氮肥投入量平均为201 kg N·hm^{-2} 和478 kg N·hm^{-2}[7],温室菜地的氮肥用量是露天菜地的2~5倍[2,8]。蔬菜生长过程中对氮肥的利用率仅为18%~33%,远低于玉米、小麦和水稻等大田作物[9]。过量的氮肥施用造成土壤中无机氮大量残留,最终通过氨挥发、淋洗和径流以及反硝化等途径损失[10]。譬如,菜地生态系统 N_2O 排放量远高于一般农田[11],占中国农田总排放的20.0%~21.4%[12]。Wang等[13]估计中国露天和温室菜地土壤 N_2O 排放量分别为2.62 kg N·hm^{-2} 和6.22 kg N·hm^{-2}。减施氮肥[14]、配施硝化抑制剂[14]、有机肥替代[6]、施用生物质炭[15]、优化灌溉[16]等被推荐为减缓菜地 N_2O 排放的优化措施。

本研究收集了中国菜地关于 N_2O 排放及各优化措施对菜地 N_2O 排放影响的田间原位观测数据,通过文献整合分析评估各优化措施对菜地 N_2O 排放的减缓效果,对于实现集约化蔬菜生产的可持续发展有重要的科学意义。

1 材料与方法

1.1 数据收集

从"中国知网"和"Web of Science"上收集关于菜地 N_2O 排放及减排的研究论文,分别以"氧化亚氮""蔬菜,菜地""nitrous oxide,N_2O"和"vegetable"为关键词,检索发表至2019年9月的研究文献。筛选标准为:(1)试验为田间原位观测且监测整个蔬菜生长期 N_2O 排放,有明确的 N_2O 累积排放量或者可通过文中数据计算获得;(2)试验同时设置对照组和处理组,对照组为常规管理措施,处理组为减施氮肥、有机肥替代、配施硝化抑制剂、施用生物质炭或优化灌溉等优化减排措施;(3)有明确的氮肥用量。最终获得 N_2O 排放及减排措施的田间原位观测论文50篇(见OSID码),包括211组有效数据。提取信息包括:对照组和试验组 N_2O 排放量平均值、标准差和样本量,未施氮空白处理 N_2O 排放量、蔬菜产量、氮肥类型、施氮量、试验时间、种植类型(露天菜地、温室菜地)。N_2O 累积排放量以N计,单位为kg N·hm^{-2};氮肥用量以N计,单位为kg N·hm^{-2};蔬菜产量为鲜质量,单位为t·hm^{-2}。

1.2 整合分析方法

以各优化措施作为处理组,常规管理措施作为对照组,利用MetaWin 2.1软件进行整合分析,其效应值计算如下:

$$\ln R=\ln(x_t/x_c)$$

式中:R为效应比;$\ln R$为效应值;x_t和x_c分别为处理组和对照组N_2O排放量。

经检验,效应值$\ln R$近似满足正态分布,其方差计算如下:

$$v=\frac{S_t^2}{n_t x_t^2}+\frac{S_c^2}{n_c x_c^2}$$

式中:v为效应值方差;S_t和S_c分别为处理组和对照组的标准差;n_t和n_c分别为处理组和对照组的重复数。

选取随机效应模型计算每一组数据的平均效应值和95%置信区间。当任一效应值的95%置信区间与0重叠时,表明试验组和对照组没有差异;反之,则认为处理组对该指标的影响具有统计学意义。各优化措施对N_2O的减排潜力计算如下:

$$M=[\exp(\ln R)-1]\times 100\%$$

式中:M表示与对照组相比,处理组N_2O排放量的变化率,%;负变化率则转换为正值,表示对N_2O的减排潜力。

若研究同时监测未施氮空白处理N_2O排放量,则计算N_2O排放系数如下:

$$N_2O\text{排放系数}=(N_2O_f-N_2O_c)/N_f\times 100\%$$

式中:N_2O_f和N_2O_c分别表示施氮和未施氮处理中N_2O累积排放量,$kg\ N\cdot hm^{-2}$;N_f表示氮肥施用量,$kg\ N\cdot hm^{-2}$。

若研究同时报道蔬菜产量,则计算单位产量N_2O排放量($kg\cdot t^{-1}$)如下:

单位产量N_2O排放量=N_2O累积排放量/蔬菜产量

利用各研究中常规处理即对照组N_2O排放量、施氮量、产量和观测周期,计算中国菜地N_2O年排放量、年施氮量和产量。

1.3 统计分析

利用MetaWin 2.1整合分析,利用Origin 2018对数据进行正态分布、线性拟合及图片制作,采用SPSS 22独立样本t检验进行指标间的差异分析,采用单因素和Tukey′s HSD法进行方差分析和多重比较(α=0.05)。

2 结果与分析

2.1 菜地生态系统N_2O排放规律

在当地常规管理措施下,露天菜地的年均氮肥用量为1383 $kg\ N\cdot hm^{-2}$(506~5400 $kg\ N\cdot hm^{-2}$),而温室菜地为2003 $kg\ N\cdot hm^{-2}$(177~4650 $kg\ N\cdot hm^{-2}$),年均蔬菜产量和N_2O累积排放量均随着氮肥用量的增加而增加,然而N_2O排放系数和单位产量N_2O排放量没有随着氮肥水平而发生显著变化(图1)。图2则是综合考虑了各优化措施的所有处理,表明露天菜地和温室菜地N_2O排放系数在实际施氮量<500 $kg\ N\cdot hm^{-2}$时基本相同,且露天菜地N_2O排放系数随着施氮量增加而增加,而温室菜地N_2O排放系数在不同施氮量下基本相同(图2a)。同时露天菜地单位产量N_2O排放量随着施氮量增加而增加,且在施氮量>1000 $kg\ N\cdot hm^{-2}$时,露天菜地单位产量N_2O排放量高于温室菜地(P<0.01)(图2c)。无机肥施用下N_2O排放系数随着施用量增加而增加;与无机肥相比,有机肥或有机无机配施降低了高氮肥投入下(>1000 $kg\ N\cdot hm^{-2}$)的N_2O排放系数(P<0.01)(图2b)。此外,无机和有机肥施用下单位产量N_2O排放量均随着氮肥用量增加而增加(图2d)。

2.2 优化措施对菜地生态系统N_2O的减排潜力

总体而言,各优化措施对菜地生态系统N_2O累积排放量的影响效应值$\ln R$符合正态分布。各优化措施处理与对照处理N_2O排放量呈显著正相关;同时其线性相关的斜率显著小于1,表明各优化措施显著影响菜地生态系统N_2O排放(图3)。

如图4所示,减施氮肥(共69组)、配施硝化抑制剂(共46组)、有机肥替代(共21组)、施用生物质炭(共45组)和优化灌溉(共30组)均能有效减少菜地生态系统N_2O排放,平均减排潜力为36.6%。减施氮肥整体上降低菜地生态系统N_2O排放达到49.4%,且随着氮肥施用量的减少,其N_2O减排率增高;配施硝化抑制剂双氰胺(DCD)和2-氯-6-三氯甲基吡啶(CP)的减排幅度分别达到43.6%和22.4%;相对于单施化肥,有机肥替代显著降低N_2O排放达19.7%;施用生物质炭降低N_2O排放29.1%,生物质炭用量为30 $t\cdot hm^{-2}$时减排潜力最高,达到58.9%;与传统灌溉相比,优化灌溉减排N_2O达34.3%。

不同施氮量下各优化措施对N_2O排放的影响不同(图5)。减施氮肥、配施硝化抑制剂或生物质炭在低施氮下(<500 $kg\ N\cdot hm^{-2}$)减排效果较好,而优化灌溉在不同施氮量下减排潜力相当。

3 讨论

3.1 氮肥在蔬菜生产和N_2O排放中的关键作用

氮素是促进植物生长和维持产量的必需营养元素。我国蔬菜种植种类繁多,其生长特点和需肥规律各不相同,但由于蔬菜生长周期短,且复种指数高,因

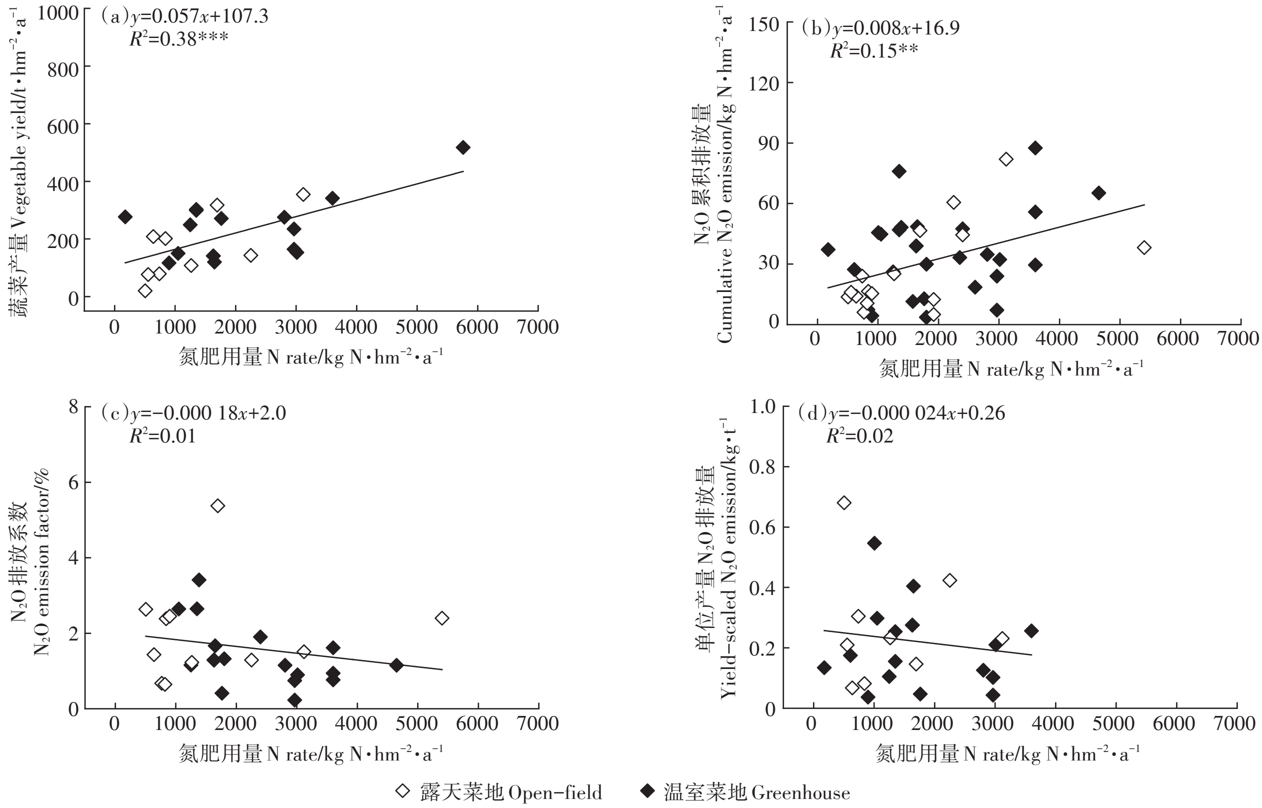


图1 常规管理措施下菜地氮肥用量与蔬菜产量、N_2O排放量、N_2O排放系数和单位产量N_2O排放量的线性回归分析

Figure 1 Relationship between N application rate and vegetable yield, cumulative N_2O emission, N_2O emission factor, and yield-scaled N_2O emission under local farmer's practices

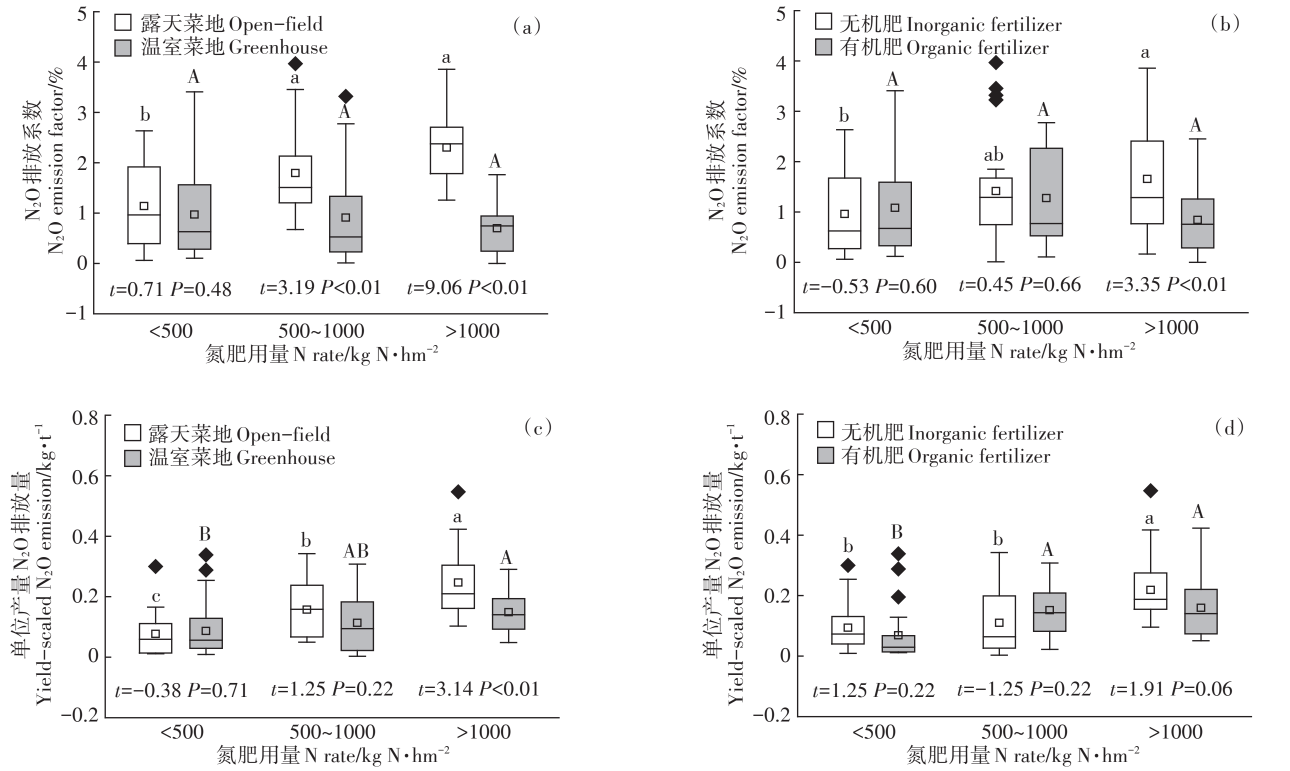
此大量频繁施用氮肥成为蔬菜高产的保障。如图1a所示，农民习惯施肥中，蔬菜产量随着氮肥施用量的增加而增加，但是在低氮用量和未施氮肥的处理中也可获得较高的产量。这可能是由于蔬菜生长过程中对氮肥的利用率低[9]，土壤中残留的氮肥仍可被下季蔬菜吸收利用。过量施氮非但不会增产，反而可能减产[10]。土壤N_2O排放随施氮量增加呈线性增加（图1b），也有研究认为N_2O排放与施氮量呈非线性增加关系[17]。

温室菜地因有更高的施肥和灌溉量而被认为其N_2O排放量会更高[13]。尽管温室菜地背景排放和施肥引起的N_2O排放比露天菜地高1.3~1.5倍，但由于温室菜地施氮量比露天菜地高1.7倍，使得温室菜地N_2O排放系数低于露天菜地，特别是在施肥量大于500 kg N·hm^{-2}时（图2a）。Gerber等[18]研究也发现，增加氮肥投入并不会增加单位施肥量的N_2O排放。综合考虑蔬菜产量和菜地N_2O排放，在氮肥投入大于500 kg N·hm^{-2}下，温室菜地单位产量N_2O排放量低于露天菜地（图2c）。因此，与露天菜地相比，高氮肥投入的温室菜地在获得更高产量的同时，能降低单位产量N_2O排放。

3.2 各优化措施对菜地生态系统N_2O的减排潜力

3.2.1 减施氮肥

施用氮肥是保证蔬菜产量的重要手段，但在我国蔬菜生产中过量施氮已成为普遍现象[10]。如图1所示，最高施氮量已远超1000 kg N·hm^{-2}。过量氮肥会造成巨大的农田N_2O排放，Song等[19]在我国华北平原研究表明，N_2O排放量与施氮量呈指数增加关系。蔬菜对土壤氮素的吸收能力有限，长期集约化种植导致菜地土壤无机氮本底值较高，而减氮后足以满足蔬菜生长对氮素的需求[14]，减施氮肥是直接降低菜地N_2O排放的措施。Zhang等[20]也发现菜地施氮量减少三分之一，能有效降低菜地单位产量N_2O排放量，这与本研究结果一致（图4b）。在菜地中实施减量施氮、合理优化施肥是有效降低集约化菜地N_2O排放的生产方式。



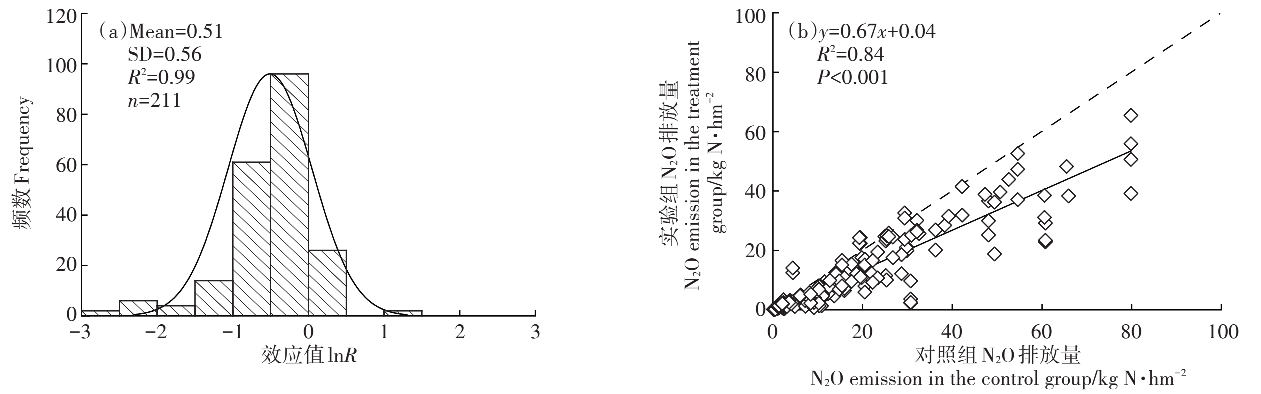
黑色方框和实线分别代表中位数和平均数，方框边界代表上下四分位数，上下横线代表最大值和最小值，黑点代表异常值

t值表示独立样本t检验结果，不同字母表示同一组内差异显著（P<0.05）

Black square and lines indicate medians and means, respectively. Box boundaries indicate upper and lower quartiles, whisker caps indicate maximum and minimum values, and spots indicate outliers. The t values were obtained from independent sample t tests, and different letters meant significant difference at α=0.05 level within each group

图2 综合分析露天*vs*温室菜地以及无机肥*vs*有机肥不同氮肥用量下N_2O排放系数和单位产量N_2O排放量

Figure 2 Integrative analyses of N_2O emission factor and yield-scaled N_2O emission as affected by N application rate in the open-field *vs* greenhouse system or inorganic *vs* organic N fertilization



图(a)中Mean为平均值，SD为标准差，n为数据数量；图(b)中虚线表示优化措施与对照组试验的1∶1理论线，细实线表示所有观测数据的线性回归线

Figure(a) Mean, SD and n indicate mean value, standard deviation and number, respectively; Figure(b) the dotted line represents the theoretical 1∶1 line, whereas the solid line represents the linear regression for all individual observations

图3 本研究中所有效应值的频率分布以及实验组与对照组N_2O排放量的线性回归

Figure 3 Frequency distributions of the effect size classes among all observations and the relationship of cumulative N_2O emissions between the treatments and the controls

3.2.2 配施硝化抑制剂

硝化抑制剂调控氮素生物化学循环[21]，抑制土壤微生物的硝化作用和反硝化作用，减少硝态氮淋失和硝化及反硝化过程中N_2O排放[22-24]。除了常用的化学

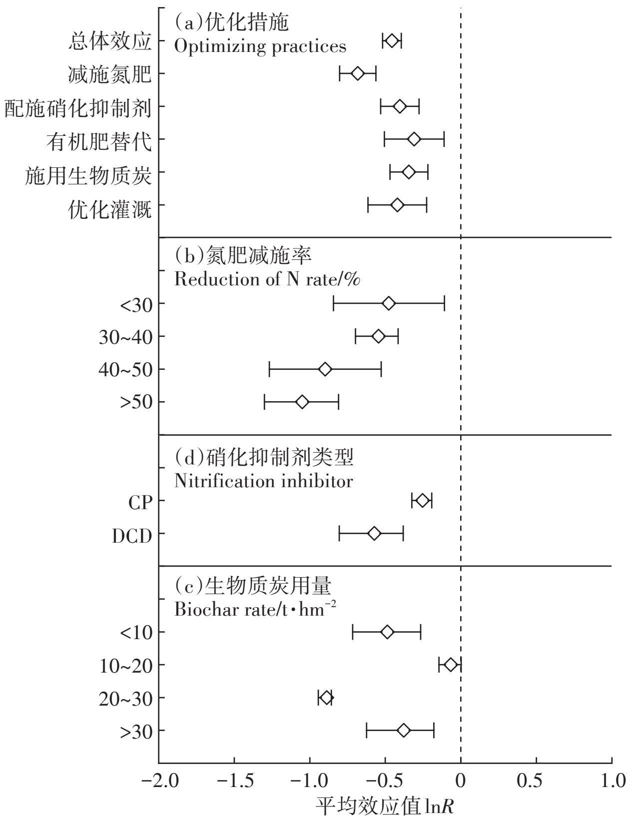
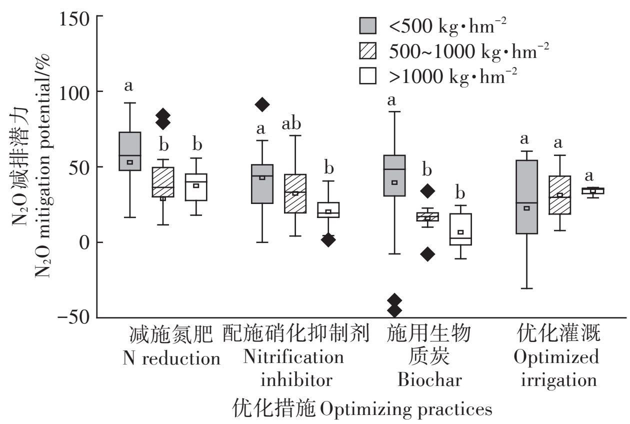


图4 各优化措施对菜地生态系统N_2O排放量的影响

Figure 4 Responses of cumulative N_2O emissions to various optimizing practices in vegetable ecosystems



不同字母表示同一组内差异显著(P<0.05)

Different letters indicate significant difference at α=0.05 level within each group

图5 不同施肥量下各优化措施对N_2O的减排潜力

Figure 5 N_2O mitigation potentials in various optimizing practices as affected by different N application rates

硝化抑制剂,生物硝化抑制剂也表现出与化学硝化抑制剂同等的N_2O减排效果[25]。

本文整合46组配施硝化抑制剂DCD和CP在菜地的应用数据,表明其降低N_2O排放幅度达33.2%。前人研究也发现配施硝化抑制剂在旱地、水田和草原等各种生态系统中降低N_2O排放达38%[26]。李双双[27]通过同位素自然丰度映射方法结合分子生物学方法,表明配施硝化抑制剂既可以降低施肥和灌溉之后硝化或真菌反硝化所产生的N_2O,也可降低细菌反硝化或硝化细菌反硝化所产生的N_2O。本研究还表明配施硝化抑制剂在低施氮下对N_2O排放的抑制效果更好(图5),说明减施氮肥结合配施硝化抑制剂具有更大的N_2O减排潜力[14, 17]。

3.2.3 有机肥替代

施用有机肥对保障农业可持续发展具有重要作用[28]。施用高C/N有机肥不仅为土壤中微生物提供碳源,增加土壤C/N和微生物对土壤无机氮的固持[29];同时有机肥替代无机氮肥,使得微生物可以直接利用的无机氮量减少,降低各种形式的氮素损失[30];从而降低硝化作用和反硝化作用底物有效性[31],影响微生物活动和N_2O排放[32]。本研究表明施用有机肥或有机无机肥配施显著降低菜地N_2O排放达26.6%(图4)。与单施化肥相比,有机肥或有机无机肥配施在高氮肥投入下降低N_2O排放系数(图2b)。同时,施用有机肥还能直接增加菜地土壤固碳量,进一步减缓气候变化[6,28-29]。

3.2.4 生物质炭添加

生物质炭是由作物秸秆、木屑或工农业中的有机废弃物在限氧或无氧下高温热分解的固体残留物,其含碳丰富,对改良土壤、提高作物产量和缓解全球变暖等有着重要作用[33]。生物质炭由于对铵态氮的吸附作用,可降低氮肥施入后的底物有效性[15,33]。同时生物质炭促进反硝化作用中N_2O进一步还原为N_2,导致反硝化产物N_2O/(N_2O+N_2)的比值降低而抑制N_2O产生[34]。由于蔬菜地灌溉频繁,反硝化是菜地土壤中N_2O的主要产生路径[35];Liu等[36]发现在反硝化主导N_2O产生的土壤中,生物质炭具有较好的减排效果;同时,生物质炭提高集约化蔬菜生产中的氮素利用率,增加蔬菜产量,降低单位产量的N_2O排放量[15]。

施用生物质炭对农田土壤N_2O排放影响不一,对N_2O减排率变化范围大,模拟实验和大田试验整合分析结果分别为54.0%[37]、30.9%[38]和12.4%[39]。这与生物质炭类型、生产过程、农田土壤类型和水肥管理等有关[37-38]。本研究生物质炭对中国菜地N_2O的减排率达到29%,与Borchard等[40]对全球谷物和蔬菜种植中生物质炭的N_2O减排率结果一致。

3.2.5 优化灌溉

土壤含水量影响土壤通气状况、微生物活性，进而影响土壤中N_2O产生、消耗和传输过程。频繁灌溉是蔬菜种植的一大特点，土壤湿度是影响N_2O排放的主要因素[41]。由于我国水资源供需矛盾突出，传统大水漫灌的模式不仅水肥利用效率低，而且增加土壤N_2O排放[41]，主要是传统大水漫灌模式下干湿交替促使土壤硝化和反硝化作用交替进行[42-43]，进一步增加反硝化作用产生的N_2O[44]。高灌溉菜地N_2O排放通量远高于低灌溉菜地[45]。优化灌溉可实现水肥一体化，适时、适量地满足农作物对水分和养分的需求，在保持或增加产量的前提下，既节水节肥又减排，是值得推荐的技术[16]。

4　结论

（1）中国菜地氮肥投入高，虽增加产量，却显著增加N_2O排放和单位产量N_2O排放量。

（2）与常规施肥措施相比，蔬菜生产中减施氮肥、配施硝化抑制剂、有机肥替代、施用生物质炭和优化灌溉等优化措施均能有效降低N_2O排放，平均减排幅度达36.6%。

（3）与露天菜地相比，温室菜地集约化生产程度更高，施肥量、产量和N_2O总排放量均高，其优化减排措施带来的减排效果更明显，N_2O排放系数和单位产量N_2O排放量较低。

参考文献：

[1] 中华人民共和国统计局. 中国统计年鉴[M]. 北京：中国统计出版社, 2019.
National Bureau of Statistics of the People's Republic of China. China statistical yearbook[M]. Beijing：China Statistic Press, 2019.

[2] 黄绍文, 唐继伟, 李春花, 等. 我国蔬菜化肥减施潜力与科学施用对策[J]. 植物营养与肥料学报, 2017, 23(6)：1480-1493.
HUANG Shao-wen, TANG Ji-wei, LI Chun-hua, et al. Reducing potential of chemical fertilizers and scientific fertilization countermeasure in vegetable production in China[J]. *Journal of Plant Nutrition and Fertilizers*, 2017, 23(6)：1480-1493.

[3] 农业部种植业管理司. 全国种植业结构调整规划（2016—2020年）[R]. 2016-04-28.
Ministry of Agriculture and Rural Affairs. National structural adjustment plan for planting industry（2016—2020）[R]. 2016-04-28.

[4] 熊正琴, 张晓旭. 氮肥高效施用在低碳农业中的关键作用[J]. 植物营养与肥料学报, 2017, 23(6)：1433-1440.
XIONG Zheng-qin, ZHANG Xiao-xu. Key role of efficient nitrogen application in low carbon agriculture[J]. *Journal of Plant Nutrition and Fertilizers*, 2017, 23(6)：1433-1440.

[5] Jia J, Ma Y, Xiong Z. Net ecosystem carbon budget, net global warming potential and greenhouse gas intensity in intensive vegetable ecosystems in China[J]. *Agriculture, Ecosystems & Environment*, 2012, 150：27-37.

[6] Zhou J, Li B, Xia L, et al. Organic-substitute strategies reduced carbon and reactive nitrogen footprints and gained net ecosystem economic benefit for intensive vegetable production[J]. *Journal of Cleaner Production*, 2019, 225：984-994.

[7] Ti C, Luo Y, Yan X. Characteristics of nitrogen balance in open-air and greenhouse vegetable cropping systems of China[J]. *Environmental Science and Pollution Research*, 2015, 22(23)：18508-18518.

[8] Hu W, Zhang Y, Huang B, et al. Soil environmental quality in greenhouse vegetable production systems in eastern China：Current status and management strategies[J]. *Chemosphere*, 2017, 170：183-195.

[9] Song X, Zhao C, Wang X, et al. Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China[J]. *Comptes Rendus Biologies*, 2009, 332(4)：385-392.

[10] 巨晓棠, 谷保静. 我国农田氮肥施用现状、问题及趋势[J]. 植物营养与肥料学报, 2014, 20(4)：783-795.
JU Xiao-tang, GU Bao-jing. Status-quo, problem and trend of nitrogen fertilization in China[J]. *Journal of Plant Nutrition and Fertilizer*, 2017, 23(6)：1480-1493.

[11] Duan P, Zhou J, Feng L, et al. Pathways and controls of N_2O production in greenhouse vegetable production soils[J]. *Biology and Fertility of Soils*, 2019, 55(3)：285-297.

[12] Wang J, Xiong Z, Yan X. Fertilizer-induced emission factors and background emissions of N_2O from vegetable fields in China[J]. *Atmospheric Environment*, 2011, 45(38)：6923-6929.

[13] Wang X, Zou C, Gao X, et al. Nitrous oxide emissions in Chinese vegetable systems：A meta-analysis[J]. *Environmental pollution*, 2018, 239：375-383.

[14] 陈　浩, 李　博, 熊正琴. 减氮及硝化抑制剂对菜地氧化亚氮排放的影响[J]. 土壤学报, 2017, 54(4)：938-947.
CHEN Hao, LI Bo, XIONG Zheng-qin. Effects of N reduction and nitrifcation inhibitor on N_2O emissions in intensive vegetable field[J]. *Acta Pedologica Sinica*, 2017, 54(4)：938-947.

[15] Li B, Bi Z, Xiong Z. Dynamic responses of nitrous oxide emission and nitrogen use efficiency to nitrogen and biochar amendment in an intensified vegetable field in southeastern China[J]. *Global Change Biology Bioenergy*, 2017, 9(2)：400-413.

[16] 江雨倩, 李　虎, 王艳丽, 等. 滴灌施肥对设施菜地N_2O排放的影响及减排贡献[J]. 农业环境科学学报, 2016, 35(8)：1616-1624.
JIANG Yu-qian, LI Hu, WANG Yan-li, et al. Effects of fertigation on N_2O emissions and their mitigation in greenhouse vegetable fields[J]. *Journal of Agro-Environment Science*, 2016, 35(8)：1616-1624.

[17] Chen H, Zhou J, Li B, et al. Yield-scaled N_2O emissions as affected by nitrification inhibitor and overdose fertilization under an intensively managed vegetable field: A three-year field study[J]. *Atmospheric Environment*, 2019, 206C: 247-257.

[18] Gerber J, Carlson K, Makowski D, et al. Spatially explicit estimates of N_2O emissions from croplands suggest climate mitigation opportunities from improved fertilizer management[J]. *Global Change Biology*, 2016, 22(10)：3383-3394.

[19] Song X, Liu M, Ju X, et al. Nitrous oxide emissions increase exponentially when optimum nitrogen fertilizer rates are exceeded in the North

China plain[J]. *Environmental Science & Technology*, 2018, 52(21): 12504-12513.
[20] Zhang M, Chen Z Z, Li Q L, et al. Quantitative relationship between nitrous oxide emissions and nitrogen application rate for a typical intensive vegetable cropping system in southeastern China[J]. *CLEAN-Soil, Air, Water*, 2016, 44(12):1725-1732.
[21] Di H, Cameron K. How does the application of different nitrification inhibitors affect nitrous oxide emissions and nitrate leaching from cow urine in grazed pastures?[J]. *Soil Use and Management*, 2012, 28(1): 54-61.
[22] Moir J, Malcolm B, Cameron K, et al. The effect of dicyandiamide on pasture nitrate concentration, yield and N offtake under high N loading in winter and spring[J]. *Grass and Forage Science*, 2012, 67(3): 391-402.
[23] Pfab H, Palmer I, Buegger F, et al. Influence of a nitrification inhibitor and of placed N-fertilization on N_2O fluxes from a vegetable cropped loamy soil[J]. *Agriculture, Ecosystems & Environment*, 2012, 150:91-101.
[24] 张苗苗, 沈菊培, 贺纪正, 等. 硝化抑制剂的微生物抑制机理及其应用[J]. 农业环境科学学报, 2014, 33(11):2077-2083.
ZHANG Miao-miao, SHEN Ju-pei, HE Ji-zheng, et al. Microbial mechanisms of nitrification inhibitors and their application[J]. *Journal of Agro-Environment Science*, 2014, 33(11):2077-2083.
[25] Zhang M, Fan C H, Li Q L, et al. A 2-yr field assessment of the effects of chemical and biological nitrification inhibitors on nitrous oxide emissions and nitrogen use efficiency in an intensively managed vegetable cropping system[J]. *Agriculture, Ecosystems & Environment*, 2015, 201:43-50.
[26] Akiyama H, Yan X, Yagi K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis[J]. *Global Change Biology*, 2010, 16(6):1837-1846.
[27] 李双双. 施用硝化抑制剂对菜地土壤N_2O排放特征的影响研究[D]. 南京:南京农业大学, 2019:54-57.
LI Shuang-shuang. The effects of nitrification inhibitors on nitrous oxide emissions from vegetable yields[D]. Nanjing: Nanjing Agricultural University, 2019:54-57.
[28] 朱兆良. 中国土壤氮素研究[J]. 土壤学报, 2008, 45(5):778-783.
ZHU Zhao-liang. Research on soil nitrogen in China[J]. *Acta Pedologica Sinica*, 2008, 45(5):778-783.
[29] Xia L, Lam S K, Yan X, et al. How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? [J]. *Environmental Science & Technology*, 2017, 51(13):7450-7457.
[30] 毕智超, 张浩轩, 房 歌, 等. 不同配比有机无机肥料对菜地N_2O排放的影响[J]. 植物营养与肥料学报, 2017, 23(1):154-161.
BI Zhi-chao, ZHANG Hao-xuan, FANG Ge, et al. Effects of combined organic and inorganic fertilizers on N_2O emissions in intensified vegetable field[J]. *Journal of Plant Nutrition and Fertilizers*, 2017, 23(1):154-161.
[31] Wang J, Zhu B, Zhang J, et al. Mechanisms of soil N dynamics following long-term application of organic fertilizers to subtropical rain-fed purple soil in China[J]. *Soil Biology and Biochemistry*, 2015, 91:222-231.
[32] 陈 晨, 许 欣, 毕智超, 等. 生物炭和有机肥对菜地土壤N_2O排放及硝化, 反硝化微生物功能基因丰度的影响[J]. 环境科学学报, 2017, 37(5):1912-1920.
CHEN Chen, XU Xin, BI Zhi-chao, et al. Effects of biochar and organic manure on N_2O emissions and the functional gene abundance of nitrification and denitrification microbes under intensive vegetable production[J]. *Acta Scientiae Circumstantiae*, 2017, 37(5):1912-1920.
[33] Sohi S, Krull E, Lopez-Capel E, et al. A review of biochar and its use and function in soil[J]. *Advances in Agronomy*, 2010, 105:47-82.
[34] Cayuela M L, Sánchez-Monedero M A, Roig A, et al. Biochar and denitrification in soils: When, how much and why does biochar reduce N_2O emissions?[J]. *Scientific Reports*, 2013, 3:1732.
[35] Shi X, Hu H, Zhu-Barker X, et al. Nitrifier-induced denitrification is an important source of soil nitrous oxide and can be inhibited by a nitrification inhibitor 3, 4-dimethylpyrazole phosphate[J]. *Environmental Microbiology*, 2017, 19(12):4851-4865.
[36] Liu Q, Zhang Y, Liu B, et al. How does biochar influence soil N cycle? A meta-analysis[J]. *Plant and Soil*, 2018, 426(1/2):211-225.
[37] Cayuela M, Van Zwieten L, Singh B, et al. Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis[J]. *Agriculture, Ecosystems & Environment*, 2014, 191:5-16.
[38] He Y, Zhou X, Jiang L, et al. Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis[J]. *Global Change Biology Bioenergy*, 2017, 9(4):743-755.
[39] Verhoeven E, Pereira E, Decock C, et al. Toward a better assessment of biochar-nitrous oxide mitigation potential at the field scale[J]. *Journal of environmental quality*, 2017, 46(2):237-246.
[40] Borchard N, Schirrmann M, Cayuela M L, et al. Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis[J]. *Science of the Total Environment*, 2019, 651: 2354-2364. doi:10.1016/j.scitotenv.2018.10.060.
[41] 韩 冰, 叶旭红, 张西超, 等. 不同灌溉方式设施土壤N_2O排放特征及其影响因素[J]. 水土保持学报, 2016, 30(5):310-315.
HAN Bing, YE Xu-hong, ZHANG Xi-chao, et al. Characteristics of soil nitrous oxide emissions and influence factors under different irrigation managements from greenhouse soil[J]. *Journal of Soil and Water Conservation*, 2016, 30(5):310-315.
[42] Cheng Y, Wang J, Zhang J B, et al. Mechanistic insights into the effects of N fertilizer application on N_2O-emission pathways in acidic soil of a tea plantation[J]. *Plant and Soil*, 2015, 389(1/2):45-57.
[43] Borken W, Matzner E. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils[J]. *Global Change Biology*, 2009, 15(4):808-824.
[44] Sánchez-Martín L, Arce A, Benito A, et al. Influence of drip and furrow irrigation systems on nitrogen oxide emissions from a horticultural crop[J]. *Soil Biology and Biochemistry*, 2008, 40(7):1698-1706.
[45] 丁军军, 张 薇, 李玉中, 等. 不同灌溉量对华北平原菜地N_2O排放及其来源的影响[J]. 应用生态学报, 2017, 28(7):2269-2276.
DING Jun-jun, ZHANG Wei, LI Yu-zhong, et al. Effects of soil water condition on N_2O emission and its sources in vegetable farmland of North China Plain[J]. *Chinese Journal of Applied Ecology*, 2017, 28(7):2269-2276.