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——庆祝厦门大学环境学科创立40周年



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中国旱作农田一氧化氮排放及减排: Meta 分析

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摘要: 农田是大气污染物一氧化氮(NO)的主要排放源之一。与水稻田相比,旱作农田 NO 排放量和排放系数高,但其异质性及影响因素尚不明确。目前,我国农田 NO 排放和减排的研究以原位观测为主,缺乏系统的整合(Meta)分析。通过收集文献数据,定量分析玉米-冬小麦、水稻-冬小麦旱地阶段、蔬菜、茶园和果园等旱作体系 NO 排放量和排放系数的异质性及主要影响因素;定量评价减量施氮、有机肥替代化肥、配施新型增效氮肥和施用生物质炭等管理措施对 NO 排放量和排放系数的影响。收集相关文献共计 49 篇(发表于 2006~2021 年)。结果表明,玉米轮作、茶园和果园体系年排放量平均值分别为 1.44、7.45 和 0.92 kg·hm⁻²,在这 3 个体系间有显著性差异($P < 0.05$),稻麦轮作旱地阶段和蔬菜季节排放量平均值分别为 2.13 kg·hm⁻²和 2.09 kg·hm⁻²。在玉米轮作、稻麦轮作旱地阶段和茶园体系中,NO 排放量均与施氮量呈正相关关系($P < 0.01$),但在蔬菜和果园体系中二者无显著相关性。玉米轮作、稻麦轮作旱地阶段、蔬菜、茶园和果园体系排放系数平均值分别为 0.31%、0.71%、0.96%、1.74%和 0.13%,除玉米轮作分别与稻麦轮作旱地阶段和蔬菜体系间的差异不显著外($P > 0.05$),在其余体系间均有显著性差异($P < 0.01$)。由于各体系间排放系数差异大,在编制区域或全国农田 NO 排放清单时,有必要对各作物体系采用不同的排放系数。减量施氮仅在减氮比例高于 25% 时可显著降低 NO 排放量(36%),但对排放系数的影响不显著。由于减氮比例过高可能会造成作物减产,尚需进一步确定既不影响作物产量又降低 NO 排放的减氮比例。有机肥替代化肥在土壤有机碳含量低[$\omega(\text{SOC}) < 15 \text{ g} \cdot \text{kg}^{-1}$]或酸性($\text{pH} < 7$)条件下以及配施新型增效氮肥在玉米轮作农田中可显著降低 NO 排放量(-46%~-38%)和排放系数(-62%~-45%),施用生物质炭的影响不显著。可为不同田间条件下分别采取有效的 NO 减排措施提供依据。

关键词: 一氧化氮(NO); 排放系数; 旱作农田; 减排措施; 整合分析

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Nitric Oxide Emissions from Chinese Upland Cropping Systems and Mitigation Strategies: A Meta-analysis

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Abstract: Agroecosystems are a significant source of nitric oxide (NO), a potent atmospheric pollutant. It has been well documented that the NO emissions from upland cropping systems and their emission factors are large relative to those from paddy fields. However, a clear understanding of their uncertainty and regulating factors is still lacking. To date, various field experiments have been conducted to investigate NO emissions and mitigation, providing an opportunity for a Meta-analysis. The aims of this study were to ① investigate the uncertainty and regulating factors of NO emissions and emission factors from maize-winter wheat rotations, non-waterlogging period in rice-winter wheat rotations, vegetable fields, tea plantations, and fruit orchards across China by extracting data from peer-reviewed publications, and ② quantify the mitigation potential of management practices, such as reducing nitrogen fertilizer input, organic substitution with chemical fertilizers, and application of enhanced-efficiency nitrogen fertilizers or biochar by performing a pairwise Meta-analysis. A total of 49 references (published from 2006 to 2021) were collected. The results showed that annual NO emissions from the maize-winter wheat rotations, tea plantations, and fruit orchards averaged 1.44, 7.45, and 0.92 kg·hm⁻², respectively, with significant differences among the three cropping systems ($P < 0.05$). The seasonal NO emissions from the non-waterlogging period in rice-winter wheat rotations and vegetable fields within a single growth period averaged 2.13 kg·hm⁻² and 2.09 kg·hm⁻², respectively. The NO emissions positively related to nitrogen inputs in the maize-winter wheat rotations, non-waterlogging period in rice-winter wheat rotations, and tea plantations ($P < 0.01$) but not in the vegetable fields and fruit orchards. The emission factors averaged 0.31%, 0.71%, 0.96%, 1.74%, and 0.13% in the maize-winter wheat rotations, non-waterlogging period in rice-winter wheat rotations, vegetable fields, tea plantations, and fruit orchards, respectively, with significant differences among the cropping systems ($P < 0.01$), except between the maize-winter wheat rotations and non-waterlogging period in rice-winter wheat rotations or vegetable fields ($P > 0.05$). Considering the substantial differences in emission factors among the cropping systems, a specific emission factor for each system should be applied when estimating an agricultural NO budget at a regional or national scale. Reducing nitrogen input only mitigated NO emissions (by 36%) at a reducing nitrogen ratio above 25% but did not impact emission factors. An optimal reducing nitrogen ratio has to be further evaluated without crop productivity penalties. Organic substitution in soils with organic carbon content $< 15 \text{ g} \cdot \text{kg}^{-1}$ or $\text{pH} < 7$ and application of enhanced-efficiency fertilizers in the maize-winter wheat rotation simultaneously mitigated NO emissions (by -46%~-38%) and emission factors (by -62%~-45%). By contrast, biochar amendment had no significant effects on either NO emissions or emission factors. These findings highlight a possibility of choosing an effective NO mitigation strategy under specific field conditions.

Key words: nitric oxide (NO); emission factor; upland cropping systems; mitigation strategy; Meta-analysis

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氮氧化物(NO_x)是气态污染物,可直接或间接危害人体健康和生态环境^[1]. NO_x 光化学活性强,是近地层臭氧浓度增加的前体物之一; NO_x 最终形成硝酸,是大气颗粒物、酸雨和氮沉降的主要成分. NO_x 主要来自于化石燃料和生物质燃烧;但在远离工业和交通源的农村地区,农田成为主要排放源^[2,3]. 农田排放的 NO_x 以一氧化氮(NO)为主,全球农田 NO 年排放量(以氮计)约为 $1.4 \sim 5.5 \text{ Tg}^{[2,3]}$. 农田 NO 减排对改善农村人居环境具有重要意义.

农田排放的 NO 主要由土壤微生物硝化和反硝化过程产生,化学反硝化过程仅在酸性条件下 ($\text{pH} < 5$) 贡献较大^[1]. 当土壤透气性较差时, NO 易通过反硝化过程被还原为氧化亚氮(N_2O). 因此, NO 排放量取决于土壤剖面中该气体产生和消耗的相对速率. 通常情况下,施用氮肥可触发 NO 脉冲式排放,总排放量与施氮量呈线性或指数增长关系^[4~6]. 排放系数(即由施肥引起的排放量与施氮量的百分比)是衡量 NO 排放的重要参数. 全球农田排放系数平均值约为 $0.5\%^{[3]}$,而实验点尺度的观测结果在 $0 \sim 28\%$ 之间^[3,7]. 排放系数极大的异质性主要是由于 NO 排放受到气候条件(如温度和降水)、土壤性质(如有机碳含量和 pH)和其它农田管理措施(如氮肥类型和作物种类)的共同影响^[1,3,7]. 已有统计结果显示我国水稻田排放系数平均值(0.04%)远低于旱作农田(0.67%),主要是由于水稻田土壤长期处于淹水状态,不利于 NO 产生和释放^[8]. 但是,旱作农田排放量和排放系数的异质性及影响因素仍不明确.

我国旱作农田主要包括玉米-冬小麦、水稻-冬小麦旱地阶段、蔬菜、果园和茶园等. 玉麦轮作分布于华北和华东地区,已有部分观测结果显示该体系 NO 排放量和排放系数较低^[9~11]. 稻麦轮作分布于长江中下游地区,尽管水稻生长期 NO 排放量低,但在旱地阶段仍有较高排放量^[12~14]. 蔬菜和果树种类多,在全国各地均有种植,其共同特点是施氮量高,具有 NO 高排放风险^[15~17]. 茶园主要分布于华

东、华南和西南地区的酸性土壤上,其 NO 排放机制与其它作物体系相比有较大差异^[18~20]. 目前,对 NO 排放的研究以实验点尺度的原位观测为主,研究较多的减排措施有减量施氮^[4,10,11]、有机肥替代化肥^[21~23]、配施新型增效氮肥^[24~26]和施用生物质炭^[18~20]等. 已有研究基于整合(Meta)分析综合考察 N_2O 和 NO 共同排放^[7,27],尚缺乏对 NO 排放和减排的系统分析. 本研究通过收集文献数据,定量分析我国旱作体系中 NO 排放量和排放系数的异质性及主要影响因素;定量评价田间管理措施对 NO 排放量和排放系数的影响,以期为 NO 减排提供基础数据支持.

1 材料与方法

1.1 数据收集

选取“氮氧化物”、“一氧化氮”、“nitrogen oxides”、“nitric oxide”和“ NO ”等为关键词,在中国知网和 Web of Science 数据库检索农田 NO 排放相关文献,筛选标准为:①必须为原位观测实验,排除土壤培养、盆栽实验和模型模拟结果;②实验地点和起止时间明确,时间跨度至少为 1 个完整生长季;③实验处理需包含 3 个及以上空间重复;④施氮量和氮肥类型明确,排除豆类作物. 最终收集到相关参考文献共计 49 篇(发表于 2006 ~ 2021 年). 作物体系包括玉麦轮作、稻麦轮作旱地阶段、蔬菜、茶园和果园等. 玉麦轮作、茶园和果园为 NO 年排放量,而稻麦轮作旱地阶段和蔬菜为季节排放量,各作物体系基本信息分别列于表 1 ~ 5. 文献提取信息包括实验地点、起止时间、土壤性质(有机碳含量和 pH)、施肥(传统氮肥类型和施氮量)、其它管理措施(新型增效氮肥和生物质炭)、 NO 排放量和排放系数等. 传统氮肥指化肥和有机肥,化肥包括尿素、复合肥、二铵 $[(\text{NH}_4)_2\text{HPO}_4]$ 、氯铵 (NH_4Cl) 、碳铵 $(\text{NH}_4\text{HCO}_3)$ 和硝酸钙 $[\text{Ca}(\text{NO}_3)_2]$ 等,有机肥包括动物粪肥、饼肥(油料残渣)和商业有机肥等. 新型增效氮肥包括脲酶抑制剂、硝化抑制剂和控释肥等.

表 1 玉米-冬小麦农田基本信息¹⁾

Table 1 Data sources of maize-winter wheat cropland												
地点	年份	$\omega(\text{SOC})$ /g·kg ⁻¹	pH	施氮量 /kg·hm ⁻²	氮肥类型		NO 排放量 /kg·hm ⁻²	排放系数 /%	新型 氮肥	生物 质炭	文献	
					化肥	有机肥						
山东	2008 ~ 2010	10.3	8.3	0 ~ 600	尿素和二铵	粪肥	0.29 ~ 3.09	0.1 ~ 0.47	有	—	[9,10]	
山东	2015 ~ 2016	17.3	7.8	0 ~ 600	尿素	—	0.49 ~ 2.65	0.28 ~ 0.35	—	—	[11]	
河北	2013 ~ 2015	8.9	8.1	0 ~ 425	氯铵和硝酸钙	—	0.01 ~ 3.26	0.35 ~ 0.74	有	—	[24,28]	
河南	2009 ~ 2019	6.1	8.3	0 ~ 420	尿素和二铵	粪肥	0.1 ~ 3.78	0.02 ~ 0.77	—	有	[29 ~ 31]	
山西	2007 ~ 2010	11.3	8.7	0 ~ 850	尿素和二铵	—	0.25 ~ 2.6	0.26 ~ 0.6	—	—	[4,6,32]	
陕西	2016 ~ 2019	15.8	8.1	0 ~ 353	尿素	粪肥	0.1 ~ 1.53	0.05 ~ 0.39	—	—	[21,22]	
江苏	2017 ~ 2019	3.3	8.3	0 ~ 600	尿素	—	0.04 ~ 0.35	0.03 ~ 0.05	有	—	[25]	
四川	2013 ~ 2014	5.1	8.2	0 ~ 280	碳铵	粪肥	-0.02 ~ 0.57	0.07 ~ 0.21	—	—	[33]	

1) “—”表示未设置该处理,下同

表 2 茶园基本信息

Table 2 Data sources of tea plantation

地点	年份	$\omega(\text{SOC})$ / $\text{g}\cdot\text{kg}^{-1}$	pH	施氮量 / $\text{kg}\cdot\text{hm}^{-2}$	氮肥类型		NO 排放量 / $\text{kg}\cdot\text{hm}^{-2}$	排放系数 /%	新型 氮肥	生物 质炭	文献
					化肥	有机肥					
江苏	2014 ~ 2019	21.4	4.5	0 ~ 450	复合肥	粪肥	1.44 ~ 8.34	0.2 ~ 1.14	—	有	[18,19]
江苏	2014 ~ 2016	17.3	4.7	0 ~ 300	复合肥	粪肥	1.18 ~ 9.81	2.17 ~ 2.65	—	有	[20]
江苏	2015 ~ 2016	24.1	4.4	0 ~ 150	尿素	粪肥和饼肥	1.42 ~ 4.64	0.03 ~ 2.15	—	有	[34]
湖北	2012 ~ 2014	12.9	5.0	0 ~ 450	尿素	饼肥	0.38 ~ 19.4	2.0 ~ 4.0	—	—	[35,36]
湖南	2013 ~ 2014	11.1	4.5	450	尿素	饼肥	2.2 ~ 5.2	—	—	—	[37]

表 3 果园基本信息

Table 3 Data sources of fruit orchard

地点	年份	$\omega(\text{SOC})$ / $\text{g}\cdot\text{kg}^{-1}$	pH	施氮量 / $\text{kg}\cdot\text{hm}^{-2}$	氮肥类型		NO 排放量 / $\text{kg}\cdot\text{hm}^{-2}$	排放系数 /%	新型 氮肥	生物 质炭	文献
					化肥	有机肥					
江苏	2013 ~ 2015	20.3 ~ 34.4	4.8	0 ~ 1006	尿素和复合肥	粪肥	0.15 ~ 2.0	0.02 ~ 0.3	—	—	[5]
江西	2013 ~ 2014	9.4	5.0	0 ~ 176	尿素和复合肥	—	2.28 ~ 3.19	0.52	—	—	[17]
海南	2009 ~ 2010	6.0 ~ 8.7	5.1 ~ 5.5	0 ~ 520	尿素	粪肥	0.01 ~ 0.13	0.001 ~ 0.02	—	—	[38]

表 4 水稻-冬小麦农田基本信息

Table 4 Data sources of rice-winter wheat cropland

地点	年份	$\omega(\text{SOC})$ / $\text{g}\cdot\text{kg}^{-1}$	pH	施氮量 / $\text{kg}\cdot\text{hm}^{-2}$	氮肥类型		NO 排放量 / $\text{kg}\cdot\text{hm}^{-2}$	排放系数 /%	新型 氮肥	生物 质炭	文献
					化肥	有机肥					
江苏	1996 ~ 2008	18.4	8.0	0 ~ 225	尿素和复合肥	—	0.11 ~ 2.05	0.23 ~ 0.83	—	—	[12 ~ 14]
	2011 ~ 2012	15.0 ~ 21.5	6.6 ~ 8.0	0 ~ 225	尿素和复合肥	—	0.16 ~ 9.5	0.12 ~ 3.97	—	—	[39]
	2011 ~ 2013	14.9	8.4	0 ~ 270	尿素和复合肥	—	0.91 ~ 7.98	0.28 ~ 2.62	有	—	[40,41]
	2011 ~ 2014	11.4 ~ 20.3	5.6 ~ 6.2	0 ~ 300	尿素和复合肥	—	0.1 ~ 4.16	0.07 ~ 0.60	有	有	[42 ~ 44]

表 5 蔬菜地基本信息

Table 5 Data sources of vegetable fields

地点	年份	$\omega(\text{SOC})$ / $\text{g}\cdot\text{kg}^{-1}$	pH	施氮量 / $\text{kg}\cdot\text{hm}^{-2}$	氮肥类型		NO 排放量 / $\text{kg}\cdot\text{hm}^{-2}$	排放系数 /%	新型 氮肥	生物 质炭	文献
					化肥	有机肥					
北京	2016	31.9	7.2	0 ~ 1200	尿素	粪肥	0.32 ~ 0.88	0.03 ~ 0.05	—	—	[15]
北京	2018 ~ 2019	17.0	7.2	0 ~ 1200	尿素	粪肥	0.09 ~ 0.96	0.03 ~ 0.09	—	—	[16]
山东	2010 ~ 2011	17.6	7.2	0 ~ 1186	尿素	粪肥	0.1 ~ 1.44	0.02 ~ 0.11	—	—	[45]
江苏	2003 ~ 2008	12.0	6.2	0 ~ 425	尿素	粪肥	0.03 ~ 19.3	0.05 ~ 28.1	—	—	[14,46]
	2007 ~ 2008	20.1	8.0	0 ~ 315	复合肥和尿素	—	0.09 ~ 1.3	0.16 ~ 0.57	—	—	[47]
	2007 ~ 2008	15.6	7.9	0 ~ 418	复合肥	饼肥	0.06 ~ 1.4	0.09 ~ 1.14	—	—	[47]
	2018	24.1	6.5	200	尿素	—	0.39	—	有	有	[26]
	2015 ~ 2016	13.0	5.6	0 ~ 180	尿素	粪肥,商品肥	0.48 ~ 1.92	-0.01 ~ 1.29	—	—	[48]
	2015 ~ 2016	14.3	5.1	0 ~ 500	尿素	粪肥	0.08 ~ 1.64	0.05 ~ 0.46	有	—	[23,49]
	2013 ~ 2014	15.2	5.5	0 ~ 520	复合肥	—	0.21 ~ 5.95	0.84 ~ 2.63	—	有	[50,51]
	2006	16.5	6.1	45 ~ 270	尿素	粪肥	0.27 ~ 30.2	—	—	—	[52,53]
湖南	2016	5.5	7.3	0 ~ 522	复合肥和碳铵	—	0.15 ~ 1.14	0.19	—	—	[54]
四川	2004 ~ 2006	17.5	7.4	0 ~ 200	复合肥	—	0.02 ~ 0.79	0.04 ~ 0.39	—	—	[55]
四川	2006 ~ 2008	16.0	8.4	0 ~ 150	复合肥	—	0.01 ~ 0.41	0.05 ~ 0.27	—	—	[55]

1.2 数据处理和统计分析

若文献同时报道施氮和未施氮处理 NO 排放量,则计算排放系数(EF_d)如下:

$$EF_d = (E_N - E_0) / FN \times 100\% \quad (1)$$

式中, E_N 和 E_0 分别为施氮和未施氮处理 NO 排放量($\text{kg}\cdot\text{hm}^{-2}$), FN 为施氮量($\text{kg}\cdot\text{hm}^{-2}$).

本研究仅分析传统施氮处理 NO 排放量和排放系数的异质性. 在确定排放量和施氮量的相关关系时纳入未施氮处理; 在 Meta 分析时纳入配施新型增效氮肥和施用生物质炭处理.

统计分析在 R 语言(版本号 3.6.3, <https://www.r-project.org/>)中完成. 采用单样本 Kolmogorov-Smirnov (K-S) 检验各作物体系 NO 排放量或排放系数是否满足正态分布($P > 0.05$), 数据异质性以变异系数(CV)表示. 采用双样本 K-S 检验各作物体系排放量或排放系数之间是否存在显著性差异($P < 0.05$). 由于各体系排放量计算时长差异大, 对排放量仅比较玉米轮作、茶园和果园的年排放量. 使用线性或非线性回归模型拟合排放量或排放系数与其它变量(如施氮量、土壤 pH 和有机碳

含量)的相关关系($P < 0.05$).

1.3 Meta 分析

对收集到的数据进行分组,分别检验不同田间条件下减量施氮、有机肥替代化肥、配施新型增效氮肥和施用生物质炭等管理措施的影响.为提高分析结果的代表性,每组中至少应包括3篇文献或3个地点的数据.为保证每组有足够且相对均匀的样本量,分组时:①减氮比例(即相对于该研究最高施氮量的减量比例)设置 $<25\%$ 和 $>25\%$ 这2个水平;②土壤pH设置 <7 和 >7 这2个水平;③土壤有机碳含量 $[\omega(\text{SOC})]$ 设置 $<15\text{ g}\cdot\text{kg}^{-1}$ 和 $>15\text{ g}\cdot\text{kg}^{-1}$ 这2个水平.受文献篇数和样本数的限制,分组时:①未区分化肥、有机肥或新型增效氮肥的类型;②未区分蔬菜类型;③有机肥处理未区分替代化肥的比例;④生物质炭未区分制备原料、工艺和性质等.

NO排放量或排放系数的效应值($\ln R$)计算如下:

$$\ln R = \ln(X_t/X_c) \quad (2)$$

式中, X_t 和 X_c 分别为处理组和对照组的排放量或排放系数.由于部分排放系数为0或负数(约占样本总数的1%),无法计算效应值,在数据分析时予以剔除.仅当各分组效应值满足正态分布($P > 0.05$)时,才进行下一步数据分析,否则该分组予以剔除.

选择处理重复数计算权重(w):

$$w = n_t \cdot n_c / (n_t + n_c) \quad (3)$$

式中, n_t 和 n_c 分别为处理组和对照组重复数.重复数越多则权重越大.

在R语言中采用Meta软件包的随机效应模型对效应值进行分析.利用自助抽样法通过999次迭代计算得到效应值95%置信区间.当效应值的95%置信区间与0重叠时,表明实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.

2 结果与分析

2.1 NO 排放量

各作物体系传统施氮处理NO排放量均为正值,除茶园排放量满足正态分布外($P = 0.20$),其余均为偏负态分布($P < 0.05$,图1).玉麦轮作、茶园和果园年排放量分别位于 $0.71 \sim 3.78$ 、 $1.47 \sim 19.4$ 和 $0.01 \sim 3.19\text{ kg}\cdot\text{hm}^{-2}$ 之间,各组数据间有显著性差异($P < 0.05$);三者平均值分别为 1.44 ($n = 50$, $\text{CV} = 73\%$)、 7.45 ($n = 20$, $\text{CV} = 79\%$)和 $0.92\text{ kg}\cdot\text{hm}^{-2}$ ($n = 12$, $\text{CV} = 115\%$).稻麦轮作旱地阶段

和蔬菜单季排放量分别位于 $0.21 \sim 9.5\text{ kg}\cdot\text{hm}^{-2}$ 和 $0.09 \sim 30.2\text{ kg}\cdot\text{hm}^{-2}$ 之间(图1),平均值分别为 $2.13\text{ kg}\cdot\text{hm}^{-2}$ ($n = 29$, $\text{CV} = 118\%$)和 $2.09\text{ kg}\cdot\text{hm}^{-2}$ ($n = 90$, $\text{CV} = 192\%$).在玉麦轮作、稻麦轮作旱地阶段和茶园体系中,排放量与施氮量呈显著正相关关系($P < 0.01$),而在蔬菜和果园体系中二者无显著相关性(图2).

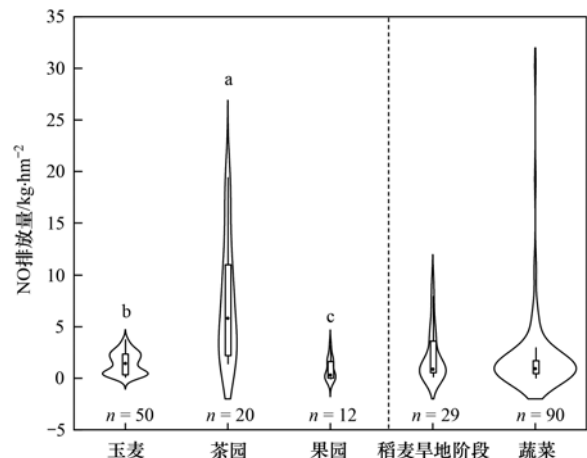


图1 各作物体系NO排放量的比较
实心点为中值,方框为25%~75%百分位数,误差线为1.5倍四分位间距, n 为样本数,不同字母表示有显著性差异($P < 0.05$)

图1 各作物体系NO排放量的比较

Fig. 1 Comparison of NO emissions among the cropping systems

2.2 排放系数

玉麦轮作、茶园、果园、稻麦轮作旱地阶段和蔬菜单季传统施氮处理NO排放系数分别位于 $0.02\% \sim 1.35\%$ 、 $0.03\% \sim 3.98\%$ 、 $0.001\% \sim 0.52\%$ 、 $0.07\% \sim 3.98\%$ 和 $-0.02\% \sim 28.1\%$ 之间(图3),仅茶园数据满足正态分布($P = 0.87$),其余均为偏负态分布($P < 0.05$);除玉麦轮作分别与稻麦轮作旱地阶段和蔬菜之间差异不显著外($P > 0.05$),在其余各体系间均有显著性差异($P < 0.01$).各体系排放系数平均值分别为 0.31% ($n = 48$, $\text{CV} = 88\%$)、 1.74% ($n = 17$, $\text{CV} = 75\%$)、 0.13% ($n = 12$, $\text{CV} = 129\%$)、 0.71% ($n = 29$, $\text{CV} = 124\%$)和 0.96% ($n = 81$, $\text{CV} = 363\%$).

2.3 管理措施对NO排放量和排放系数的影响

减量施氮总体上能够显著降低NO排放量约35% (95%置信区间: $-49\% \sim -15\%$),但仅当减量比例高于25%时NO排放量显著降低(图4).减量施氮对玉麦轮作和蔬菜单季NO排放量的影响均不显著,且在各条件下对排放系数均无显著影响.有机肥替代化肥总体上分别降低NO排放量和排放系数约32% (95%置信区间: $-48\% \sim -12\%$)和48% (95%置信区间: $-60\% \sim -32\%$),但在 $\omega(\text{SOC}) > 15\text{ g}\cdot\text{kg}^{-1}$ 或 $\text{pH} > 7$ 时影响不显著(图4).配施新型增效氮肥总体上分别降低NO排放量和排放系数约

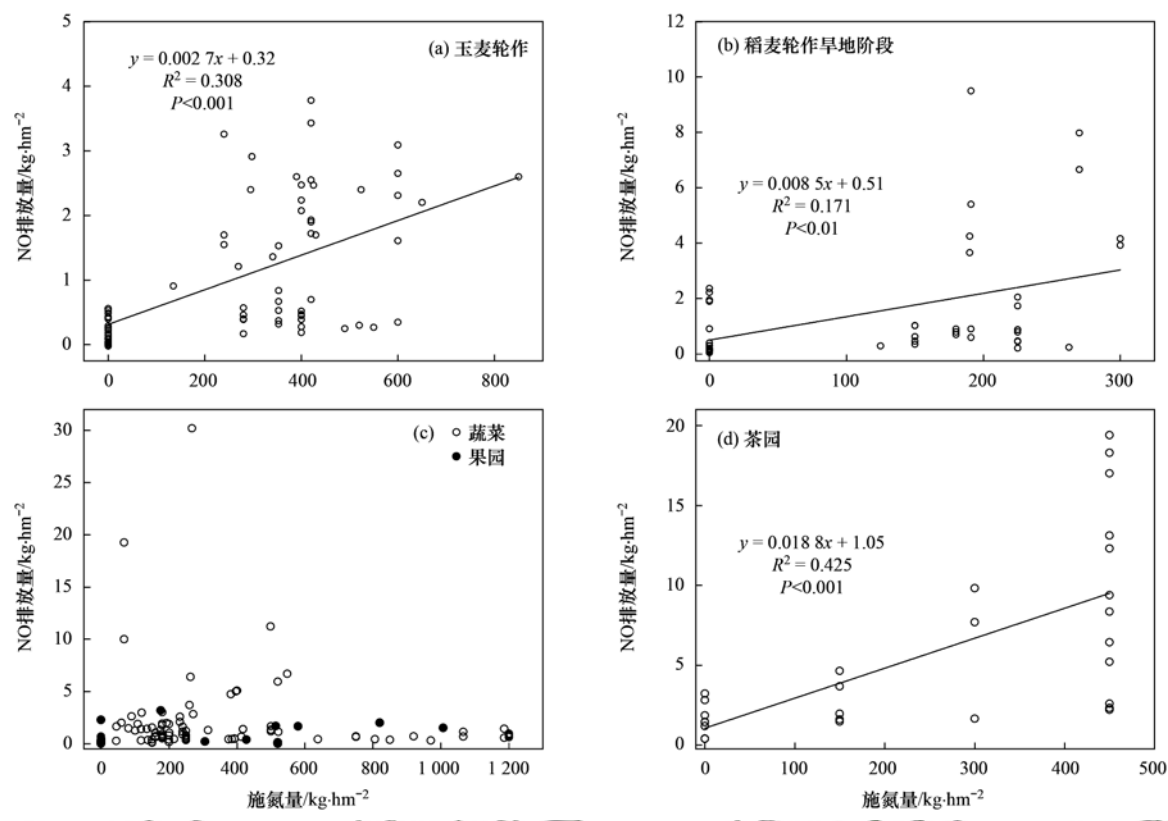
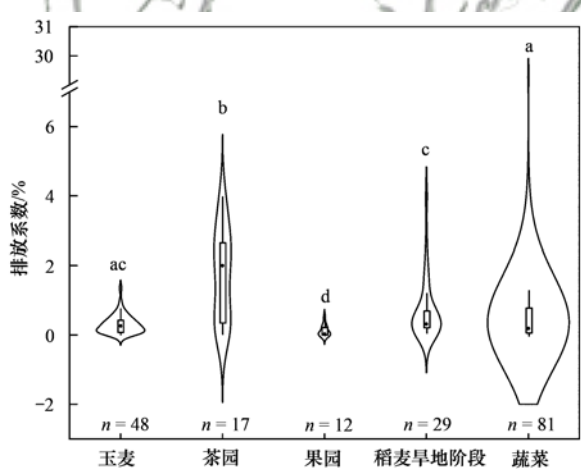


图2 各作物体系 NO 排放量与施氮量的关系
Fig. 2 Relationships between NO emissions and nitrogen input rates among the cropping systems



实心点为中值,方框为 25%~75% 百分位数,误差线为 1.5 倍四分位间距, n 为样本数,不同字母表示有显著性差异 ($P < 0.05$)

图3 各作物体系 NO 排放系数的比较
Fig. 3 Comparison of NO emission factors among the cropping systems

42% (95% 置信区间: $-57\% \sim -22\%$) 和 54% (95% 置信区间: $-66\% \sim -37\%$),而施用生物质炭无显著影响(图4).

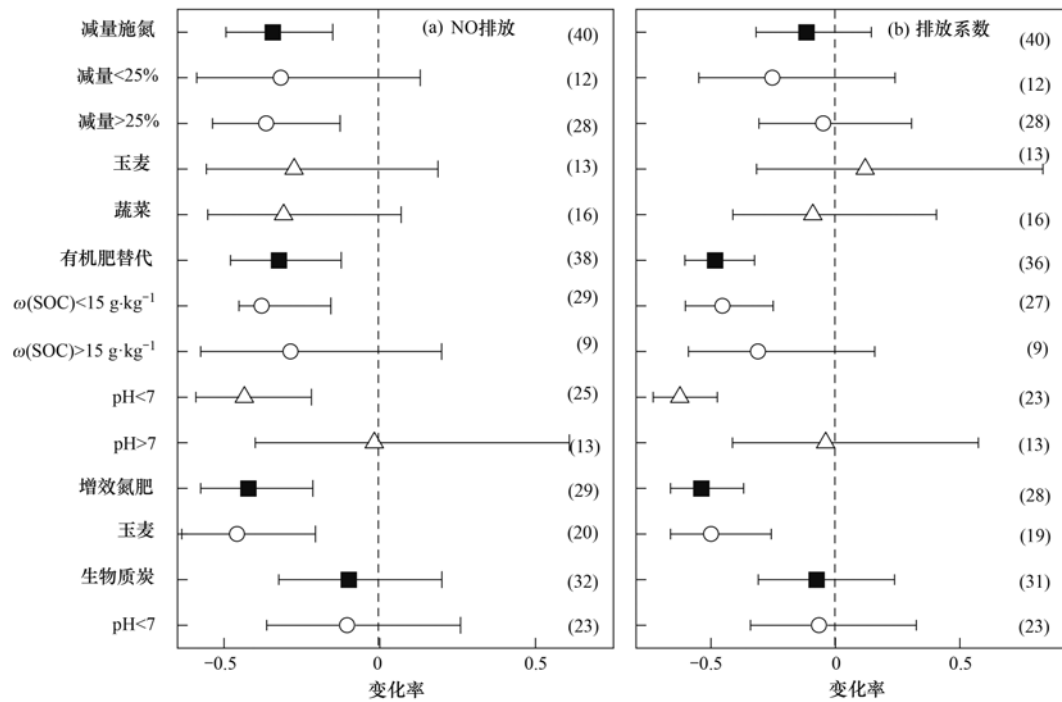
3 讨论

3.1 NO 排放量和排放系数

果园 NO 年排放量和排放系数平均值分别为 $0.92 \text{ kg} \cdot \text{hm}^{-2}$ 和 0.13%,均显著低于玉米轮作及茶

园体系平均值(图1和图3).但现有果园观测结果非常有限(表3),该统计值不能代表全国果园 NO 排放的平均状态.未来仍需更多果园体系的观测研究.

玉米轮作年排放量和排放系数平均值分别为 $1.44 \text{ kg} \cdot \text{hm}^{-2}$ 和 0.31% (图1和图3),其中排放系数较全国旱地农田^[8]和全球农田平均值^[3]偏低 38%~54%.这可能与玉米和冬小麦在所考察的作物中氮肥利用率较高有关^[4,5].茶园年排放量平均值($7.45 \text{ kg} \cdot \text{hm}^{-2}$)较玉米轮作显著偏高 4 倍($P < 0.001$),其排放系数平均值(1.74%)较玉米轮作、全国旱地农田^[8]和全球农田平均值^[3]偏高 1.6~4.5 倍,表明茶园是 NO 强排放源.一方面,茶园仅采摘新叶,产量和氮肥利用率低,且修剪枝叶还田率高,为 NO 产生提供了充足的氮底物^[35,36];另一方面,茶园土壤为酸性(pH 在 4.4~5.0 之间,表3),可通过化学反硝化过程释放 NO 气体^[1].稻麦轮作旱地阶段季节排放量平均值为 $2.13 \text{ kg} \cdot \text{hm}^{-2}$ (图1),可粗略估计该值即为稻麦轮作年排放量(假定水稻生长季 NO 排放量可忽略不计),较玉米轮作排放量偏高约 50%.尽管稻麦轮作旱地阶段排放系数平均值(0.71%)约为玉米轮作排放系数(0.31%)的 2.3 倍,但二者差异不显著(图3).玉米轮作、稻麦轮作旱地阶段和茶园 NO 排放量与施氮量均呈正



括号内数字为样本数,误差线为 95% 置信区间

图4 田间管理措施对 NO 排放量和排放系数的影响

Fig. 4 Effects of field management practices on NO emissions and emission factors

相关关系(图2),说明施氮量是这3个旱作体系NO排放的主要调控因素;回归模型的斜率分别为0.27%、0.85%和1.88%(图2),与各体系排放系数平均值相差不大。

蔬菜NO季节排放量平均值为 $2.09 \text{ kg} \cdot \text{hm}^{-2}$ (图1),蔬菜复种指数高,每年可种植2~5季,虽然无法精确估计蔬菜地年排放量,但大体可认为与茶园相当。蔬菜地排放系数平均值(0.96%)较玉米轮作偏高2倍($P < 0.001$),较全国旱地农田^[8]和全球农田平均值^[3]偏高43%~92%,但与茶园相比偏低45%($P < 0.001$)。Liu等^[7]的Meta分析结果显示蔬菜体系排放系数平均值为1.71%($n = 49$),较本研究的结果偏高78%,这是由于本研究中样本数较多($n = 81$)造成的差异。由于蔬菜体系排放系数不满足正态分布(图3),随着观测结果的增加,该平均值可能还会发生变化。另外,Liu等^[7]的分析结果显示蔬菜体系排放系数在旱地农田中最高,因为该研究收集的数据中茶园观测结果少而暂未单列。蔬菜NO排放量与施氮量无显著相关性(图2),原因有:①蔬菜类型多,各类型蔬菜生长和管理方式差异大^[14,16,47];②土壤氮底物残留量高,由于蔬菜生长周期短,未能完全吸收本季施氮量^[45~47];③蔬菜分布广,土壤性质差异大(表5)。

我国旱作体系NO排放系数在-0.02%~28.1%之间(表1~5),变化范围与全球农田基本一致^[3,7]。本研究排放系数平均值为0.77%,略高于全

国旱地农田^[8]和全球农田平均值^[3]。但本研究样本中蔬菜体系所占比例较大(约为45%),该平均值对我国旱地农田的代表性差。由于各作物体系间排放系数差异大(图3),在编制区域或全国农田NO排放清单时,有必要对各作物体系采用不同的排放系数。本研究分析结果表明排放系数与土壤pH或有机碳含量均无显著相关性(结果未显示),全面考察排放系数的影响因素还需纳入更多环境因子。

3.2 NO减排措施

配施新型增效氮肥能够显著降低NO排放量和排放系数(图4),与已有的Meta分析结果一致^[27],说明该管理方式是NO减排的有效措施。本研究收集到的数据中,配施新型增效氮肥处理多设置于玉米轮作农田(图4),该管理措施在其它作物系统中的减排作用尚需进一步考察。配施新型增效氮肥主要通过降低土壤氮底物的可利用性减少NO产生^[24~26]。而减量施氮是减少氮底物最直接的方法,本研究结果显示减量施氮可显著降低NO排放量但对排放系数无影响(图4)。当减氮比例由低于25%增加到高于25%时,排放量和排放系数效应值分别有所降低和增加,但后者始终与0无显著性差异。分析结果进一步显示排放量和排放系数效应值分别与减氮比例呈弱正相关($P = 0.06$)和显著负相关($P < 0.01$)关系(图5),表明减氮比例是减量施氮减排作用的重要影响因子。必须注意的是,过高的减氮比例可能会造成作物减产,在今后的研究中尚需进一步

确定既能保证作物产量又能减少 NO 排放及其它氮损失的最优减氮比例. 减量施氮对玉米轮作 NO 排放量的影响不显著,可能是由于该体系排放系数小且减氮比例低,排放量随减量施氮的变化小;减量施氮对该体系排放系数的影响也不显著,主要是由于排放量与施氮量呈线性相关(图 2),即排放系数是常数,随施氮量无变化或变化很小. 减量施氮对蔬菜 NO 排放量和排放系数的影响不显著,可能与土壤氮底物残留量高有关^[14,45,50]. 减量施氮在其它作物系统中的减排作用尚需进一步考察.

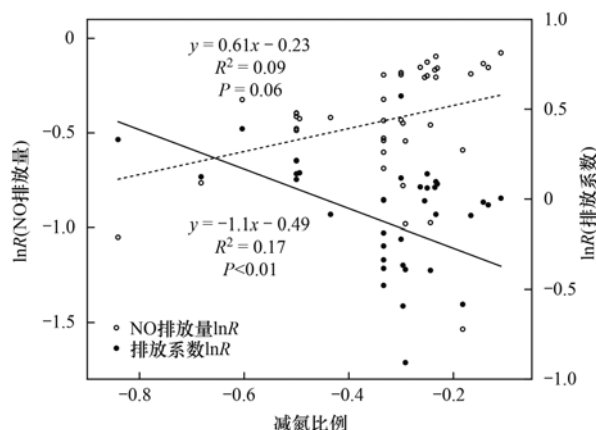


图5 NO排放量和排放系数效应值与减氮比例的关系
Fig. 5 Relationships of the response ratio of NO emissions and emission factors against the ratio of reducing nitrogen fertilizers

施用有机肥可通过多种途径改变 NO 产生和消耗^[21~23]. 本研究结果显示有机肥替代化肥在 $\omega(\text{SOC}) < 15 \text{ g} \cdot \text{kg}^{-1}$ 或 $\text{pH} < 7$ 时可显著降低 NO 排放量和排放系数(图 4),主要原因包括:①土壤有机碳含量低,有机肥提供的有机碳底物促进了反硝化过程和 NO 消耗^[35,36];②有机肥提高了土壤 pH,降低了化学反硝化过程产生的 NO 气体^[34];③有机肥在土壤中引入难分解有机质,在矿化过程中固定氮底物^[18]. 相反,当 $\omega(\text{SOC}) > 15 \text{ g} \cdot \text{kg}^{-1}$ 或 $\text{pH} > 7$ 时,施用有机肥对 NO 排放量和排放系数无显著影响. 另外,陕西省玉米轮作农田长期定位施肥实验结果显示^[21,22],相对于全化肥处理,长期施用有机肥可显著提高土壤有机质含量,而有机质含量高的土壤在适宜的环境条件下可提供更丰富的氮底物并促进 NO 排放. 此长期实验结果已纳入本研究(表 1),可能是导致有机肥替代在 $\omega(\text{SOC}) > 15 \text{ g} \cdot \text{kg}^{-1}$ 或 $\text{pH} > 7$ 时影响不显著的部分原因.

生物质炭是研究较多的土壤改良剂,已有大量实验结果表明生物质炭对土壤物理、化学和生物化学过程均有显著影响^[18~20]. 本研究收集的数据中,施用生物质炭处理多在 $\text{pH} < 7$ 的田间条件下开展,主要是由于生物质炭为碱性,可中和酸性土壤的酸

碱性^[19,20]. 结果显示施用生物质炭对 NO 排放量和排放系数的影响不显著(图 4),可能是生物质炭对 NO 排放促进和削弱共同作用的最终结果. 一方面,施用生物质炭可提高土壤透气性,有利于硝化过程和 NO 排放^[19]. 另一方面,施用生物质炭不利于 NO 产生,主要原因有:①生物质炭比表面积大,可吸附土壤氮底物,降低其可利用性^[13,18];②生物质炭可为反硝化过程提供有机碳底物^[20]. 施用生物质炭在其它田间条件下对 NO 排放量和排放系数的影响尚需进一步考察.

4 结论

(1)我国旱作体系 NO 排放量和排放系数差异大,其中茶园是强排放源. 在玉米轮作、稻麦轮作旱地阶段和茶园体系中,施氮量是 NO 排放量的主要调控因素,但在蔬菜和果园体系中二者相关性不显著.

(2)减量施氮仅在减氮比例高于 25% 时可显著降低 NO 排放量,但对排放系数的影响不显著. 有机肥替代化肥在土壤有机碳含量低 [$\omega(\text{SOC}) < 15 \text{ g} \cdot \text{kg}^{-1}$] 或酸性 ($\text{pH} < 7$) 条件下及配施新型增效氮肥在玉米轮作农田中可有效降低 NO 排放量和排放系数,而施用生物质炭的减排效果不显著.

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