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缓控释肥深施对黏性土壤麦田氮素去向的影响

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摘要: 黏性土壤严重影响土壤水肥运移. 采取适宜的农艺措施优化土壤无机氮分布, 减少该类型土壤的氮素损失是农业绿色可持续发展的关键. 为明确缓控释肥种肥深施对黏性土壤麦田氮素损失的影响, 选择常规化肥 (CN) 和缓控释肥 (RCU) 这 2 种类型肥料, 采用撒播撒施 (B) 和机械化条播深施 (D), 研究了缓控释肥种肥深施对黏性土壤小麦产量、季节麦田氮素径流流失、氨挥发和 N_2O 排放的影响; 并分析了其耕层土壤的无机氮时空分布特征. 结果表明, 相同肥料类型下, D 处理的小麦产量显著高于 B 处理; 而相同施肥方式下, RCU 处理的产量显著高于 CN 处理. D-RCU 处理的小麦产量最高, 达 $6.97 \text{ t} \cdot \text{hm}^{-2}$. 季节径流和氨挥发氮损失量高于 N_2O 形态的氮损失, 且不同损失途径对肥料类型和施肥方式的响应不同. 肥料类型和径流发生时间是麦田径流氮素流失的主要影响因素. 受监测年份降雨年型分配影响, RCU 处理的季节径流氮素流失量 ($20.35 \text{ kg} \cdot \text{hm}^{-2}$) 较 CN 处理 ($10.49 \text{ kg} \cdot \text{hm}^{-2}$) 显著增加. 生育后期是麦田氨挥发损失的主要时期, 并受施肥方式和肥料类型共同影响. B-CN 处理的季节氨挥发损失量最高 ($18.15 \text{ kg} \cdot \text{hm}^{-2}$), 并显著高于其它处理 ($7.31 \sim 8.38 \text{ kg} \cdot \text{hm}^{-2}$). 此外, D-RCU 处理 ($2.41 \text{ kg} \cdot \text{hm}^{-2}$) 较 B-CN 处理 ($4.02 \text{ kg} \cdot \text{hm}^{-2}$) 有降低 N_2O 排放的潜力. 结果同时表明, 试验土壤无机氮的径向移动高于垂直移动; 缓控释肥条播深施有利于优化土壤无机氮的时空分布, 是小麦产量增加和麦田氮素损失控制的主要原因. 结果说明, 缓控释肥是黏性土壤麦田增产减排的适宜替代肥料; 采用缓控释肥料条播深施能够通过优化土壤的无机氮时空分布, 增加小麦产量, 减少麦田氨挥发和 N_2O 损失, 但其对非肥期径流氮素流失的增加效应值得关注.

关键词: 黏性土壤; 小麦; 缓控释肥; 深施肥; 氮损失; 土壤无机氮

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Effect of Deep Fertilization with Slow/Controlled Release Fertilizer on N Fate in Clayey Soil Wheat Field

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Abstract: Clayey soil seriously affects water-holding capacity and nutrient movement. Adopting appropriate agronomic measures to optimize the distribution of soil inorganic nitrogen (SIN) and reduce the nitrogen (N) loss in this soil is the key to agricultural sustainable development. To clarify the effect of deep fertilization of slow/controlled release fertilizer with sowing on N loss in a clayey soil wheat field, two types of fertilizers, conventional fertilizer (CN) and slow/controlled release fertilizer (RCU), were selected in this study. Here, we evaluated the effects of these two fertilizer types on wheat yield, seasonal N runoff loss, ammonia volatilization, and N_2O emissions in wheat fields in two typical fertilization modes (manual surface sowing and spreading (B) and belowground fertilization of slow/controlled release urea with mechanized strip sowing (D)). The temporal and spatial distribution characteristics of SIN in topsoil were also analyzed. The results showed that under the same fertilizer type, the wheat yield of D treatment was significantly higher than that of B treatment, whereas the yield of RCU was notably higher than that of CN under the same fertilization mode. D-RCU achieved the highest yield of $6.97 \text{ t} \cdot \text{hm}^{-2}$. The seasonal N losses from runoff and ammonia volatilization were higher than that from N_2O emissions, and the responses of different N loss pathways to fertilizer types and fertilization methods were diverse. Fertilizer type and runoff occurrence time were the main influencing factors of N runoff loss, and N runoff loss of the RCU treatment was higher in the non-fertilization period. Unfortunately, affected by annual rainfall pattern, the seasonal N runoff loss of the RCU treatment ($20.35 \text{ kg} \cdot \text{hm}^{-2}$) was significantly higher than that of the CN treatment ($10.49 \text{ kg} \cdot \text{hm}^{-2}$). The late growth period was the main phase of ammonia volatilization, and the later period was jointly affected by fertilization modes and fertilizer types. The B-CN treatment induced the highest seasonal ammonia volatilization ($18.15 \text{ kg} \cdot \text{hm}^{-2}$), which was significantly higher than that of the other treatments ($7.31 \sim 8.38 \text{ kg} \cdot \text{hm}^{-2}$). Additionally, the D-RCU treatment ($2.41 \text{ kg} \cdot \text{hm}^{-2}$) tended to reduce the N_2O emissions in comparison to that in the B-CN treatment ($4.02 \text{ kg} \cdot \text{hm}^{-2}$). The results also indicated that the horizontal movement of SIN was higher than the vertical movement. Deep fertilization of RCU was conducive to optimizing the spatial and temporal distribution of SIN, which was the main reason for the increase in wheat yield and the control of N loss from wheat fields. These results suggest that RCU is a suitable alternative fertilizer for increasing yield and reducing N loss in clayey soil wheat fields; D-RCU can increase the wheat yield and reduce ammonia volatilization and N_2O emissions in wheat fields by optimizing the spatial and temporal distribution of SIN, and its increasing effect on N runoff loss in the non-fertilization period deserves attention.

Key words: clayey soil; wheat; slow/controlled release fertilizer; deep fertilization; nitrogen loss; soil inorganic nitrogen

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小麦是我国重要的粮食作物,维持单位面积小麦产量对保证国家口粮安全具有重要作用,尤其在当前人口红利政策刺激和人口增加背景下^[1,2].除优良品种选育,化肥尤其是氮肥施用在稳定粮食产量方面发挥了重要作用^[3,4].然而,由于作物养分吸收特性、肥料释放特性和水分管理的特殊性等因素叠加影响,氮肥的当季利用率一般不足 50%,其余大部分通过径流、渗漏、氨挥发和反硝化损失等进入水体或大气环境,引发系列环境问题^[5~7].因此,采取适宜的农艺措施,如新型肥料替代和施肥方式改变等^[8,9],在保证作物单产的同时减少农田氮素损失对保障国家粮食安全和改善生态环境具有重要意义.

近年来,随着研究技术和制备工艺的进步,缓控释肥料的研发取得了长足进步^[10,11].由于该类型肥料通过材料包涂改变了氮素释放动力学参数,能够实现肥料养分的控制和延迟释放,因此具有广泛的应用前景^[12~14].郝胜磊等^[15]和 Zhu 等^[16]均通过荟萃分析证实了缓控释肥料有利于提高三大粮食作物的产量和氮素吸收利用率.这说明,缓控释肥是提高小麦产量和氮素利用率,减少氮素环境损失的有效替代肥料.值得一提的是,赵明等^[17]提出新时期作物生产需要从生产系统的整体性出发,协同优化气候-土壤-作物之间的关系,实现作物生产的可持续发展.而缓控释肥料的养分释放也和土壤水热条件等密切相关^[18,19].因此,不同类型作物和土壤的缓控释肥稳产减排效果不能一概而论.

土壤质地显著影响水肥运移,是土壤重要的物理特性之一,也是土系划分的重要指标^[20~22].我国大部分地区都存在黏性土壤.由于该类型土壤黏性强且耕作阻力大,往往存在适耕条件差(湿烂田)的问题,特别是在南方雨水充沛地区旱季作物种植季节^[23,24].同时,由于该类型土壤水肥运移能力弱,肥料养分的释放运移(空间分布)必然不同于其他类型土壤,并深刻影响氮素损失^[25~27].以太湖地区黏性土壤稻麦农田为例,由于水稻收获至小麦播种的茬口期短,且常遇降水,农户撒播撒施已经成为常态,这对氮素损失的影响有多大?改速效氮肥为缓控释肥是否会由于肥料的缓慢释放,克服黏性土壤弱水肥运移能力的限制,通过优化土壤的无机氮时空分布,增加氮素减排空间,特别是在肥料深施条件下?为此,本研究选择太湖地区长期稻麦轮作黏性土壤(具有典型犁底层结构),在适种年份研究了缓控释肥机械化种肥深施对麦田氮素损失的影响,并分析了其耕层土壤的无机氮时空分布特征,以期为南方地区典型黏土旱地作物的高产高效栽培和氮素

损失控制提供理论支撑和技术参考.

1 材料与方法

1.1 试验设计

本试验于 2018~2019 年在南京市江宁区汤山街道阜庄村进行.供试小麦品种为扬麦 28 号,播种量 $375\text{ kg}\cdot\text{hm}^{-2}$.试验于 2018 年 11 月 29 日播种,2019 年 5 月 31 日收获.试验田为长期水旱轮作水稻土,土壤类型为马肝土,其黏粒、粉粒和砂粒的比例为 39.34%、29.18% 和 31.48%,为典型黏性土壤(国际制).耕作层土壤理化性质为:pH 5.93; ω (有机碳) $16.87\text{ g}\cdot\text{kg}^{-1}$; ω (全氮) $1.95\text{ g}\cdot\text{kg}^{-1}$; ω (有效磷) $6.87\text{ mg}\cdot\text{kg}^{-1}$; ω (速效钾) $83.78\text{ mg}\cdot\text{kg}^{-1}$.

试验选择常规化肥(CN)和缓控释肥(RCU)这 2 种类型肥料,每种肥料采用人工撒播撒施(B)和机条播正位深施(D)这 2 种播种施肥方式,共 4 个处理.所有处理氮(N)、磷(P_2O_5)和钾(K_2O)肥用量均相同,分别为 240、96 和 $96\text{ kg}\cdot\text{hm}^{-2}$.磷、钾肥分别选择过磷酸钙和氯化钾于整地前一次性基施.常规化肥处理的氮肥采用普通商品尿素,分基肥(40%)、越冬肥(30%)和拔节孕穗肥(30%)3 次施用.常规化肥撒播撒施处理(B-CN)的基肥为人工撒施;条播深施处理(D-CN)采用农业农村部南京农业机械化研究所新研的小麦旋耕条播正位深施肥开沟一体化机器进行机条播深施(播种深度 3 cm,施肥深度 8 cm).人工追施越冬肥和拔节孕穗肥.缓控释肥处理的氮肥采用 3 个月树脂包膜尿素,一次性人工撒施(B-RCU)或条播深施(D-RCU).此外,撒播撒施处理播种施肥后采用小型旋耕机进行旋耕盖土,并按条播深施机器等规格开丰产沟.为便于机器作业,试验采用条区顺序排列,小区面积 300 m^2 ($10\text{ m}\times 30\text{ m}$),并将每个小区单独划分为 3 个独立样区用于采样分析.由于试验地区降水丰富、地下水位高,田间水分管理以雨养灌溉为主,不进行主动灌溉;病虫害防治同当地常规管理.

1.2 采样和测定方法

径流样品采集测定:于降水径流发生后记录径流体积,并采集径流水样带回实验室过滤后用 SKALAR 流动分析仪测定水样的氮素浓度($\text{mg}\cdot\text{L}^{-1}$).按径流体积计算单次氮素径流流失量,并加和折算季节氮素径流流失量($\text{kg}\cdot\text{hm}^{-2}$).

氨挥发测定:采用密闭室间歇通气法,分别于每天 06:00~08:00 和 13:00~15:00 进行 2 个时间段 4 h 的连续抽气测定,2% H_3BO_3 指示剂变色后更换指示剂并带回使用 $0.01\text{ mol}\cdot\text{L}^{-1}$ 的 H_2SO_4 滴定后,折算区间氨挥发损失量($\text{kg}\cdot\text{hm}^{-2}$).田间气体采

集换气高度设定为 2 m, 密闭室直径和条播行间距相同(25 cm), 高度为 30 cm.

N_2O 采集测定: 使用静态暗箱法进行田间温室气体样品的采集, 采集频次为 10 ~ 15 d, 施肥后 7 d 内加密采集. 为增加样品代表性, 按条播处理行间距(25 cm)2 行宽度将采集箱长和宽均设置为 50 cm, 完整覆盖 2 行植株和土壤空间, 并预埋同规格带有水槽的底座用于水封处理. 此外, 生育后期在生育前期 50 cm 采集箱高度基础上增加 50 cm 高的加高箱进行气体样品采集. 每小区每次采集 4 组气体样品, 时间间隔为 10 min, 样品采集后带回实验室采用 Agilent 7980 进行 N_2O 浓度测定后折算 N_2O 排放通量 [$\mu g \cdot (m^2 \cdot h)^{-1}$], 并计算季节 N_2O 排放量 ($kg \cdot hm^{-2}$).

土壤样品采集和测定: 小麦 3 次施肥后的第 1 d 和第 7 d, 其它时间每 10 ~ 15 d 采集一次耕层土壤样品, 用于土壤无机氮含量测定. 为明确其时空变化, 种肥深施处理以施肥点为中心, 按照径向距离 2、5 和 10 cm 采集土壤样品, 每个径向点按播种施肥深度采集 0 ~ 3、3 ~ 8、8 ~ 13 和 13 ~ 20 cm 土壤样品. 撒播撒施处理以任意点为中心进行相同操作. 样品采集后经过 $2 mol \cdot L^{-1}$ 的 KCl 浸提, 振荡后过滤, 连续流动分析仪测定铵态氮和硝态氮含量, 并求和计算无机氮含量.

成熟期小麦产量: 于小麦生理成熟期, 每小区在非样品采集区随机选择长势一致的 3 个割方区(每个 $1 m^2$) 收割小麦实产样品, 晾晒后脱粒测定小麦实产和籽粒含水量, 并按标准含水量(13.5%)折算小麦单产.

1.3 统计分析方法

需要说明的是, 由于本试验聚焦缓控释肥条播深施的效果分析和原因解析, 因此田间 N_2O 排放和土壤无机氮时空分布特征仅选择常规化肥撒播撒施(对照)和缓控释肥条播深施 2 处理进行采集分析, 其它指标对所有处理进行样品采集分析.

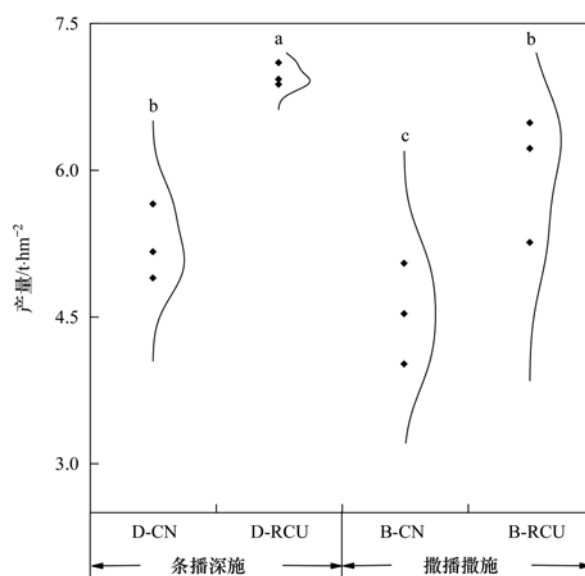
采用 Microsoft Excel 2010 建立数据库, 分别用 SPSS 23.0 和 OriginPro 2021 进行数据统计分析和作图. 采用独立 T 检验和 Duncan 法进行处理间差异分析, 并计算不同处理指标的平均值和标准误.

2 结果与分析

2.1 缓控释肥种肥深施对小麦产量的影响

不同类型肥料和施肥方式对小麦产量影响的结果列于图 1. 结果表明, 不同类型肥料和施肥方式均显著影响小麦产量($P < 0.05$). 相同肥料类型下, 条播深施处理(D)的小麦产量显著高于撒播撒施处理

(B), D-CN 和 D-RCU 处理的小麦产量分别较 B-CN 和 B-RCU 处理增加 15.45% 和 16.36%. 此外, 相同施肥方式下, 缓控释肥处理(RCU)的小麦产量显著高于常规化肥处理(CN), D-RCU 和 B-RCU 处理的小麦产量分别较 D-CN 和 B-CN 处理增加 33.27% 和 32.23%. 所有处理比较结果表明, 缓控释肥条播深施处理(D-RCU)的小麦产量最高($6.97 t \cdot hm^{-2}$), 处理间表现为: D-RCU > B-RCU 和 D-CN > B-CN.



不同小写字母表示小麦产量的差异显著性($P < 0.05$)

图 1 不同类型肥料和施肥方式对小麦产量的影响

Fig. 1 Wheat yield as affected by different fertilizer types and fertilization modes

2.2 缓控释肥种肥深施对麦田 N 素损失的影响

2.2.1 径流流失

图 2 为不同类型肥料、施肥方式下麦田径流氮素浓度和季节流失量的结果. 结果表明, 试验年份共发生 8 次径流事件, 且主要集中在小麦生育前期. 不同发生时间处理间的径流氮素浓度表现不一致. 施肥后短时间内(肥期)常规化肥(CN)处理的径流氮素浓度较高, 且撒施处理(B)的氮素浓度高于深施处理(D). 缓控释肥处理(RCU)的非肥期径流氮素浓度较高, 且深施处理(D)的氮素浓度高于撒施处理(B). 从季节径流氮素流失量比较结果来看, 缓控释肥处理(RCU)的径流氮素流失量($20.35 kg \cdot hm^{-2}$)显著高于常规化肥处理($10.49 kg \cdot hm^{-2}$), 相同肥料类型下 2 种施肥方式的季节径流氮素流失量无显著差异. 结果说明, 肥料类型是影响麦田径流氮素流失的主要控制因子, 径流氮素流失和发生时间密切相关.

2.2.2 氨挥发损失

对麦田氨挥发损失的动态监测结果分析表明,

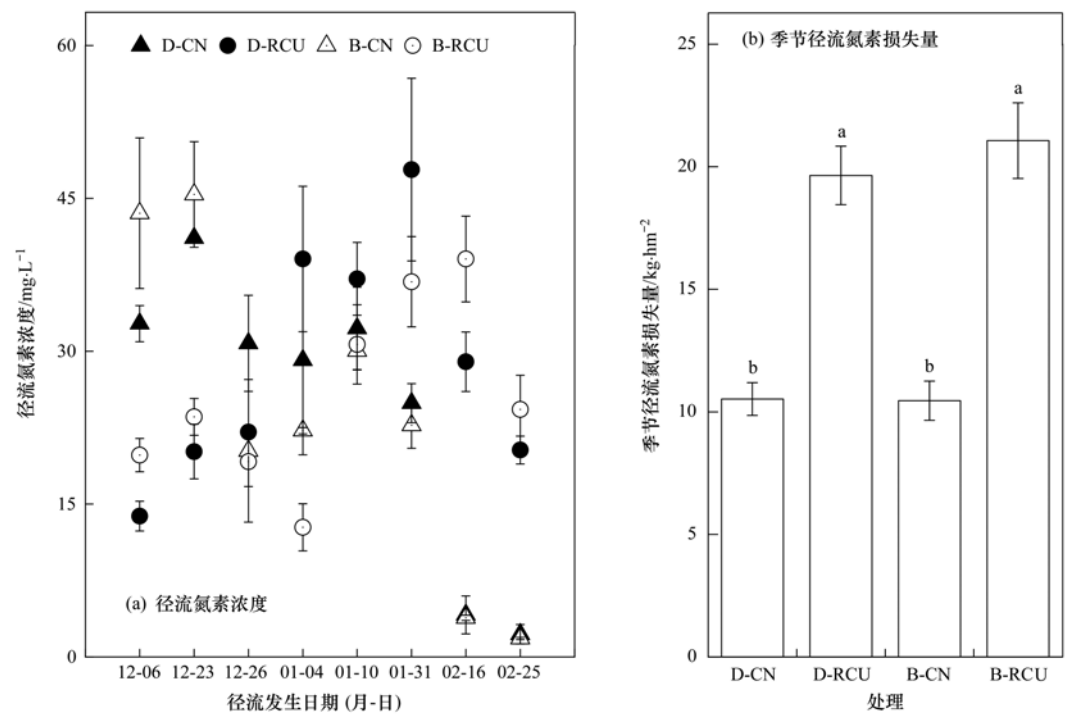


图 2 不同类型肥料和施肥方式对麦田氮素径流损失的影响

Fig. 2 N runoff loss in wheat fields as affected by different fertilizer types and fertilization modes

不同处理下麦田氮挥发损失表现为明显的阶段特征,生育后期的氮挥发损失明显高于生育前期(图 3). 常规化肥撒施处理生育后期的氮挥发通量明显高于其他处理. 季节损失量比较结果表明,同一施肥处理下,条播深施处理(D)的 2 种类型肥料的氮挥发损失量无显著差异;但撒播撒施(B)处理的 2 种肥料类型间差异显著 ($P < 0.05$),常规化肥撒施处

理(B-CN)的季节氮挥发损失量最高 ($18.15 \text{ kg} \cdot \text{hm}^{-2}$),并显著高于其他处理 ($7.31 \sim 8.38 \text{ kg} \cdot \text{hm}^{-2}$).

2.2.3 N_2O 排放

图 4 结果表明,2 种施肥方式下生育前期的麦田 N_2O 排放通量明显高于后期,特别是常规化肥处理. 2 种施肥处理下播种-返青阶段的 N_2O 排放量占

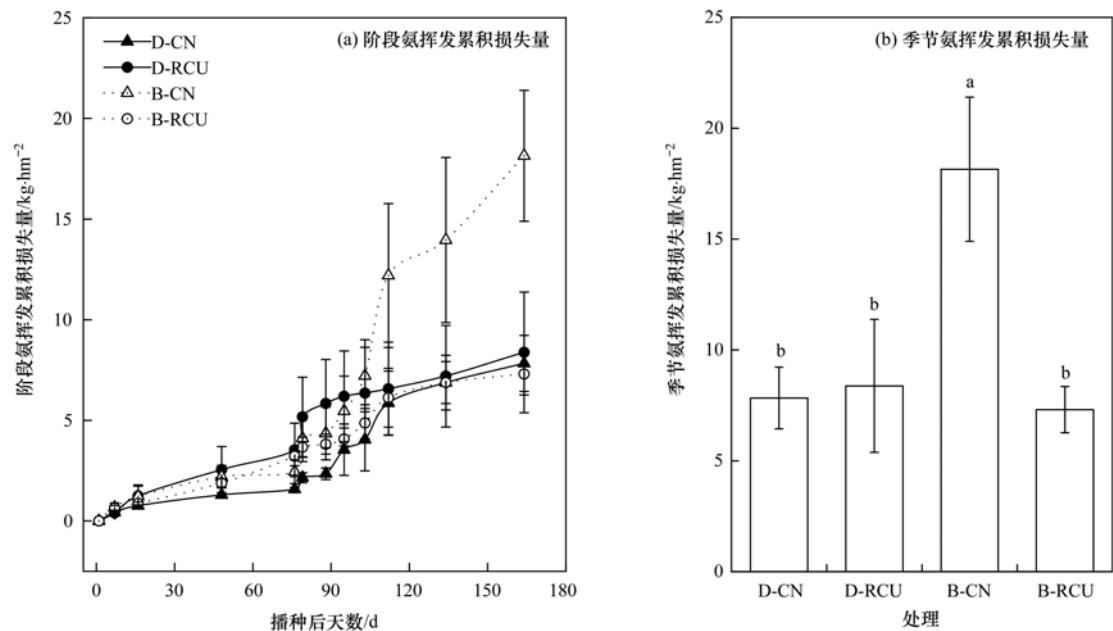


图 3 不同类型肥料和施肥方式对麦田氨挥发损失的影响

Fig. 3 Ammonia volatilization in wheat fields as affected by different fertilizer types and fertilization modes

比较高,分别为 78.61% (B-CN) 和 61.41% (D-RCU)(表 1). 此外,2 种施肥处理下 N_2O 排放通量差异主要集中在生育前期;该阶段常规化肥撒施处理(B-CN)的 N_2O 排放通量和累积排放量明显高于缓控释肥条播深施处理(D-RCU). N_2O 排放量比较结果表明,尽管 2 种施肥处理下季节 N_2O 排放量无显著差异,但 B-CN 处理的季节 N_2O 排放量 ($4.02\text{ kg}\cdot\text{hm}^{-2}$)明显高于 D-RCU 处理($2.41\text{ kg}\cdot\text{hm}^{-2}$).

表 1 缓控释肥条播深施对麦田 N_2O 排放量的影响/ $\text{kg}\cdot\text{hm}^{-2}$

Table 1 N_2O emissions from wheat fields as affected by deep fertilization of slow/controlled release urea with mechanized strip sowing/ $\text{kg}\cdot\text{hm}^{-2}$				
处理	播种-返青	返青-抽穗	抽穗-成熟	全生育期
B-CN	3.16	0.67	0.19	4.02
D-RCU	1.48	0.76	0.17	2.41

2.3 缓控释肥种肥深施对土壤无机氮时空分布的影响

常规化肥撒播撒施处理(B-CN)和缓控释肥条播深施处理(D-RCU)的土壤无机氮时空分布特征如图 5 所示. 结果表明,B-CN 处理的土壤无机氮含

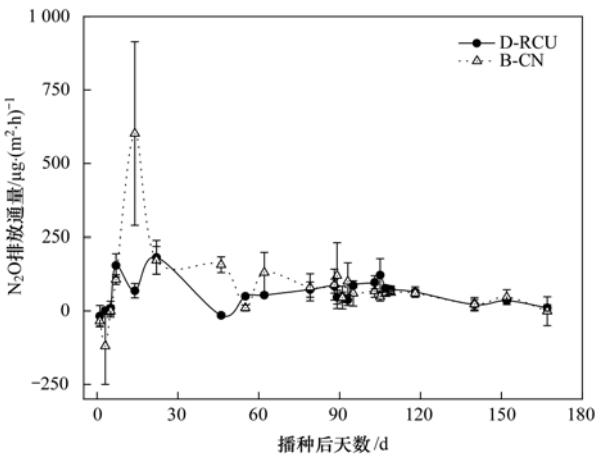
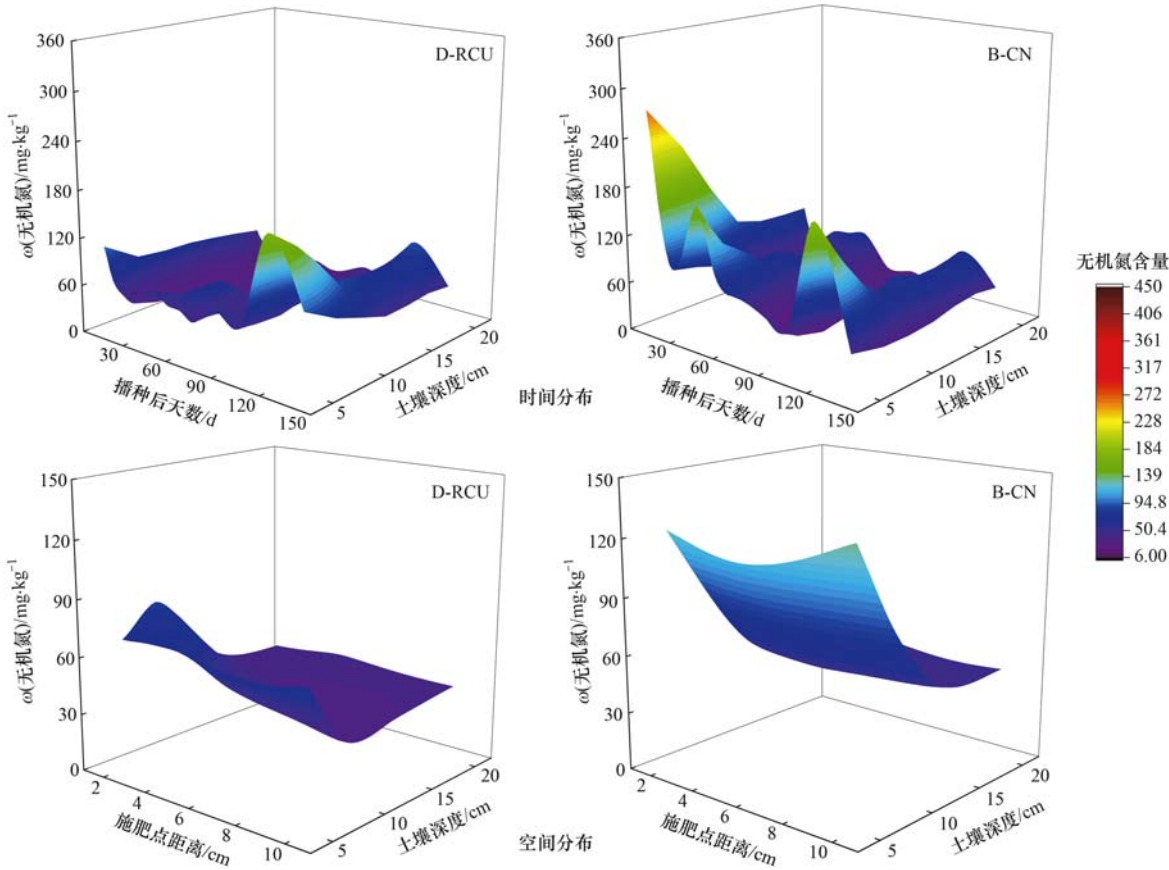


图 4 缓控释肥条播深施对麦田 N_2O 排放通量的影响

Fig. 4 N_2O emitting rate from wheat fields as affected by deep fertilization of slow/controlled release urea with mechanized strip sowing

量整体高于 D-RCU 处理,2 种施肥处理的时空变化明显不同. 常规化肥处理的表层土壤无机氮含量较高,并随耕层深度增加而降低;且表现出明显时间阶段特征,3 次施肥后的土壤无机氮含量明显增加. 而缓控释肥深施处理的土壤无机氮含量随施肥点距



色柱为土壤无机氮含量对应数值的颜色映射(无量纲)

图 5 缓控释肥条播深施对麦田土壤无机氮时空分布的影响

Fig. 5 Temporal and spatial distribution characteristics of soil inorganic N in wheat fields as affected by deep fertilization of slow/controlled release urea with mechanized strip sowing

离的延长而降低,且随生育期延长的变化较平缓,生育后期的土壤无机氮含量整体高于前期.此外,2种施肥处理的土壤无机氮径向移动(随施肥点距离的无机氮含量变化)均明显高于垂直移动(不同深度土壤无机氮含量变化).

3 讨论

稳定基本苗的同时保证群体花后光合生产是小麦安全生产的关键^[28,29].赵凌天等^[30]的研究指出,小麦机械化耕播有利于提高小麦出苗率,通过培育健壮群体,增加群体穗数和总粒数提高小麦产量.本研究也发现,2种肥料类型下,条播深施处理的黏性土壤小麦产量均显著高于撒播撒施处理(图1).此外,本研究还发现,相同施肥方式下,缓控释肥RCU处理的小麦产量显著高于常规化肥CN处理,缓控释肥条播深施处理(D-RCU)的小麦产量最高(6.97 t·hm⁻²).基于荟萃分析,郝胜磊等^[15]和Zhu等^[16]的研究也证实了缓控释肥施用有利于提高小麦产量.这可能与缓控释肥料的养分控制和延迟释放有关^[10,11].对常规化肥撒播撒施处理(B-CN)和缓控释肥条播深施处理(D-RCU)的土壤无机氮时空分布特征分析发现,缓控释肥的缓效释放特征明显(图5).与B-CN处理相比,D-RCU处理的土壤无机氮含量随施肥点(根侧)距离的延长而降低,且生育期内变化较平缓,生育后期的土壤无机氮含量整体高于前期.这有利于协调作物土层根系养分吸收和后期养分供应,提高小麦产量.

本研究同时发现,常规化肥撒播撒施和缓控释肥深施处理的土壤无机氮含量径向移动(随施肥点距离的无机氮含量变化)均明显高于垂直移动(不同深度土壤无机氮含量变化).这可能与本研究的土壤类型有关.本研究选择我国大部分地区普遍存在的黏性土壤作为研究体系,而该类型土壤普遍存在土壤水肥运移能力弱的特点^[20,25].黄耀华等^[26]对不同质地紫色土的研究发现,壤质黏土的水肥运移能力弱于黏壤土弱于砂质壤土,且受土壤胶体对铵态氮吸附影响,土壤无机氮的径向移动更明显.结果说明,由于黏性土壤的水肥运移能力较差,根据作物根系分布特征进行耕深施肥有利于进一步促进作物的养分吸收利用,提高产量.

不同处理的氮素损失监测结果表明,肥料类型是麦田径流氮素损失的主要影响因素,深施并未减少不同类型肥料的氮素径流损失.这可能与旱地农田产流机制和试验区土壤类型、水分管理方式有关^[31].本试验所在的太湖地区降水丰富且地下水位较高,旱地水分管理以排水降渍为主.此外,如前述

分析,试验区土壤为水旱轮作黏性土壤,具有典型犁底层结构,且土壤的径向移动高于垂直移动.据此,在以超渗产流为主的旱地径流产流过程中,降水下渗至犁底层后即迅速裹挟耕层养分流失^[31],施肥深度可能不是影响径流氮素损失的主要因素.研究还发现,麦田径流损失表现出明显的时间特征(图2).如施肥后短期内(肥期)发生径流,常规化肥CN处理的径流氮素损失较高,而缓控释肥RCU处理的非肥期径流氮素损失较高.与缓控释肥的缓慢释放相比,常规化肥的短期暴发释放可能会加速施肥后短期内的农田氮素径流损失^[32~34].土壤无机氮时空分布特征结果也表明,常规化肥处理在3次施肥后的土壤无机氮含量迅速增加,增加该时期的流失风险.这说明,肥料类型(养分释放速率)和径流发生时间是影响黏性土壤麦田径流氮素损失的主要因素,不同类型肥料对麦田氮素径流损失的控制效果和降水年型密切相关,不能一概而论^[35,36].

对气态氮挥发损失结果分析发现,麦田生育后期的氮挥发损失明显高于生育前期,是氮挥发损失的主要阶段(图3).这可能与季节温度的变化有关^[37].氮挥发损失是受温度影响的物理过程,作为越冬作物,小麦生育前期温度较低不利于氮挥发,而后期温度的增加可能会促进氮挥发损失,尽管该时期植被郁闭度较高^[38,39].研究还发现,常规化肥撒施处理(B-CN)的季节氮挥发损失量显著高于其他处理.不同处理下作物群体和肥料养分的吸附释放差异可能是主要原因.一方面,缓控释肥的缓效释放特点^[10,11]和较低的土壤无机氮含量(图5)有利于降低氮挥发损失风险.同时,条播深施处理的作物产量较高,群体较大,这会通过增加生育后期的植被郁闭度和养分吸收能力减少氮挥发损失风险^[25,40].此外,深施下表下层较黏的质地使土壤胶体对铵态氮吸附能力的增强也可能是氮挥发损失降低的原因^[22,26].

麦田N₂O监测结果表明,受肥料养分释放和土壤无机氮时空变化影响,缓控释肥条播深施有降低N₂O排放的趋势(图4和表1).如前所述,深施下表下层较黏的土壤质地可能会增强其对铵态氮的吸附能力^[22,26].而缓控释肥料的缓效释放会进一步降低土壤铵态氮底物浓度^[11].这有利于减少土壤中可自由移动的铵态氮含量,降低硝化产生的硝态氮含量,减少N₂O损失^[27].值得注意的是,2种施肥方式下生育前期的麦田N₂O排放通量明显高于后期.这可能与试验年份的降水分布有关^[41].径流监测结果发现,试验年份降水主要分布在生育前期(图2).而彭毅等^[42]的研究发现,播种施肥后的降水增加了土壤

湿度,并通过刺激旱地肥料氮素转化,促进 N_2O 排放.这也说明,降水引起的土壤含水量增加可能有利于提高土壤氮素的可利用性,但也有增加 N_2O 排放的风险,尤其在生育前期作物养分吸收能力较弱的条件下^[43-45].需要指出的是,尽管本研究通过田间试验明确了缓控释肥条播深施的增产减排效果,但研究也发现,缓控释肥条播深施由于肥料的缓慢释放改变了土壤无机氮的时空分布特征.因此,该方式下是否存在肥料减施空间,土壤无机氮时空分布和氮素损失动态过程的定量关系等值得在今后的研究中关注.

4 结论

(1)黏性土壤无机氮的径向移动高于垂直移动;缓控释肥条播深施优化了土壤无机氮的时空分布特征,有利于增加小麦产量,减少麦田氨挥发和 N_2O 损失.

(2)肥料类型是影响麦田径流氮素流失的主要控制因子,不同类型肥料的径流氮素流失和发生时间密切相关,不能一概而论.

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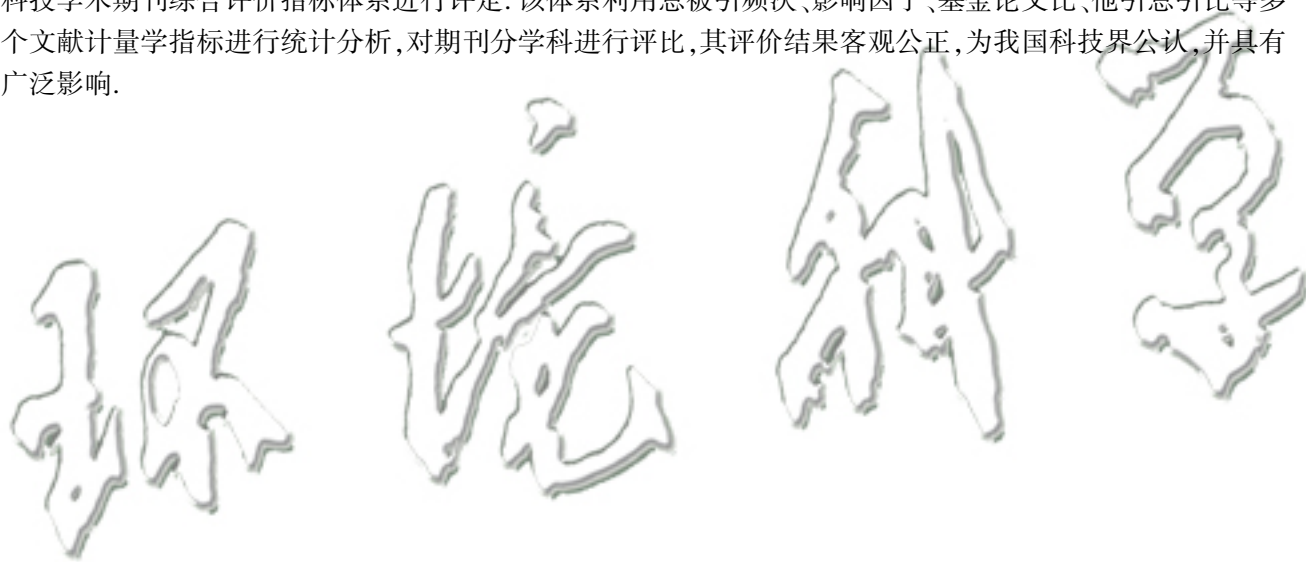
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《环境科学》再获“百种中国杰出学术期刊”称号

2021年12月27日, 中国科技论文统计结果发布会在北京举行, 会议发布了“百种中国杰出学术期刊”获奖名单. 《环境科学》连续20次荣获“百种中国杰出学术期刊”称号. “百种中国杰出学术期刊”是根据中国科技学术期刊综合评价指标体系进行评定. 该体系利用总被引频次、影响因子、基金论文比、他引总引比等多个文献计量学指标进行统计分析, 对期刊分学科进行评比, 其评价结果客观公正, 为我国科技界公认, 并具有广泛影响.



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