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施肥处理对旱地红壤反硝化潜势的影响

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摘要 为探究土壤反硝化潜势与施肥之间的关系,对长期定位试验地采用4种不同施肥处理:不施肥(CK)、施用氮磷钾肥(NPK)、施用有机肥(OM)、施用氮磷钾肥加有机肥(NPKOM),采用田间取样与实验室分析相结合的方法,测定了4种施肥处理下土壤的反硝化潜势,并结合土壤基本理化性质,比较分析不同施肥处理下土壤反硝化潜势的差异及其与环境因子之间的内在关系。结果显示:施用有机肥的土壤反硝化潜势最高,施用氮磷钾肥的土壤反硝化潜势最低。影响土壤反硝化潜势的主要因素有pH、有机质、全磷和速效磷。施用有机肥在提高土壤pH值的同时会提高土壤反硝化潜势,增加土壤 N_2O 的排放。氮磷钾肥会降低土壤的pH值导致土壤反硝化潜势降低。氮磷钾肥加有机肥混合施用提高土壤pH值的同时可以降低单施有机肥土壤反硝化潜势,并降低土壤 N_2O 的排放。

关键词 反硝化潜势;施肥方式;有机肥;氮损失;旱地;红壤

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氮是植物生长发育必需的元素之一,同时也是重要的农业产量限制因子。因此,在农业生产过程中,氮肥的合理使用可以有效提高农作物的产量并且对农业可持续发展产生重要影响。在氮素循环过程中,硝化作用会将土壤内铵态氮转换为易淋失的硝态氮,从而促进土壤反硝化作用过程,加剧土壤中氮素的挥发损失^[1]。研究表明,土壤反硝化作用中损失的氮量约占总施氮量的14%~40%^[2]。此外,反硝化作用过程产生的 N_2O ,是一种重要的温室气体,并会对臭氧层造成破坏,进而加剧全球气候变暖^[3]。因此,在我国碳达峰和碳中和的背景下,研究农田生态系统反硝化作用机制对减缓全球气候变化具有重要意义。

我国农业生产活动中,有机肥和无机肥的搭配施用一直以来被认为是提高作物产量与增加土壤有机质的最佳选择。丁洪等^[4]研究发现,不合理的施肥措施会显著影响土壤反硝化速率进而导致土壤氮损失量增加,长期施用氮肥对土壤反硝化有促进作用并且导致 N_2O 的大量排放^[5]。此外,Enwall等^[6]发现有机肥处理的反硝化潜势要显著高于无机

肥处理,但也有相关研究表明施用无机肥导致土壤反硝化排放的 N_2O 要显著高于施用有机肥^[7]。因此,研究不同施肥处理与土壤反硝化之间的关系能为解析农业生态系统土壤氮素损失途径提供重要参考。

国内外学者对于土壤反硝化作用已经开展了许多研究,其中大部分以土壤类型、土壤管理方式以及作物为主,并且发现土壤理化性质与土壤反硝化之间的关联,比如土壤的pH值、土壤含水量、土壤温度和土壤有机质含量等都会影响土壤反硝化潜势和 N_2O 的排放^[8-10]。研究发现土壤pH、有机碳和全氮含量被认为是影响土壤反硝化潜势较为重要的影响因子^[11-12]。Shao等^[13]发现不同施肥处理会导致土壤的pH值、 NO_3^- -N和 NH_4^+ -N的改变,并显著影响土壤的反硝化微生物群落。这些研究均表明施肥处理与土壤理化性质以及土壤反硝化作用之间有紧密的联系。

目前,关于施肥处理对土壤反硝化作用的影响研究^[7-15]多在较小的空间尺度内进行,并且各研究之间存在差异,对于揭示土壤施肥处理与土壤反硝

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化之间联系的特征尚显不足。因此,通过研究不同施肥处理土壤的反硝化潜势差异,掌握农业施肥方式对于土壤反硝化潜势的影响,对改善农业土壤氮循环、减少土壤 N_2O 排放具有积极意义。本研究采用长期定位试验,探究不同施肥处理对于土壤反硝化作用的长期影响。试验采集4种不同的施肥处理的田间土壤样品,对比分析土壤反硝化潜势和理化性状之间的相关性,阐明不同施肥处理土壤的反硝化作用差异以及影响土壤反硝化特征变化的影响因素,旨在为农业施肥中反硝化导致的氮流失和旱地红壤培肥提供理论支撑。

1 材料与方法

1.1 供试土壤

样品采集于江西省红壤研究所的红壤旱地施肥长期定位试验基地,该地位于江西省中部,亚热带季风气候,春夏降水较多,夏秋季较为炎热,地势起伏平缓,全年平均温度为 $16\sim 23\text{ }^\circ\text{C}$,无霜期平均为282 d,日照时数1 900~2 000 h,降雨量为1 500 mm左右,降水丰富但季节分配不均,4—7月、7—10月内降水分别占全年降水的37.8%和14.4%。土壤以红壤为主,土壤肥力水平中等,土壤全氮含量为0.11%,全磷含量0.12%,全钾含量1.35%,有机质15.95 g/kg,碱解氮90.64 mg/kg,有效磷67.34 mg/kg,速效钾146.72 mg/kg,可溶性有机碳0.29 g/kg,硝态氮9.24 mg/kg,铵态氮6.65 mg/kg,pH值5.5左右。

1.2 试验设计与样品采集

试验中采用4种施肥处理:不施肥处理(CK)、施氮磷钾肥处理(NPK)、施有机肥处理(OM)、施氮磷钾肥加有机肥处理(NPKOM),施肥情况详见表1。每个处理3个重复,总共12个小区(每个小区面积为 22.2 m^2)。CK、NPK、OM、NPKOM 4种施肥处理土壤的pH值分别为:5.09、4.72、6.28、5.94。样点之间设置有水泥隔离墙,防止样品交叉污染。采集不同处理0~15 cm的土壤,带回实验室进行分析。样品采集后,一部分置于 $4\text{ }^\circ\text{C}$ 冰箱保存,用于分析土壤反硝化潜势、pH和速效氮;一部分风干,用于有机质、全氮和土壤其他理化性状的分析。

1.3 土壤反硝化潜势测定

土壤反硝化潜势的测定参照Pell等^[16]的方法进行,称取25 g解冻鲜土放入125 mL广口瓶中, $25\text{ }^\circ\text{C}$ 过夜;次日加入25 mL底物(1 mmol/L葡萄糖和1 mmol/L KNO_3),橡胶塞密封广口瓶后用氮气填

表1 不同处理施肥量

Table 1 Statistical table of fertilizer application in different treatments kg/hm^2

处理	肥料及用量 Fertilizer and application amount
CK	不施肥 None
NPK	氮肥 Nitrogenous fertilizer:尿素 Urea 60
	磷肥 Phosphate fertilizer:钙镁磷肥 Calcium magnesium phosphate fertilizer(P_2O_5) 30
	钾肥 Potash fertilizer:KCl (K_2O) 60
OM	有机肥 Organic fertilizer:猪粪 Pig manure 15 000
	氮肥 Nitrogenous fertilizer:尿素 Urea 60
NPKOM	磷肥:钙镁磷肥 Phosphate fertilizer:Calcium magnesium phosphate fertilizer(P_2O_5) 30
	钾肥 Potash fertilizer:KCl (K_2O) 60
	有机肥:猪粪 Pig manure 15 000

充然后抽真空,重复3次,把瓶内的空气冲干净,最后1次将瓶内10%的氮气置换为乙炔,并使瓶内气压与瓶外气压保持一致。将广口瓶放入摇床培养6 h ($225\text{ r}/\text{min}$, $25\text{ }^\circ\text{C}$),每小时收集1次气体。采气方法为用5 mL注射器通过橡胶塞顶部的三通阀采集2 mL瓶内气体,充入12 mL真空气瓶中,再向气瓶中注入28 mL高纯氮气。气体样品采用气相色谱法检测 N_2O 浓度,所用仪器为安捷伦公司生产的GC7890A(Agilent, USA)。反硝化潜势的计算参照文献^[16]。

1.4 土壤理化性质测定

采用硫酸消化后的自动流动注射法测定全氮。采用氢氧化钠湿消化法和火焰光度法分别测定全磷和全钾。土壤有机碳用重铬酸钾氧化法测定。碱性水解氮用碱扩散法测定。速效磷在用0.5 mol/L碳酸氢钠提取后测定,速效钾用原子吸收光谱法(AAS)测定。土壤pH值采用电位法测定。通过在浓硫酸介质中用重铬酸钾氧化来测定土壤有机物含量。 NH_4^+-N 用KCl浸出法和靛蓝比色法测定, $NO_3^- -N$ 用紫外分光光度法测定^[17]。

1.5 数据处理与统计分析

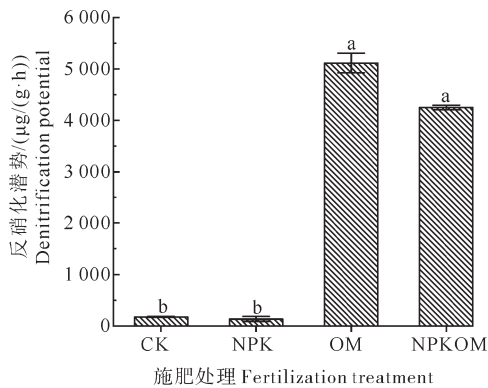
本研究数据的统计分析均采用SPSS软件(version 26.0, Chicago, Illinois, USA)进行。不同类型土壤理化性质和反硝化潜势的差异性分析采用单向方差分析法(one way ANOVA, LSD检验)。土壤理化性质与反硝化潜势的相关分析采用Pearson相关分析。采用Origin 2021软件作图。

2 结果与分析

2.1 不同处理的反硝化潜势影响

如图1所示,不同施肥处理间其反硝化潜势差异较大。施氮磷钾肥加有机肥(NPKOM)与施有机肥(OM)处理的反硝化潜势差异无显著差异($P>0.05$),2种施肥处理都有较高的反硝化潜势,其中OM处理的反硝化潜势最高,其反硝化潜势为5 306.55 $\mu\text{g}/(\text{g}\cdot\text{h})$,其次是NPKOM处理,其反硝化潜势为4 291.81 $\mu\text{g}/(\text{g}\cdot\text{h})$ 。CK与NPK处理的反硝化潜势分别为181.89和184.02 $\mu\text{g}/(\text{g}\cdot\text{h})$,均显著低于OM和NPKOM处理。

由图2可知,CK与NPK处理的 N_2O 排放量无显著差异,6 h内2个处理 N_2O 平均排放量分别为



CK:不施肥 No fertilization; NPK:施氮磷钾肥 Application of nitrogen, phosphorus and potassium fertilizer; OM:施有机肥 Application of organic fertilizer; NPKOM:施氮磷钾肥加有机肥 Application of nitrogen, phosphorus, potassium and organic fertilizer. 下同 The same as follows.

图1 不同施肥处理对旱地红壤反硝化潜势影响
Fig.1 Effect of different fertilization treatments on denitrification potential of dryland red soil

表2 土壤理化性质与土壤反硝化潜势相关性分析

Table 2 Pearson correlation analysis of physical and chemical properties of soils

	pH	全磷 TP	全钾 TK	全氮 TN	有机质 SOM	碱解氮 AN	速效钾 AK	速效磷 AP	土壤有机碳 SOC	铵态氮 $\text{NH}_4^+\text{-N}$	硝态氮 $\text{NO}_3^-\text{-N}$
Pearson相关性 Pearson correlation	0.978	0.983	0.042	0.351	0.995	0.948	0.289	0.991	-0.299	-0.033	-0.196
P	0.022*	0.017*	0.958	0.649	0.005**	0.052	0.711	0.009**	0.701	0.967	0.804
个案数 Cases No.	4	4	4	4	4	4	4	4	4	4	4

注 Note: TP: Total P; TK: Total K; TN: Total N; SOM: Soil organic matter; AN: Alkali-hydrolyzed nitrogen; AK: Available potassium; AP: Available phosphorus; SOC: Soil organic carbon. *: $P<0.05$; **: $P<0.1$.

3 讨论

土壤是 N_2O 产生的主要来源之一^[18]。本研究利用长期定位试验,分析不同施肥处理下土壤反硝化

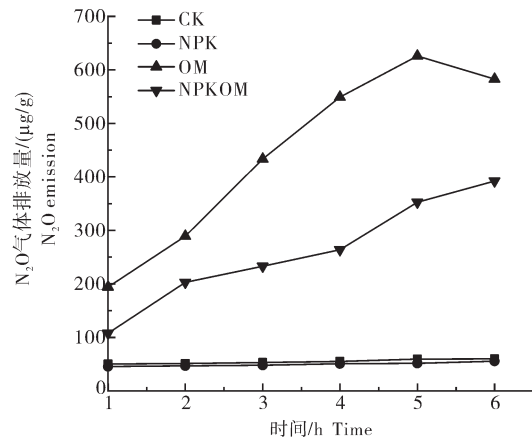


图2 不同施肥处理的土壤 N_2O 排放量动态变化图
Fig.2 Soil N_2O emission dynamics of different fertilization treatments

55.42 $\mu\text{g}/\text{g}$ 和50.05 $\mu\text{g}/\text{g}$ 。OM处理下 N_2O 排放量总体呈上升趋势,其中1 h的 N_2O 平均排放量为188.81 $\mu\text{g}/\text{g}$,1~6 h的 N_2O 平均排放量为512.44 $\mu\text{g}/\text{g}$,总平均排放量为410.75 $\mu\text{g}/\text{g}$ 。4种模式中OM施肥模式的 N_2O 排放量显著高于其他3种模式。NPKOM模式中 N_2O 排放量也呈上升趋势,其中1 h的 N_2O 排放量为93.09 $\mu\text{g}/\text{g}$,6 h的 N_2O 平均排放量为305.68 $\mu\text{g}/\text{g}$,6 h总平均排放量为198.89 $\mu\text{g}/\text{g}$ 。

2.2 土壤反硝化潜势和土壤理化性质的相关性

不同的施肥模式对土壤的反硝化潜势的影响有一定差异,为明确施肥方式对于土壤反硝化潜势的影响,对不同施肥方式下的土壤反硝化潜势与土壤理化性状进行Pearson相关性分析(表2),结果显示,pH值、全磷、有机质和速效磷对于4种施肥模式下土壤反硝化潜势有显著影响($P<0.05$)。

潜势的差异及其与环境因子之间的内在联系。研究结果表明,不同施肥处理下反硝化潜势介于88.50~5 306.55 $\mu\text{g}/(\text{g}\cdot\text{h})$,差异显著,整体上以施有机肥处理最高,氮磷钾加有机肥处理其次,施氮磷钾肥处理

最低。

土壤水分含量、土壤类型和土壤有机碳等均对土壤反硝化作用具有重要影响,而土壤pH被认为是影响土壤反硝化潜势最为关键的影响因素^[19-21]。通过对反硝化潜势和土壤理化性状的相关性分析,发现pH值与不同施肥处理下的土壤反硝化潜势存在极显著的正相关关系。Yin等^[22]研究发现施用无机肥会显著降低土壤pH值并显著影响反硝化细菌群落丰度,导致反硝化潜势降低。Herold等^[23]的研究也发现低pH值会限制土壤反硝化微生物的活动,从而影响土壤反硝化潜势。并且相关研究表明,土壤中较低的pH可能导致反硝化微生物可利用的有机碳和矿质氮的有效性下降,从而限制土壤的反硝化作用^[24]。本研究中施氮磷钾肥处理(NPK)下土壤pH值最低,平均为4.72,因此,我们推测无机肥的施用会导致土壤pH值降低并限制反硝化微生物的活动,导致较低的反硝化潜势。

前人研究发现,有机肥处理(OM)与施氮磷钾肥加有机肥处理(NPKOM)会影响土壤pH值,同时N₂O排放量有显著差异^[25],本研究也得到类似结果。施用有机肥可以有效提高作物产量,但同时也会提高土壤的反硝化潜势。林伟等^[7]研究发现在较高pH值的土壤施用有机肥后会促进反硝化作用,但排放的N₂O显著低于施用无机肥处理的土壤,说明在碱性土壤内适当提高有机肥比例可以减缓N₂O排放。但Pelster等^[26]发现有机肥相对于无机肥在提高土壤pH同时会带来更高的N₂O排放量。土壤反硝化作用出现差异的原因可能是不同土壤pH值导致的。因此,不同肥料尤其是有机肥料影响土壤反硝化潜势的具体机制尚需要进一步研究,但不同施肥处理对于土壤反硝化作用以及N₂O排放的影响应得到重视。

除了土壤pH值以外,土壤有机质(SOM)对土壤反硝化潜势也有显著影响。研究发现在短时间内施加外源有机质对于土壤反硝化有促进作用,同时会增加土壤N₂O的排放率和累积量^[27-28]。因此,有机肥的施用导致土壤有机质含量上升,并为反硝化微生物生长和活动提供有机底物和厌氧的环境^[29],导致OM和NPKOM 2种施肥处理下反硝化潜势升高,同时N₂O排放量显著提高,本研究验证了这一点。

土壤有机残留物的沉积在短期内增加N₂O的排放速率之后,可能是由于残留物中最不稳定的部分被分解后,排放量会回归较低值^[30]。本研究施有机

肥(OM)模式下反硝化潜势在5~6 h呈下降趋势,说明引起土壤N₂O排放的有机质可能要被分解殆尽,导致反硝化潜势减弱,N₂O排放量减少。此外,全磷和速效磷对于土壤反硝化潜势也有显著影响,磷是基因合成和细胞组成、代谢和能量传递所必需的元素,磷的有效性也会影响微生物的活动。Mehnaz等^[31]发现反硝化作用受到土壤中磷供应的限制。Mori等^[32]也发现在土壤施用磷肥后会刺激土壤的异养菌群的活性从而增加土壤反硝化潜势,并且导致土壤N₂O的排放量增加。

本研究结果表明,不同施肥处理对于旱地红壤反硝化潜势影响有显著差异,4种不同处理的表现分别为施加有机肥处理的土壤反硝化潜势最高,其次是施用氮磷钾加有机肥处理的土壤,而单施用氮磷钾肥处理的土壤反硝化潜势最低。本试验测定的土壤性状中,土壤的pH值、SOM、TP和AP可能是导致不同处理下土壤反硝化潜势差异的主要因素。因此,为保持土壤肥力同时减少N₂O温室气体排放,应考虑有机肥和氮磷钾肥混合施用,并充分考虑土壤特征,因地制宜采取相应措施。

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Effect of fertilization treatments on denitrification potential on upland red soil

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Abstract Four fertilization treatments including no fertilization (CK), nitrogen, phosphorus and potassium fertilization (NPK), organic fertilization (OM), and nitrogen, phosphorus and potassium organic fertilization (NPKOM) were applied to the long-term positioning test sites. The denitrification potential of soil under the four fertilization treatments was determined by a combination of field sampling and laboratory analyses. The differences of soil denitrification potential under different fertilization treatments and its intrinsic relationship with environmental factors were compared and analyzed based on the basic physical and chemical properties of soil to study the relationship between the denitrification potential of soil and fertilization treatments. The results showed that the denitrification potential of soil with organic fertilizer was the highest, and that of soil with NPK fertilizer was the lowest. The main factors affecting soil denitrification potential were pH, organic matter, total phosphorus and fast available phosphorus. The application of organic fertilizer increased soil denitrification potential and N₂O emission while increasing soil pH. Nitrogen, phosphorus and potassium fertilizer reduced the soil pH, leading to the reduction of soil denitrification potential. The mixed application of NPK and organic fertilizer can increase soil pH, reduce soil denitrification potential of single application of organic fertilizer, and reduce soil N₂O emissions.

Keywords denitrification potential; fertilization methods; organic fertilizer; loss of nitrogen; dry land; red soil

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