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寿光设施菜地土壤 N_2O 排放规律及其影响因素*

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摘 要 设施栽培是我国蔬菜生产的重要方式之一.设施菜地土壤高温、高湿、持续且大量施肥等特点,可能改变土壤氮素周转及 N_2O 排放.寿光是我国重要的蔬菜生产基地之一.然而,鲜有研究关注寿光市设施菜地土壤 N_2O 排放规律及其影响因素.本文以寿光市农田、种植6、12年设施菜地及荒废设施菜地为例,研究农田转变为设施菜地后土壤 N_2O 排放规律,并探讨其影响机理.结果表明,设施菜地土壤 N_2O 年排放量明显高于农田及荒废设施菜地,且种植6年设施菜地土壤 N_2O 年排放量显著大于种植12年设施菜地($P<0.05$).其原因可以归结为:(1)设施菜地种植过程中施加大量有机肥及化肥,会促进土壤氮素周转.(2)设施菜地土壤温度、含水率及硝态氮含量均高于农田,且均与土壤 N_2O 排放通量呈显著正相关关系($P<0.05$),表明设施菜地土壤高温、高湿的环境特点会促进土壤硝化过程,加速土壤 N_2O 排放.(3)设施菜地具有较高的土壤脲酶活性,且与土壤硝态氮含量、含水率呈显著正相关关系($P<0.05$),表明农田变为设施菜地增加了土壤脲酶活性,促进土壤硝化过程及硝态氮累积,这可能间接加速土壤 N_2O 排放.

关键词 设施菜地, N_2O 排放, 寿光市, 土壤.

N_2O emission from the greenhouse soils in Shouguang City, northern China

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Abstract: Nitrous oxide (N_2O) is an important greenhouse gas. Greenhouse is a vital method of vegetable production in China. Due to high soil temperature, moisture and continuous and large quantities of fertilizer application, these factors may change the nitrogen cycling and N_2O emissions. Shouguang city is one of the largest bases for vegetable production in China where many farmland (FL) were changed into greenhouse for the vegetable production. However, little attention has been paid to the N_2O emissions from the greenhouse soils in Shouguang city. In the present study, farmland(FL), greenhouse soils that were cultivated for 6 (6GH) and 12 (12GH) years and greenhouse abandoned for 12 years (AG) were taken as samples to investigate the variation of soil N_2O emissions along the changes from FL to greenhouse and AG. The results showed that FL had similar annual N_2O emissions with AG. Greenhouse had higher annual N_2O emissions compared with FL, while the annual N_2O emission in 6GH was larger than that in 12GH. It may be attributed to the following reasons. (1) More organic fertilizer were applied in the greenhouse soils compared with

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FL, which may supply more available substrates for the soil microbes. (2) Greenhouse had higher soil temperature, moisture and nitrate concentration compared with FL. These factors also had positive relationships with N_2O emissions, which indicate that the increased soil temperature and moisture in greenhouse soils may promote the nitrification and then the N_2O emissions. (3) Alteration from FL to Greenhouse enhanced urease activity. The urease activity had positive relationships with soil nitrate and moisture, respectively. These indicate that the increased urease activity may enhance the accumulation of soil nitrate and indirectly accelerate the N_2O emissions through affecting the nitrification. When the greenhouse was cultivated over ten years, the application of fertilizer reduced. This may decrease the supply of available substrates and thus N_2O emission.

Keywords: greenhouse soils, N_2O emission, Shouguang City, soil.

N_2O 是一种重要的温室气体,其温室效应是 CO_2 的 298 倍[1].据估计,全球 38%的 N_2O 来自于农业土壤排放[1-2].由于氮肥及有机肥的施加,农业土壤 N_2O 排放将进一步增加[3].土壤 N_2O 排放主要受硝化[4]及反硝化[5]过程影响.研究表明,土壤 N_2O 排放主要来自于反硝化过程[6-7].然而,其它研究发现,异养硝化过程也是土壤 N_2O 排放的主要来源,占土壤 N_2O 排放总量的 27%—85%[8-11].土壤温度[12]、水分[13]及施肥[14-15]等因素能显著改变土壤的硝化/反硝化速率,进而影响 N_2O 排放.

温度是影响土壤 N_2O 排放的主要因素之一.增温促进土壤硝化[12]和反硝化过程[16],进而加速土壤 N_2O 排放.土壤水分是影响土壤 N_2O 排放的另一主要因素.研究表明,土壤含水率增加促进土壤 N_2O 排放,且最大排放通量发生在 60%—80%最大持水量(WHC)条件下[13,17].因为较高的土壤含水率限制氧气在土壤中扩散,进而提高土壤反硝化速率,促进 N_2O 排放[17].也有研究发现,土壤硝化过程是 N_2O 产生的主要来源,其发生在土壤含水率低于 60% WHC 条件下[18].施加有机肥为土壤微生物提供较多养分,可能提高土壤反硝化细菌活性[14],或提高土壤硝化速率[15],促进土壤 N_2O 排放.此外,施加氮肥能促进土壤 N_2O 排放[19],且该促进作用随土壤温度及含水率变化而不同[12].设施栽培是我国蔬菜生产的重要方式之一,设施菜地土壤高温、高湿、持续且大量施肥等特点[20],可能改变土壤氮素转化过程,影响土壤 N_2O 排放.

寿光市是我国主要的蔬菜生产基地之一,超过 50%的农田转变为设施菜地,生产反季节蔬菜[21].为提高蔬菜产量,种植过程中长期施加大量有机肥及化肥,且灌溉频繁[20].由于设施菜地常处于半封闭状态,土壤温度高于外部,在冬季尤为明显[21].设施菜地独特的土壤环境特点,可能影响土壤氮素转化,改变土壤 N_2O 排放.然而,鲜有研究报道寿光市农田变为设施菜地后土壤 N_2O 排放规律及其影响因素.

本文以寿光市为例,利用原位监测手段研究农田(对照)、种植 6、12 年设施菜地及荒废 12 年设施菜地土壤 N_2O 排放规律及其影响因素.以期明确农田转变为设施菜地后土壤 N_2O 排放过程及其影响因素,为设施菜地土壤温室气体减排提供依据.

1　材料与方法(Materials and methods)

1.1　研究区概况

研究区位于山东省寿光市.该区年均降水量 594 mm,年均气温 12.7 ℃.据调查,农田为玉米-冬小麦轮作,年均施化肥量($N:P_2O_5:K_2O=15:15:15$)为 1.27 $t\cdot hm^{-2}$.研究区设施菜地为蔬菜大棚(长×宽 = 80 m×10 m).1 年种植 2 茬蔬菜,换茬蔬菜主要为黄瓜、辣椒,生长季为 1—7 月初、8 月下旬—12 月.7 月中旬—8 月下旬施加一次有机肥(干鸡粪)作为底肥(7 月中下旬施加),并将蔬菜大棚密封、休耕,期间无灌溉及施加化肥等耕作措施.12 月底至次年 1 月初蔬菜换茬时再施加等量的有机肥(干鸡粪).每个大棚每次有机肥施加量为 3 t (种植 6 年设施菜地)、2.88 t (种植 12 年设施菜地).生长季定期施加水溶性复合肥($N:P_2O_5:K_2O=22:14:14$),每个大棚每次施加 15 kg(种植 6 年设施菜地)、10 kg(种植 12 年设施菜地),每隔 7—10 d 施加 1 次,随同灌溉施用.第二次全国土壤普查资料表明,转变为设施菜地前农田的基本理化性质具有相似性[22].荒废设施菜地(荒废 12 年)的保温措施均已撤除,生长杂草.

1.2 样品采集与测试

1.2.1 气体样品采集与测试

选取农田(对照)、种植 6、12 年设施菜地及荒废 12 年设施菜地为研究对象.农田选取 3 块相邻的固定样地,每块样地面积为 50 m × 50 m;每类设施菜地均选取 3 个相邻的大棚作为固定样地.实验开始前 1 个月,在每块样地或每个大棚中心设置一个位置固定的基座(长×宽×高=50 cm × 50 cm × 20 cm),基座插入土中 16 cm,地上留深度 4 cm 水槽.除翻耕土地外,基座位置固定,减少频繁插入基座对土壤的干扰.土地翻耕后,基座重新插入原位置.

2015 年 9 月—2016 年 8 月,每月选取天气晴朗的 3 d,利用静态箱采集气体样品.静态箱尺寸长×宽×高=50 cm × 50 cm × 50 cm,外包白色保温材料,内置风扇,以保证取样时箱内气体均匀.当作物植株高度超 45 cm 时,再接一个外包白色保温材料的延长箱(长×宽×高=50 cm × 50 cm × 100 cm),避免采样时影响作物生长.每次的采样时间设定在 9:00—11:00.采样时,将静态箱插入基座水槽内,并在槽内灌水、密封箱体.密封后第 0、10、20、30 min 用注射器从箱内抽取气体每次 100 mL,存贮于真空气袋内.同步观测 5 cm 深度土壤温度及箱内气温.N_2O 含量采用气相色谱(Agilent 7890A, USA)测试,N_2O 排放通量根据 Song 等的方法计算[23]:

$$\mathrm{NE} = \frac{\mathrm{d}C}{\mathrm{d}t} \cdot \frac{M}{V_0} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \cdot H$$

其中,NE 为 N_2O 排放通量($\mathrm{mg \cdot m^{-2} \cdot h}$);$C$ 为气体浓度($\mathrm{\mu g \cdot m^{-3}}$);$\mathrm{d}C/\mathrm{d}t$ 为采样时气体浓度随时间变化的直线斜率;M 为被测气体摩尔质量;p 为采样点气压;T 为采样时绝对温度;V_0、P_0、T_0为标准状态下气体摩尔体积、气压及空气绝对温度,H 为采样箱高度.所测通量数据,只有当回归系数 $R^2>0.95$ 时才视为有效数据.

N_2O 年排放总量采用如下公式计算,

$$A = \sum_{i=1}^{12} (\mathrm{NE}_i \times D \times 24 \times 10^{-6})$$

其中,A 为年排放总量($\mathrm{g \cdot m^2}$);NE_i为每月 3 次观测排放通量均值($\mathrm{\mu g \cdot m^{-2} \cdot h^{-1}}$, $n=9$);D 为每月天数.

1.2.2 土壤样品采集与测试

每月最后一次采集气体样品结束后,于每块样地采集 5 个 0—10 cm 深度土壤样品并混匀,保存于铝盒内,于 4 h 内送回至实验室、4 ℃冷藏.土壤样品用于分析土壤含水率、硝态氮及氨态氨含量、脲酶活性.脲酶活性采用靛酚蓝比色法测试[24];硝态氮及氨态氮含量采用比色法、土壤含水率采用烘干法测试[25].2015 年 9 月采集土壤样品,取部分风干、研磨、过 0.15 mm、2 mm 筛,用于测试土壤有机碳及全氮含量、pH、土壤机械组成及土壤最大持水量(WHC),并取原状土测试土壤容重.土壤有机碳采用重铬酸钾容量法,全氮采用开氏法,土壤 pH 采用电位法,土壤机械组成采用比重计法,容重采用环刀法测试[25].土壤最大持水量采用 Rey 等的方法[26].土壤基本理化性质见表 1.

表 1 土壤理化性质

Table 1 Basic characteristics of soils in research sites

	SOC/($\mathrm{g \cdot kg^{-1}}$)	TN/($\mathrm{g \cdot kg^{-1}}$)	BD/($\mathrm{g \cdot cm^{-3}}$)	WHC/%	机械组成 Soil texture/%		
					砂粒 Sand (2—0.05 mm)	粉粒 Silt (0.05—0.002 mm)	黏粒 Clay (<0.002 mm)
FL	13.41±0.77c	1.01±0.07c	1.15±0.01b	39.84±0.16c	21.26±0.62b	57.92±0.08a	20.93±0.55b
6GH	26.28±0.25a	3.51±0.21a	0.86±0.01d	59.26±0.41a	23.79±1.17ab	53.71±1.13b	22.51±0.04b
12GH	18.58±0.47b	1.85±0.05b	1.05±0.01c	44.10±3.08b	21.00±2.76b	53.91±1.61b	25.10±1.61a
AG	13.39±0.92c	1.32±0.05c	1.25±0.05a	45.65±1.27b	26.21±1.08a	52.48±1.06b	21.32±0.01b

注:表中数据为平均值±标准差.FL 为农田;6GH、12GH 分别为种植 6、12 年设施菜地;AG 为荒废设施菜地;SOC 为土壤有机碳;TN 为土壤全氮;BD 为土壤容重;WHC 为土壤最大持水量.每列不同字母代表显著差异,$P<0.05$.

Note: Data is average value ± standard deviation. FL is the farmland. 6GH and 12GH are the greenhouse soils that were cultivated for 6 and 12 years, respectively. AG is the abandoned greenhouse soil. SOC is the soil organic carbon. BD is the soil bulk density. WHC is the water holding capacity. Different lowercase in each column indicate significant differences in mean among land use types ($P<0.05$).

1.3 数据分析

土壤理化性质、N_2O 年排放量、环境因子及脲酶活性在不同样地类型间的差异采用单因素方差分析检验.各因素之间的相关性采用 Pearson 相关系数检验.统计显著水平 $P=0.05$.采用 Excel2007 及 SPSS13.0 软件对相关数据进行统计分析.采用 Origin9.0 软件作图,图中误差棒代表标准差,不同的小写字母代表每月各样地间有显著差异($P<0.05$).

2 结果与讨论(Results and discussion)

2.1 不同土地利用方式对土壤 N_2O 排放的影响.

研究区土壤 N_2O 年排放量分别为种植 6 年设施菜地(4.62 ± 0.43 g·m^{-2})>种植 12 年设施菜地(1.43 ± 0.20 g·m^{-2})>农田(0.11 ± 0.02 g·m^{-2})>荒废设施菜地(0.012 ± 0.003 g·m^{-2}).方差分析显示,设施菜地土壤 N_2O 年排放量显著高于农田,且种植 6 年设施菜地明显高于种植 12 年设施菜地($P<0.05$),农田与荒废设施菜地无显著差异(图 1).研究表明,施加有机肥显著促进土壤 N_2O 排放[27-28].施加有机肥增加了农业土壤硝态氮含量及 N_2O 排放,表明硝化过程是产生 N_2O 的主要过程[15].原位监测结果表明,设施菜地土壤 N_2O 年排放量显著高于农田,且种植 6 年设施菜地的土壤 N_2O 排放量显著高于种植12 年的设施菜地($P<0.05$);设施菜地荒废 12 年后土壤 N_2O 年排放量与农田无显著差异.冗余分析结果显示,研究区内设施菜地土壤氨氧化细菌丰度与土壤有机碳及硝态氮含量相关,且土壤硝化过程主要受氨氧化细菌调节[29].设施菜地在种植过程中施加了大量有机肥及化肥(表 1),为土壤微生物提供较多的能量,有利于土壤氮素的转化,加速土壤 N_2O 排放.随着种植年限的增长,设施菜地易产生连作障碍[30],有机肥及化肥施加量有所下降,降低了易分解有机质组分的供应,减少了土壤微生物能量来源,导致种植 12 年设施菜地土壤 N_2O 排放下降.此外,设施菜地土壤容重显著小于农田,且种植 6 年设施菜地土壤容重明显小于种植 12 年设施菜地($P<0.05$;表 1),表明设施菜地较农田具有较大的土壤孔隙度,这可能促进土壤 N_2O 向大气中扩散.

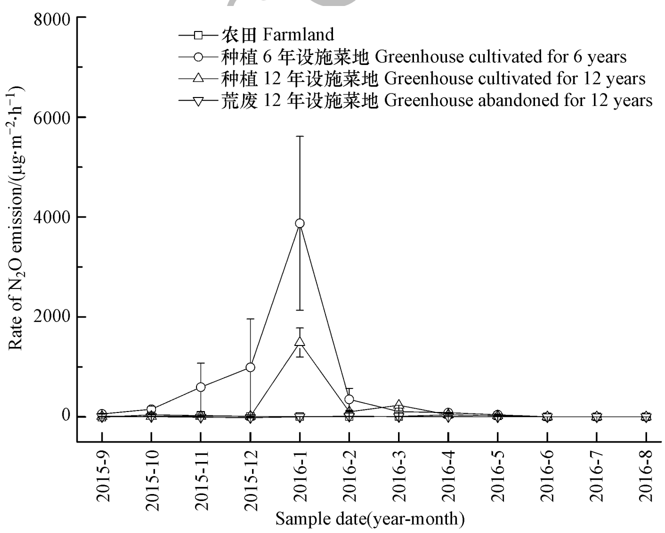

图 1　土壤 N_2O 排放通量

Fig.1　The rate of N_2O emissions.

2.2 土壤理化属性对 N_2O 排放的影响

通常,土壤温度[31]及含水率[32]分别与土壤 N_2O 排放通量呈显著正相关关系.土壤温度增加促进土壤硝化过程,加速土壤 N_2O 排放[12,33].灌溉或明显降水后,农业土壤往往保持较高的 N_2O 排放水平[34].本研究发现,设施菜地土壤温度及含水率明显高于农田($P<0.05$).2015 年 11 月至次年 3 月间,设施菜地与农田保持较大的土壤温差,2016 年 1 月尤为显著($P<0.05$,图 2、3).由于设施菜地种植过程中的保温措施及频繁灌溉,其土壤温度及含水率均显著高于农田及荒废 12 年设施菜地($P<0.05$,图 2、3),且土

壤温度、含水率及 N_2O 排放通量间呈显著正相关关系(表 2).表明设施菜地高温、高湿的土壤环境特点,提高了土壤氮素的周转速率,进而加快土壤 N_2O 排放.

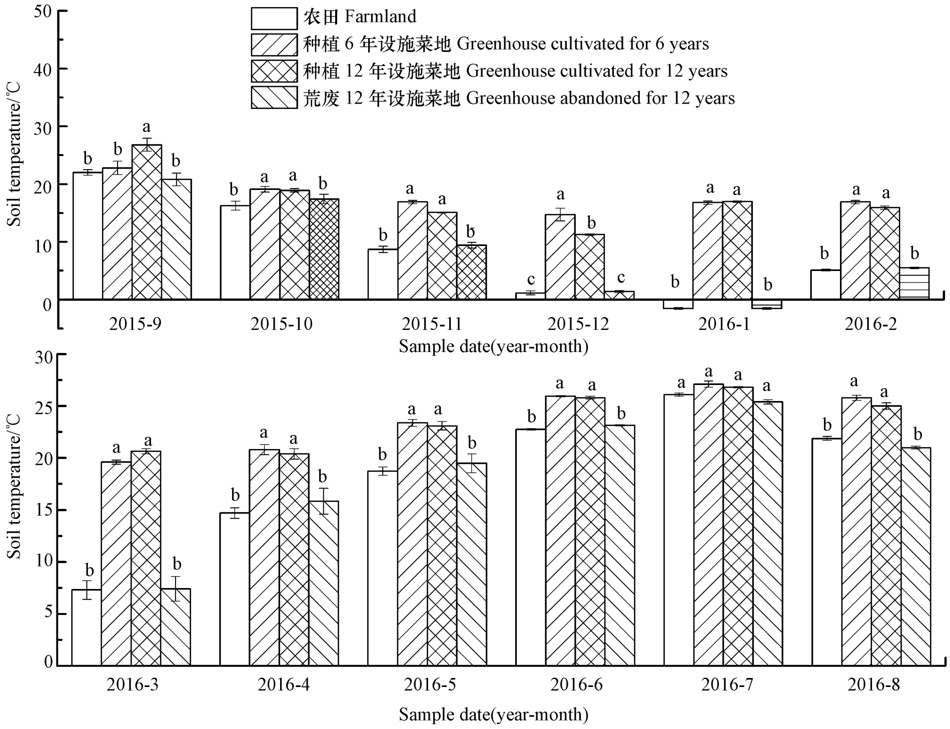

图 2 研究区 0—5cm 土壤温度

Fig.2 Soil temperature at the depth of 5 cm

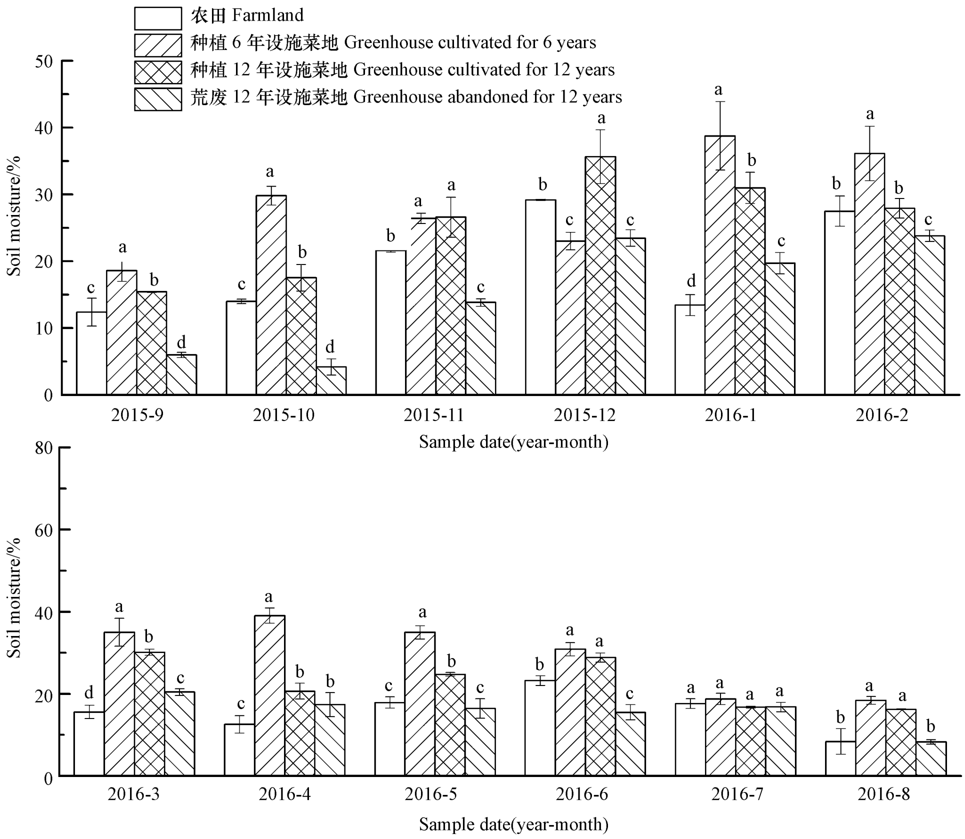

图 3 研究区 0—10 cm 土壤含水率

Fig.3 Contens of soil moisture at the depth of 10 cm

设施菜地土壤 N_2O 排放通量峰值出现在 1 月份(图 1).2015 年 11 月至次年 3 月间,种植 6、12 年设施菜地土壤 N_2O 排放量分别占年排放总量的 94.56%、95.72%,而农田仅为 37.45%.2016 年 1 月,种植 6、12 年设施菜地土壤 N_2O 排放量分别占年排放总量的 62.43%、77.43%,而农田仅为 2.73%.表明设施菜地土壤 N_2O 排放在年内分配极不均匀.据调查,12 月底至次年 1 月初为蔬菜换茬时期,设施菜地施入了大量有机肥作为底肥,这可能为微生物活动提供了大量的可利用底物,有利于提高微生物活性,促进土壤氮素的转化,从而产生 N_2O 排放高峰.张仲新等也发现,设施菜地翻耕、施入大量有机肥后,导致蔬菜苗期土壤 N_2O 排放量较大[35],与本研究结果类似.此外,7 月份设施菜地虽然也施加一次有机肥,但7 月中旬至 8 月下旬设施菜地处于休耕期,无灌溉及化肥施用,这可能是导致 7、8 月份未观测到 N_2O 排放高峰的原因.

表 2　土壤 N_2O 排放通量与土壤属性相关关系

Table 2　The Pearson′s relationship between N_2O emission and soil properties

	脲酶 Urease activity	NH_4-N	NO_3-N	土壤温度 Soil temperature	土壤含水率 Soil moisture	N_2O 排放通量 N_2O emission rate
脲酶 Urease activity	1.000	−0.212*	0.229**	0.122	0.225**	−0.053
NH_4-N			0.167*	0.083	0.001	0.190*
NO_3-N				0.290**	0.392**	0.575**
土壤温度 Soil temperature					−0.107	0.235**
土壤含水率 Soil moisture						0.388**

注:** 差异显著水平,$P<0.01$.Correlation is significant at the 0.01 level (2-tailed). * 差异显著水平,$P<0.05$.Correlation is significant at the 0.05 level (2-tailed).

研究发现,土壤硝态氮含量与土壤 N_2O 排放通量呈显著正相关关系,表明硝化过程是控制农业土壤 N_2O 排放的主要过程[15].然而,也有研究发现,农业土壤大部分 N_2O 排放来自反硝化过程[6].当土壤含水率低于 60%WHC 时,土壤氮素转化以硝化过程为主[18].本研究发现,多数月份设施菜地土壤含水率低于 60%最大持水量(图 3).而且,种植 6 年设施菜地土壤硝态氮含量明显高于农田($P<0.05$),10、11 月除外.2、4、5、6、7、8 月种植 6 年设施菜地土壤硝态氮含量大于种植 12 年设施菜地($P<0.05$),其它月份种植 6 年设施菜地土壤硝态氮含量小于种植 12 年设施菜地($P<0.05$)、或无显著差异.农田与荒废设施菜地硝态氮含量无显著差异 (图 4).同时,全年大部分月份设施菜地土壤氨态氮含量小于农田、或与农田无显著差异,仅 8、11、12 月份设施菜地土壤氨态氮含量大于农田($P<0.05$),农田与荒废设施菜地氨态氮含量无显著差异(图 5).此外,土壤硝态氮含量与 N_2O 排放通量、土壤温度、含水率均呈显著正相关关系(表 2). 综上所述,设施菜地较高的土壤温度可能加速硝化过程,降低土壤氨态氮含量,促进硝态氮累积,进而提高 N_2O 排放.这也说明研究区土壤 N_2O 排放主要来自于硝化过程.

2.3　土壤酶活性对 N_2O 排放的影响

土壤酶活性可以调节土壤氮素转化速率[36],进而影响土壤 N_2O 排放.近期研究发现,脲酶活性与土壤有机质含量呈显著正相关关系[37],且施用化肥能明显提高土壤脲酶活性[38].本研究发现,种植 6 年设施菜地土壤脲酶活性显著高于农田($P<0.05$),种植 12 年及荒废设施菜地全年大部分月份土壤脲酶活性与农田无显著差异(图 6).其原因可能是设施菜地持续且大量施加有机肥及化肥,为脲酶提供了较多的酶促底物.此外,脲酶活性与硝态氮含量及土壤含水率呈显著正相关关系,但与土壤 N_2O 排放通量无显著相关关系(表 3).由此推测,农田变为设施菜地提高了脲酶活性,促进了酶促产物-氨态氮的产出及土壤硝化过程,间接加速土壤 N_2O 排放.

研究表明,施肥、灌溉措施对菜地土壤 N_2O 排放有“激发效应”,施肥、灌溉后土壤 N_2O 排放易出现峰值,其后随时间推移排放水平逐渐降低[39].因此,采样时间对土壤 N_2O 排放水平将产生明显的影响.由于不同样地,尤其是两种类型设施菜地的施肥及灌溉时间不统一,本研究未区分灌溉及施肥前后土壤 N_2O 排放水平的差异.后续研究应该侧重对比灌溉及施肥前后土壤 N_2O 排放速率的变化,并加密采样时间,以期更为精确地研究不同利用方式农业土壤 N_2O 排放水平.

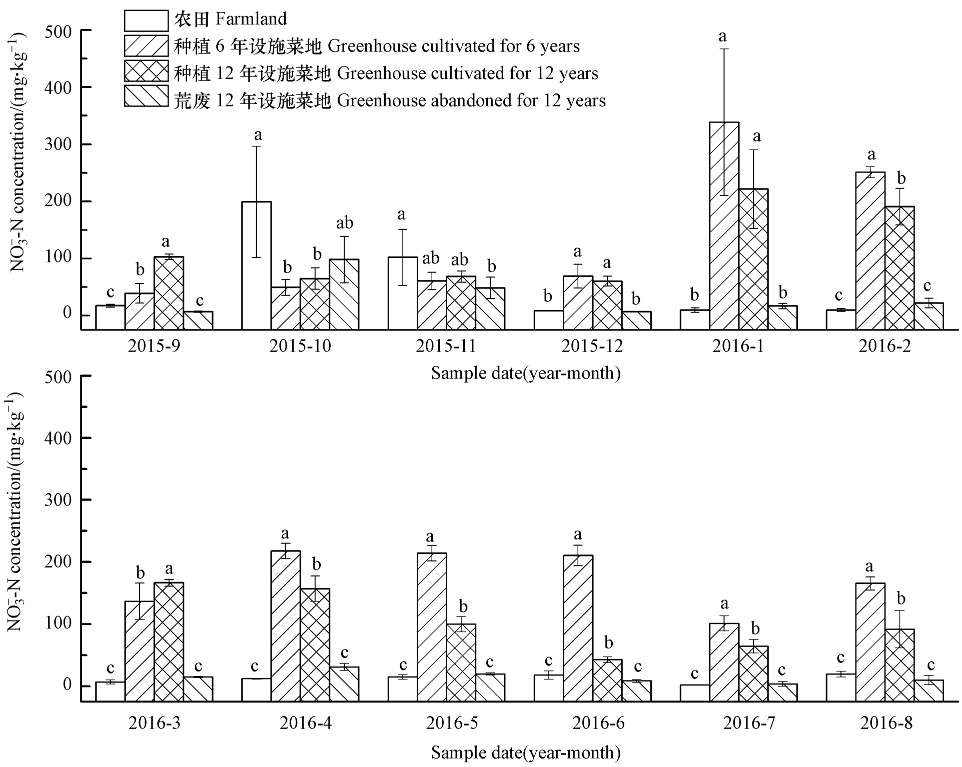

图 4 土壤硝态氮含量

Fig.4 Concentration of soil nitrate

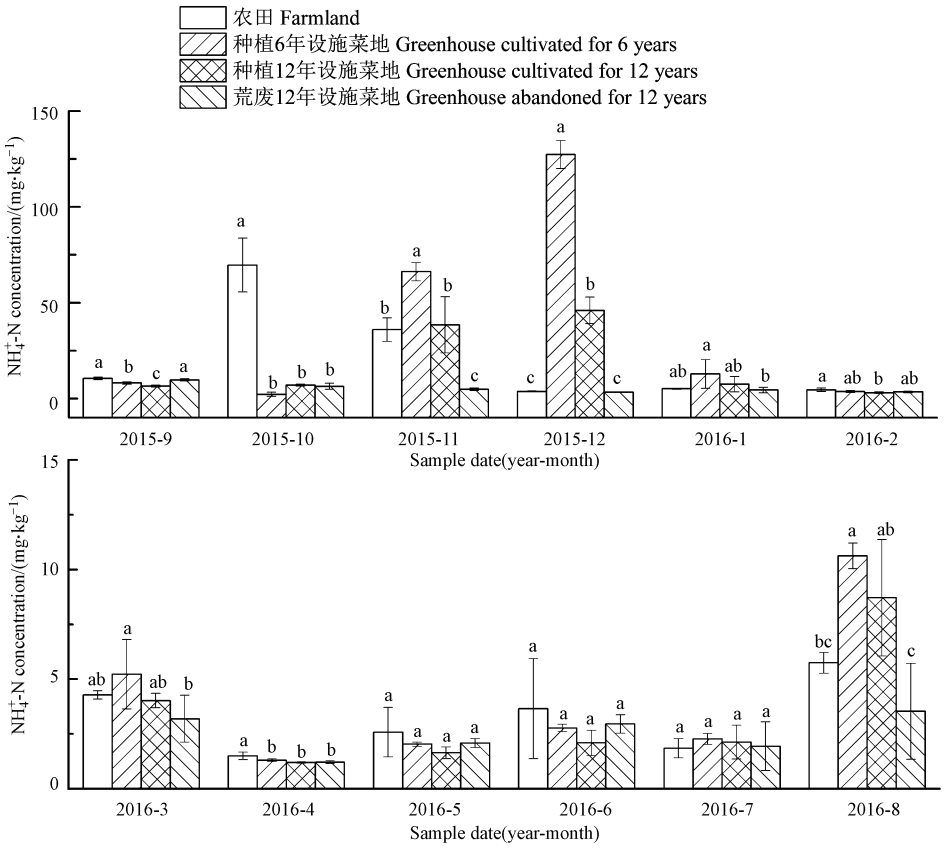

图 5 土壤氨态氮含量

Fig.5 Concentration of soil ammonium

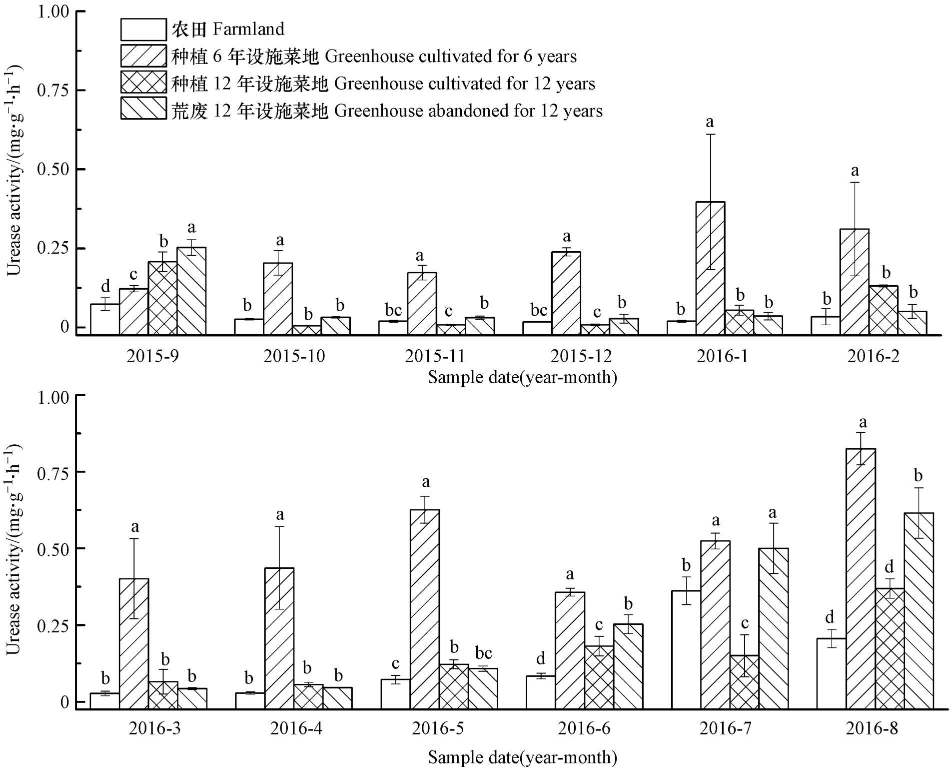

图 6　土壤脲酶活性

Fig.6　The urease activity in soil

3　结论（Conclusion）

（1）设施菜地土壤高温、高湿、持续且大量施肥等环境特点，使其土壤 N_2O 年排放量显著高于农田，且种植 6 年设施菜地土壤 N_2O 排放量明显高于种植 12 年设施菜地.设施菜地荒废后土壤 N_2O 排放降至农田水平.

（2）设施菜地土壤 N_2O 排放年内分配极不均匀，约 95%的 N_2O 集中于 11 月至次年 3 月间排放.种植 6、12 年设施菜地，1 月 N_2O 排放量占全年的 62.43%和 77.43%.

（3）农田变为设施菜地提高了脲酶活性，促进了酶促产物氨态氮的产出及硝化过程，间接加速土壤 N_2O 排放.

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