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太湖地区稻麦轮作农田改葡萄园对土壤氮转化过程的影响

王　敬　张金波† 蔡祖聪

（南京师范大学地理科学学院，南京　210023；江苏省物质循环与污染控制重点实验室，南京　210023；江苏省地理信息资源开发与利用协同创新中心，南京　210023）

摘　要　采用^{15}N成对标记技术结合数值模型，测定太湖地区两种土地利用方式（稻麦轮作农田和葡萄园）下的土壤氮素初级转化速率，探讨了土地利用方式改变对土壤供氮和保氮能力的影响。结果表明，葡萄园土壤初级矿化速率高于稻麦轮作农田土壤，但是其NH_4^+-N 同化速率几乎可以忽略不计（0.02 mg kg^{-1} d^{-1}），自养硝化成为培养条件下葡萄园土壤NH_4^+-N 的唯一去向。葡萄园土壤初级自养硝化速率（15.85 mg kg^{-1} d^{-1}）显著高于稻麦轮作农田土壤（13.65 mg kg^{-1} d^{-1}），但两者初级异养硝化速率和NO_3^--N同化速率均接近零值。可见，太湖地区稻麦轮作农田改种为葡萄园后，土壤NH_4^+-N同化速率显著降低而自养硝化速率增加，由此导致更多的NO_3^--N在土壤中累积，进而可能增加土壤中N的淋溶和径流损失风险。

关键词　土壤氮素初级转化速率；^{15}N示踪；土地利用方式；土壤保氮能力

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目前，太湖地区面源污染日益严重，已经引发水体富营养化等环境问题。研究表明，农田土壤中过量N、P的淋失是水体面源污染的主要来源[1-2]。作为中国的五大主要水稻产区之一，太湖地区水稻种植面积占其总耕地面积的75%，其主要耕作制度是夏水稻-冬小麦轮作[3]。然而，由于近年来人们对水果需求的持续增长，太湖地区稻改果现象日益突出[4]。稻改果引起的土地利用方式和管理措施改变可能会影响土壤的理化性质，进而改变土壤N素循环及氮肥去向[5-8]。因此，深入研究不同土地利用方式下土壤N素的循环转化过程，对于发展合理的氮肥管理措施及提出控制面源污染的有效策略具有十分重要的意义。

已有大量研究报道了土地利用方式对土壤N素净转化速率的影响[9-11]。N素净转化速率是控制其转化的多种途径的初级转化速率综合作用的结果，如N素净矿化速率反映的是N素初级矿化速率与初级自养硝化速率、初级同化速率的差值，因此，净转化速率不能代表土壤真实的N素循环状态[12-13]。例如，土壤中NH_4^+-N和NO_3^--N浓度很低，并不表明土壤中没有发生矿化和硝化过程，可能只是因为矿化和硝化产生的NH_4^+-N和NO_3^--N已经被微生物同化所抵消[12-15]。Tlustos等对耕作和草地土壤的研究也发现，两种土壤净矿化速率相似，但初级矿化速率却相差约27倍[16]。所以，只有认识控制氮含量变化的各个氮转化途径的初级转化速率才能真正明确土地利用方式对土壤氮转化的影响。

迄今为止，定量研究土地利用方式对土壤氮素初级转化速率影响的报道很少，且主要集中在非农业用地转变为农业用地对土壤N转化的影响方

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† 通讯作者Corresponding author，E-mail：zhangjinbo@njnu.edu.cn

作者简介：王　敬（1988—），女，河南新乡人，博士研究生，主要研究土壤氮素转化。E-mail：jwangcxx@126.com

面[14，17-19]，鲜有研究涉及一种农业用地转变为另一种农业用地对土壤N素转化的影响。森林转变为农业用地通常会提高总硝化速率，这主要是长期施用氮肥的结果[19]，而绝大多数农业用地都在经历着长期施肥和持续耕作，因此，我们推测农业用地之间的转变对土壤N素初级转化速率的影响可能会与非农业用地转变为农业用地不同。对于稻麦轮作体系下的稻田土壤而言，尿素等铵态氮施入土壤后，除一部分经过氨挥发损失外，肥料氮主要通过硝化过程生成硝态氮。稻田土壤长期处于淹水状态，氨挥发和反硝化成为氮损失的主要途径，尤其是反硝化占稻田氮素损失的36.4%～48.2%[20-21]。作为太湖地区两种典型的农业土地利用方式，稻麦轮作农田和改种自稻麦轮作农田的果园的水分状况（稻麦轮作农田间歇性淹水，果园处于非饱和状态）和施肥管理措施（稻麦轮作农田不施有机肥，果园是有机无机肥配施）均明显不同。那么，受通气状况和施肥管理措施的影响，这两种土壤的N素初级转化过程（如硝化和反硝化）也将有所差异。本文以太湖地区稻麦轮作农田和改种自稻麦轮作农田的葡萄园为研究对象，采用15N示踪技术结合数值模型，研究土地利用方式改变对土壤N素初级转化过程和土壤保氮能力的影响。

1 材料与方法

1.1 土壤样品采集

研究区位于中国太湖流域竺山湾上游汇水区域的稻麦轮作农田和葡萄园（30°55′42″～31°33′50″N，119°53′45″～120° 36′15″E），流域年平均气温15～17 ℃，多年平均降水量为1 177 mm。两种土壤都是从湖积物发育而来的人为土，稻麦轮作农田土壤和葡萄园土壤的粒径组成分别为黏粒23.2%和17.6%，粉粒69.1%和69.9%，砂粒7.7%和12.5%。葡萄园改种自稻麦轮作农田，种植年限为5 a，供试土壤的主要理化性质见表1。稻麦轮作农田每年稻季和麦季施用尿素-N分别约为300和200 kg hm^{-2}，基本不施有机肥。葡萄园每年氮肥施入量为N 474 kg hm^{-2}，其中化学肥-N 250 kg hm^{-2}和有机肥-N 224 kg hm^{-2}。2013年11月采集0～20 cm的土样，每种土壤取3个空间重复样品之后混匀。新鲜土样采集之后即刻去除作物残茬等，过2 mm筛后于4 ℃保存备用。

1.2 土壤化学分析[22]

（1）土壤pH采用电位法测定，水土质量比2.5∶1；（2）土壤有机质含量采用重铬酸钾-外加热法测定，有机质含量乘以系数0.58得到土壤有机碳；（3）土壤全氮采用半微量开氏法测定；（4）土壤中NH_4^+-N和NO_3^--N的含量采用2 mol L^{-1} KCl（按水土质量比5∶1）浸提-MgO-定氮合金蒸馏法测定。

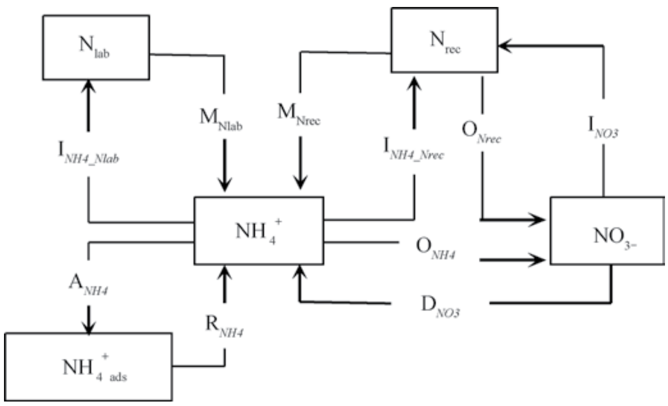
1.3 试验方法

本研究采用^{15}N成对标记技术结合基于Markov Chain Monte Carlo（MCMC）算法的数值优化模型[23]测定土壤氮素主要转化过程的初级转化速率。每个土壤分为两组标记处理：①标记NH_4^+-^{15}N处理，即加入$^{15}NH_4{}^{14}NO_3$溶液（^{15}N丰度为10.12%）和②标记NO_3^--^{15}N处理，即加入$^{14}NH_4{}^{15}NO_3$溶液（^{15}N丰度为10.21%），每组设置3个重复。具体方法：称取相当于20 g烘干土的鲜土样置于250 ml三角瓶中，用移液管均匀滴入1 ml $^{15}NH_4{}^{14}NO_3$或$^{14}NH_4{}^{15}NO_3$溶液，使NH_4^+-N和NO_3^--N的加入量均为N 100 mg kg^{-1}。随后将土壤含水量调节到60%最大持水量（WHC），置于25 ℃黑暗条件下培养6 d。分别在标记液加入后的第0.5 h、1 d、3 d、6 d破坏性取样，测定土壤中的NH_4^+-N、NO_3^--N的浓度及其^{15}N丰度。另外设置一组如上所述样品，用硅胶塞将三角瓶密封，置于25 ℃黑暗条件下培养，分别在第0、24、72、144 小时取气测定N_2O浓度。每次取气前进行换气，然后密封培养4 h。具体操作如下：将培养瓶用硅胶塞密封，用真空泵抽取培养瓶中的气体30 s后充入新鲜空气，接着再用真空泵抽30 s后充入新鲜空气，如此反复3次，确保培养瓶中充满新鲜空气。培养瓶换气后置于25 ℃黑暗条件下培养4 h，用注射器从各瓶的顶部空间取20 ml气体用于测定N_2O浓度。N_2O浓度用气相色谱仪（Agilent 7890；Agilent Technologies，Waldbronn，Germany）进行测定，电子俘获检测器温度设定为300 ℃。气体经过3 m长（内径2 mm）填满二乙烯基苯与乙烯基乙苯聚合物（80/100 的网）的分析柱，柱子温度维持在40 ℃，承载气体氩气-甲烷（5%）的速度为30 ml min^{-1}。

测定土壤中NH_4^+-N、NO_3^--N的浓度和^{15}N丰度的具体操作如下：将100 ml 2 mol L^{-1} KCl（按水土质量比5∶1）加入三角瓶中，于25 ℃ 250 r

min^{-1}下震荡1 h后过滤，取50 ml滤液，先加入0.25 g MgO使用凯氏定氮仪（SCINO KT260凯氏定氮仪）蒸馏3 min，用5 ml 20 g L^{-1}硼酸吸收蒸馏液，分离得到NH_4^+-N样品，再加入0.25 g氮氏合金继续蒸馏3 min得到NO_3^--N样品，之后用0.01 mol L^{-1} H_2SO_4标准液滴定得到的硼酸吸收液即可得到NH_4^+-N和NO_3^--N的浓度[24]。将上述蒸馏滴定并酸化的液体样品放于鼓风干燥箱中80 ℃条件下烘干得到$(NH_4)_2SO_4$晶体，之后用同位素质谱仪（Europa Scientific Integra 20-22，UK）测定$_{15}N$丰度。

本研究采用^{15}N成对标记技术测定土壤中多个氮素转化过程的初级速率[23]。基于MCMC算法的数值优化模型能同时计算10个氮素过程的初级转化速率（图1）：M_{Nlab}，不稳定性有机氮矿化为NH_4^+；M_{Nrec}，稳定性有机氮矿化为NH_4^+-N；$I_{NH4-Nrec}$，微生物同化NH_4^+-N进入稳定性有机氮库；$I_{NH4-Nlab}$，微生物同化NH_4^+-N进入不稳定性有机氮库；R_{NH4}，NH_4^+-N解吸，NH_4^+-N从阳离子交换位点解吸；A_{NH4}，NH_4^+-N吸附，NH_4^+-N吸附到阳离子交换位点上；O_{NH4}，NH_4^+-N氧化为NO_3^--N（自养硝化）；O_{Nrec}，稳定性有机氮氧化为NO_3^--N（异养硝化）；I_{NO3}，微生物同化NO_3^--N进入稳定性有机氮库；D_{NO3}，NO_3^--N异化还原为NH_4^+-N。模型运算时，根据不同氮素初级转化特征选取合适的动力学方程，如0级、1级或2级米氏方程。将^{15}N成对标记处理各取样点的NH_4^+-N和NO_3^--N的浓度和丰度（平均值±标准差）输入模型，选取合适动力学方程，运行模型即可得到各个N素初级转化速率。模型运算数据结果的好坏通常用数据输出文件中Aikaike信息标准（Aikaike's information criterion，AIC）值的大小来判定：AIC值是寻找最优动力学方程组合的依据，改值越小表明氮转化过程的动力学方程越适合。



注：Nlab，土壤不稳定性有机氮；N_{rec}，土壤稳定性有机氮；NH_4^+，土壤铵态氮；NO_3^-，土壤硝态氮；NH_{4ads}^+，吸附态铵态氮

Note：Nlab，soil labile organic-N；N_{rec}，recalcitrant organic-N；NH_4^+，soil NH_4^+-N；NO_3^-，soil NO_3^--N；NH_{4ads}^+，NH_4^+-N adsorbed on cation exchange sites

图1　土壤氮素初级转化速率的^{15}N示踪模型[23]

Fig. 1　^{15}N tracing model for analysis of gross soil N transformation rates

1.4　统计分析

基于MCMC算法的数值优化模型[23]计算氮素转化过程的初级转化速率的原理是：将培养期间氮素某一转化过程的总转化速率除以培养时间得到的平均值，即为该过程的初级转化速率[25]。由于^{15}N示踪模型运行会产生大量的迭代次数，因而无法使用统计分析方法比较参数的差异显著性[26]。因此，本研究是基于标准偏差和95%置信区间比较参数之间的差异性。当95%置信区间不重叠时表明参数之间差异显著[27]。同时，采用T检验比较稻麦轮作农田和葡萄园土壤之间的理化性质以及N2O累积排放量差异的显著性。

2　结　果

2.1　土壤理化性质

如表1所示，稻麦轮作农田改种为葡萄园使土壤pH显著降低。葡萄园土壤的有机碳和总氮含量均低于稻麦轮作农田土壤，但差异不显著。两种土壤中无机氮库均以硝态氮为主，铵态氮/硝态

氮浓度比分别为0.26和0.06。稻麦轮作农田土壤NO_3^--N浓度高达37.0 mg kg^{-1}，这可能与我们在水稻收割后采集土壤样品有关，此时土壤处于好氧状态，且作物不再吸收利用氮肥，土壤残留的铵态氮在好氧条件下发生硝化作用，导致土壤中NO_3^--N的累积。葡萄园土壤中NO_3^--N浓度是稻麦轮作农田土壤的2.2倍，表明葡萄园土壤NO_3^--N累积速率显著高于稻麦轮作农田土壤。

表1 太湖地区稻麦轮作农田和葡萄园表层土壤（0～20 cm）理化性状

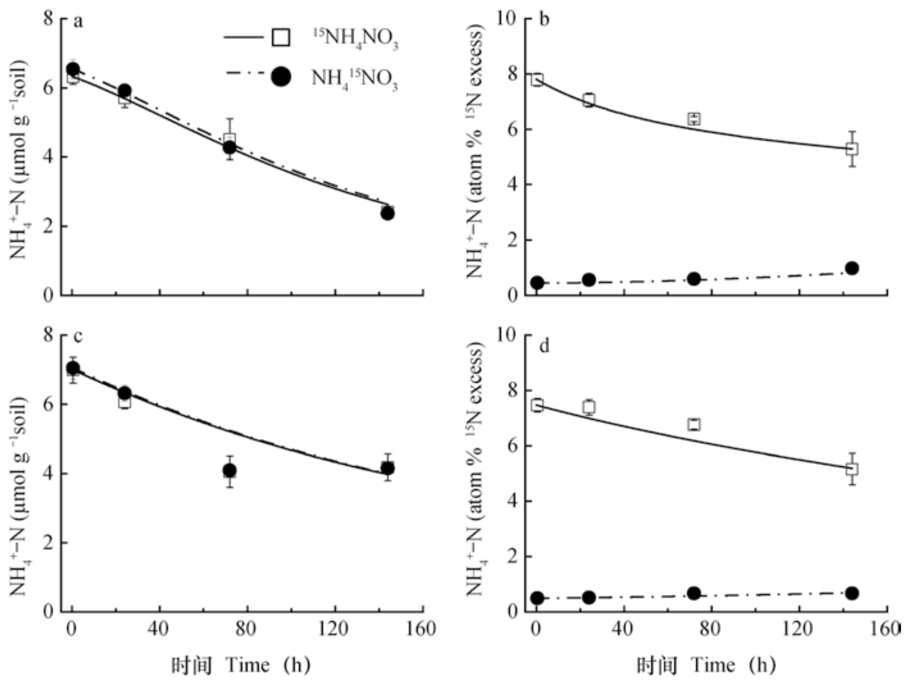
Table 1 Soil properties（0～20 cm）of the paddy field and the vineyard in the Taihu Lake region of China

类型 Type	pH	全碳 Total C（g kg^{-1}）	全氮 Total N（g kg^{-1}）	C/N	NH_4^+-N（mg kg^{-1}）	NO_3^--N（mg kg^{-1}）
稻麦轮作农田 Rice paddy	5.74 ± 0.01b	2.15 ± 0.02a	0.22 ± 0.00a	9.77 ± 1.1a	7.8 ± 1.2b	37.0 ± 1.2a
葡萄园 Grape orchard	5.14 ± 0.07a	2.00 ± 0.01a	0.19 ± 0.01a	10.53 ± 0.9a	4.7 ± 0.7a	81.3 ± 1.5b

注：表中相同行中的不同字母表示稻麦轮作农田和葡萄园土壤相应氮素转化速率间有显著差异（$p < 0.05$）Note：Different letters within the same line denote significantly differences between the paddy field and the vineyard（$p < 0.05$）

2.2 培养过程中土壤氮库和^{15}N丰度变化

两种不同利用方式土壤的NH_4^+-N、NO_3^--N浓度及其^{15}N丰度随时间的变化趋势如图2、图3所示。两种土壤中NH_4^+-N浓度在整个培养期间内逐渐下降（图2a，图2c），而硝态氮浓度则相应增加（图3a，图3c）。培养期间，$^{15}NH_4NO_3$标记处理的NH_4^+-N库^{15}N丰度有降低趋势，表明有自然丰度或低丰度的NH_4^+-N输入NH_4^+-N库（图2b，图2d），而NO_3^--N库^{15}N丰度的变化趋势与NH_4^+-N库^{15}N丰度变化趋势相反（图3b，图3d）。$NH_4{}^{15}NO_3$标记的样品中，NO_3^--N库的^{15}N丰度随培养时间延长而下降（图3b，图3d），而NH_4^+-N库的^{15}N丰度则逐渐增加（图2b，图2d）。



注：图中误差线为重复间标准误。下同 Note：Error bars indicate SD. The same below

图2 太湖地区稻麦轮作农田（a和b）和葡萄园土壤（c和d）铵态氮浓度及其^{15}N丰度的实测值（点）与模型拟合值（线）

Fig. 2 Measured（dotted line）and model-fitted（solid line）values of concentration and ^{15}N abundance of the NH_4^+ in the soils（0～20 cm）of the paddy field（a and b）and the vineyard（c and d）in the Taihu Lake region of China

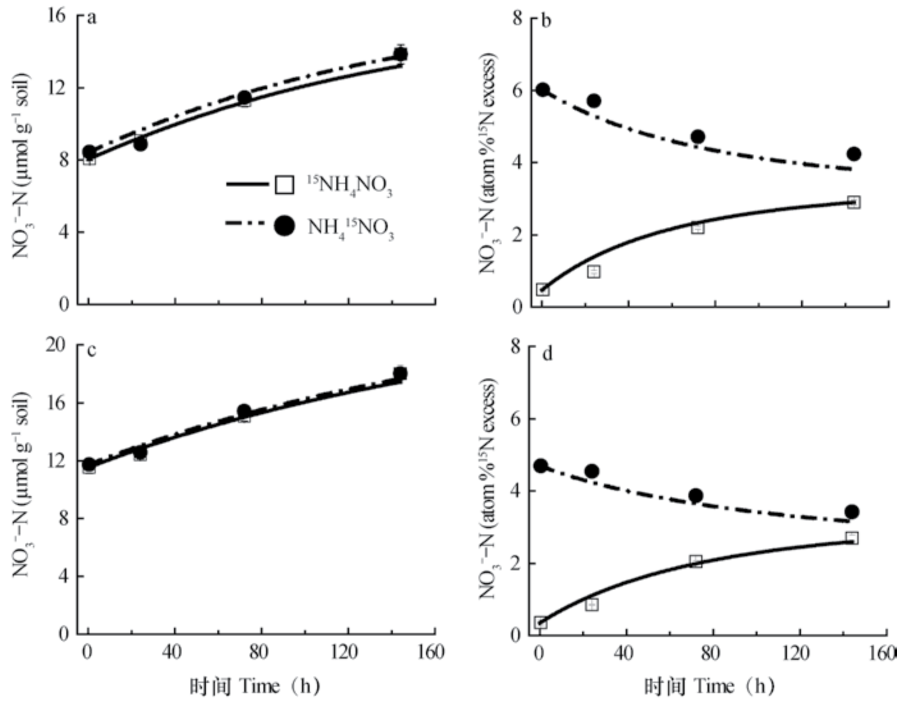


图3　太湖地区稻麦轮作农田（a和b）和葡萄园土壤（c和d）硝态氮浓度及其^{15}N丰度的实测值（点）与模型拟合（线）结果

Fig. 3　Measured (dotted line) and model-fitted (solid line) values of concentration and ^{15}N abundance of the NO_3^- in the soil (0 ~ 20 cm) of the paddy field (a and b) and the vineyard (c and d) in the Taihu Lake region of China

2.3　氮素初级转化速率

如图2和图3所示，模型拟合的数据基本上通过了实测的数据点，表明拟合效果很好。稻麦轮作农田和葡萄园土壤氮素初级氮矿化速率分别为N 3.90和4.52 mg kg^{-1} d^{-1}，两者差异不显著（表2）。稻麦轮作农田土壤NH_4^+-N初级同化速率为 0.56 mg kg^{-1} d^{-1}，占NH_4^+-N总产生量的14%，而葡萄园土壤NH_4^+-N初级同化过程可以忽略不计。

葡萄园土壤初级自养硝化速率为N 15.85 mg kg^{-1} d^{-1}，显著高于稻麦轮作农田土壤（N 13.65 mg kg^{-1} d^{-1}），而这两种土壤均不具有异养硝化能力（表2）。因此，自养硝化是土壤NO_3^--N产生的唯一途径。稻麦轮作农田和葡萄园土壤中总硝化与总NH_4^+-N同化的比值（N/IA）分别为24和793，表明氨氧化细菌竞争NH_4^+-N的能力强于异养微生物，因而NH_4^+-N的主要去向是硝化过程，尤其是葡萄园土壤。

基于MCMC算法的数值优化模型拟合得出土壤中NO_3^--N有两个消耗途径，即NO_3^--N同化和NO_3^--N异化还原为铵（DNRA）。本研究中两种不同利用方式的土壤都不发生NO_3^--N同化，致使DNRA过程成为培养条件下NO_3^--N主要消耗途径，且两种土壤的DNRA速率没有显著差异。

2.4　N_2O排放

稻麦轮作农田土壤N_2O排放在培养初期即出现最高峰，而葡萄园土壤则是在培养第3天出现排放最高峰（图4）。整个培养期间，稻麦轮作农田土壤的N_2O累积排放量为N 34.23 μg kg^{-1}，显著低于葡萄园土壤（N 97.16 μg kg^{-1}）（p < 0.05）。

3　讨　论

3.1　稻田改果园对土壤铵态氮转化的影响

本研究中两种不同利用方式土壤的初级矿化速率在Lan等[28]对中国江苏南、北部稻麦轮作农田土壤（0.3 ~ 3.8 mg kg^{-1} d^{-1}）和Zhang等[19]对中国亚热带农田土壤（2.4 mg kg^{-1} d^{-1}）的测定范围之内。C、N底物的有效性是调控土壤初级矿化速率的一个重要因素。已有研究证明土壤N素初级矿化速率与土壤总C、N含量呈显著正相关关系[29]。本研究发现，稻麦轮作农田改种为葡萄园对土壤总C、N含量没有显著影响，因而两种土壤的初级矿

表2 太湖地区稻麦轮作农田和葡萄园表层土壤（0 ~ 20 cm）的氮素初级转化速率

Table 2 Gross N transformation rates in the soils（0 ~ 20 cm）of the paddy field and the vineyard in the Taihu Lake region of China

参数[1)] Parameter	氮素转化速率[2)] N transformation rate（mg kg^{-1} d^{-1}）	
	稻麦轮作农田 Rice paddy	葡萄园 Grape orchard
总矿化 M_N Total gross N mineralization	3.9 ± 1.0a	4.52 ± 1.02a
NH_4^+-N同化 I_{NH4} NH_4^+ immolization	0.56 ± 0.09a	0.017 ± 0.001b
NH_4^+-N吸附 A_{NH4} NH_4^+ adsorption	0.061 ± 0.009a	0.000 ± 0.000b
NH_4^+-N解吸 R_{NH4} NH_4^+ released	0.008 ± 0.003b	2.238 ± 0.297a
自养硝化 O_{NH4} Autotrophic nitrification	13.65 ± 0.04b	15.85 ± 0.39a
异养硝化 O_{Nrec} Heterotrophic nitrification	0.000 ± 0.000a	0.000 ± 0.000a
NO_3^--N同化 I_{NO3} NO_3^- immolization	0.000 ± 0.000a	0.004 ± 0.000a
NO_3^--N异化还原为铵 D_{NO3} Dissimilatory NO_3^- reduction to NH_4^+	1.40 ± 0.49a	2.00 ± 0.38a

1）总矿化，土壤稳定性和不稳定性有机N矿化之和；NH_4^+-N同化，NH_4^+-N同化进入稳定性有机氮库和不稳定性有机氮库之和；NH_4^+-N解吸，NH_4^+-N从阳离子交换位点解吸；NH_4^+-N吸附，NH_4^+-N吸附到阳离子交换位点上；自养硝化，NH_4^+-N氧化为NO_3^--N的过程；异养硝化，稳定性有机氮氧化为NO_3^--N的过程；NO_3^--N同化，NO_3^--N同化进入稳定性有机氮库；NO_3^--N异化还原为铵MN：Sum of M_{Nrec}（mineralization of recalcitrant organic-N（N_{rec}）to NH_4^+）and M_{Nlab}（mineralization of labile organic-N（N_{lab}）to NH_4^+）；I_{NH4}: $I_{NH4-Nrec}$（immobilization of NH_4^+ to N_{lab}）and $I_{NH4-Nlab}$（immobilization of NH_4^+ to N_{rec}）；R_{NH4}，release of adsorbed NH_4^+；A_{NH4}，adsorption of NH_4^+ on cation exchange sites；O_{NH4}，oxidation of NH_4^+ to NO_3^-；O_{Nrec}，oxidation of recalcitrant organic-N to NO_3^-（heterotrophic nitrification）；I_{NO3}，immobilization of NO_3^- to recalcitrant organic-N and D_{NO3}，dissimilatory NO_3^- reduction to NH_4^+（DNRA）

2）表中相同行中的不同字母表示稻麦轮作农田和葡萄园土壤相应氮素转化速率间有显著差异（$p < 0.05$）Different letters within the same line denote significantly differences between the paddy field and the vineyard（$p < 0.05$）

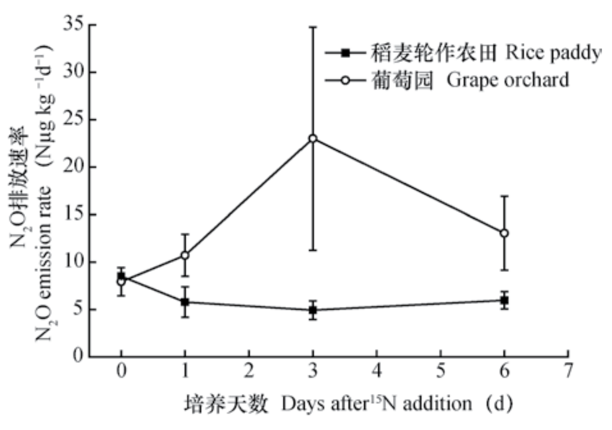


图4 太湖地区稻麦轮作农田和葡萄园土壤N_2O排放速率

Fig. 4 N_2O emission rate in the paddy field and the vineyard in the Taihu Lake region of China

化速率没有显著差异。

稻麦轮作农田土壤约有14%的矿化产生的NH_4^+-N通过微生物同化途径进入土壤有机质，而葡萄园土壤的NH_4^+-N同化速率几乎为零（表2），稻麦轮作农田改种为葡萄园显著降低了土壤微生物对NH_4^+-N的同化能力。两种土壤的NH_4^+-N同化能力不同可能是由于不同的施肥管理措施导致的。在太湖地区，秸秆还田被普遍应用于稻麦轮作农田土壤以期达到维持或提高土壤C、N含量的目的，而葡萄园土壤则大量施用低C/N比的动物粪肥。稻麦秸秆具有较高的C/N，施入土壤后可提高微生物对无机氮的需求进而促进NH_4^+-N同化[30-31]。

3.2　稻田改果园对土壤硝态氮转化的影响

土地利用方式改变显著刺激了土壤的自养硝化作用，这与Zhang等[19]发现林地改种为农田刺激了自养硝化的研究结果相一致，但两者刺激自养硝化的机制可能不同。与林地相比，农业用地长期施用石灰和N肥，石灰可以提高土壤pH进而促进自养硝化[32]，而长期施用矿质N肥则会刺激氨氧化细菌生长进而促进硝化[33-34]。通常认为，土壤pH是调控自养硝化的一个重要因素。有研究发现，土壤pH与自养硝化速率呈显著正相关关系[35-36]。我们的结果则发现pH较低的葡萄园土壤自养硝化速率高于pH较高的稻麦轮作农田土壤。有研究发现，自养硝化过程产生H^+进而酸化土壤[37-38]，但是长期施用N肥导致的土壤酸化对硝化速率的抑制作用很可能会被长期施用N肥对该过程的刺激作用所抵消[4]。例如，中国三个主要的一年两熟制农田系统（小麦–玉米，水稻–小麦，水稻–水稻）平均施氮量通常均在N 500 kg hm^{-2}以上，N肥利用率仅为30%～50%，那么土壤中残留的N肥将产生H^+ 20～33 kmol hm^{-2} a^{-1}的质子[39]。由此推测，葡萄园土壤较低的pH可能是较高的自养硝化速率及其产生的相应H+酸化土壤造成的。N肥对自养硝化的刺激作用可能是pH较低的葡萄园土壤自养硝化速率却较高的原因之一。另一方面，稻麦轮作农田改种为葡萄园对自养硝化的刺激作用也可能是由土壤水分状况和施肥管理措施的差异引起的。稻麦轮作农田土壤通常是处于阶段性淹水状态，而葡萄园土壤则是长期处于不饱和水状态。自养硝化作用一般发生在土壤水分不饱和状态下，其最适水分范围为65%～80%（WHC）[40-42]。长期淹水可能会抑制稻麦轮作农田土壤的自养硝化能力，进一步减弱了施肥对自养硝化的刺激作用。此外，太湖地区葡萄园施肥模式为有机无机配施，而稻麦轮作农田只施用化学N肥。有研究表明，施用有机肥，如动物粪肥，可以显著刺激自养硝化[43-44]，这不仅因为动物肥通常含有高浓度的NH_4^+–N，为自养硝化提供充足的底物[44]，还因为有机肥大多属于碱性物质，施入土壤后很可能提高微域的pH，再加上其本身不断矿化致碱，进而提高自养硝化速率。

自养硝化和NH_4^+–N同化是土壤中NH_4^+–N的两个主要去向，因此不可避免存在自养硝化细菌和异养微生物对NH_4^+–N的竞争作用[27]。本研究表明，稻麦轮作农田改种为葡萄园导致NH_4^+–N同化速率显著降低，因而与稻麦轮作农田土壤相比，葡萄园土壤中自养硝化细菌比异养微生物能竞争到更多的NH_4^+–N，从而提高自养硝化速率。这可能与两种不同利用方式土壤的施肥方式有关。稻麦轮作农田土壤中还田的水稻秸秆通常有较高C/N比，而葡萄园土壤施用的动物粪肥C/N比较低，高C/N比的水稻秸秆提高了微生物对无机N的需求进而促进了NH_4^+–N同化[30-31]。

与NH_4^+–N同化相比，两种土壤的NO_3^-–N同化速率均可忽略不计（表2），这与Shi和Norton[45]的研究结果相吻合。在NH_4^+–N和NO_3^-–N同时存在的条件下，微生物优先利用NH_4^+–N[46-48]，因为微生物利用NH_4^+–N所消耗的能量比NO_3^-–N少。前人资料表明，土壤中NH_4^+–N浓度即使很低也能抑制NO_3^-–N同化[49-51]。此外，本研究中两种不同利用方式土壤的C/N比均在土壤微生物生物量8∶1～12∶1的变化范围内[52-54]，致使微生物分解有机C时不需要额外的无机N源。

总硝化与总NH_4^+–N同化的比值（N/IA）通常用来比较土壤NH_4^+–N两个主要去向的相对重要性及表征土壤NO_3^-–N的淋溶损失风险[17, 55]。当N/IA比大于1时，自养硝化细菌对NH_4^+–N的竞争作用要大于异养微生物，土壤微生物通过自养硝化过程将NH_4^+–N转化为更多易淋失NO_3^-–N的可能性增加。本研究中，稻麦轮作农田土壤的N/IA比值高达24，表明自养硝化是该土壤NH_4^+–N的主要去向。然而，改种为葡萄园后土壤初级硝化速率显著增加而初级NH_4^+–N同化速率几乎为零，使得自养硝化几乎成为该土壤NH_4^+–N的唯一去向。以上结果表明，太湖地区这两种不同利用方式的土壤可能都有较高的NO_3^-–N淋溶和径流损失风险，且稻麦轮作农田转变为葡萄园将加剧这种风险。因此，发展能够提高土壤保氮能力的有效策略是刻不容缓的。目前的研究发现，硝化抑制剂可以有效地抑制土壤NO_3^-–N的产生并提高N肥利用率[56-58]。此外，施用高C/N比的有机肥也是提高土壤NH_4^+–N和NO_3^-–N的同化能力进而减少NO_3^-–N损失有效措施[59-61]。

4　结　论

本研究结果表明，稻麦轮作农田改种为葡萄园显著影响土壤自养硝化和NH_4^+–N同化速率。葡萄园土壤初级自养硝化速率显著高于稻麦轮作农

田土壤，而与后者相比其NH_4^+-N同化速率可忽略不计，致使自养硝化成为葡萄园土壤中NH_4^+-N的唯一去向。太湖地区稻田改果园后土壤NH_4^+-N同化速率的降低和自养硝化速率的提高，将增加土壤中NO_3^--N的累积，进而可能增加NO_3^--N淋溶和径流损失的风险。本研究建议在农田土壤上施用硝化抑制剂或高C/N有机肥来降低NO_3^--N的淋溶和径流损失风险。

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effects of Conversion of Paddy Field into Vineyard on Soil Nitrogen Transformation in the Taihu Lake Region of China

WANG Jing ZHANG Jinbo† CAI Zucong

(*School of Geography Sciences*, *Nanjing Normal University*, *Nanjing* 210023, *China*; *Jiangsu Provincial Key Laboratory of Materials Cycling and Pollution Control*, *Nanjing* 210023, *China*; *Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application*, *Nanjing* 210023, *China*)

Abstract In response to the growing demand for fruits, farmers in the Taihu Lake region are rushing to convert paddy fields into fruit orchards in recent years. Changes in land-use and management may affect or alter physico-chemical properties of the soil, and hence cycling of soil N and fate of N fertilizer. Up to date, little has been reported on quantification of effects of changes in land use on soil N gross transformation rate, besides some works that have been mainly focused on effects of the conversion of non-agricultural land into agricultural land, and rarely on the effects of the conversion from one type to another type of agricultural land use. In the Taihu Lake region, paddy fields under rice-wheat crop rotation and orchards coverted from paddy fields are the two typical types of agricultural land-use, which differ sharply in water regimes

(periodically waterlogged for paddy fields and water-unsaturated for orchards) and fertilizer management (no input of organic manure for paddy fields and combined application of chemical fertilizer and organic manure for orchards) . Therefore, gross N processes (e.g., nitrification and denitrification) in the soils under the two types of land use also differ sharply, as affected by their different aeration conditions and fertilizer managements. The paddy field under rice-wheat crop rotation and the vineyard converted from paddy field under study are located in the upper-streams of the Zhushan Bay Catchment in the Taihu Lake Region of China. Gross transformation rates of soil N under the two types of land use were measured using the ^{15}N tracing technique combined with the Markov Chain Monte Carlo (MCMC) algorithm-based numerical optimization model, and effects of the conversion on soil N supply and N retention capacity were investigated. Results show that the conversion reduced soil pH (from 5.74 in paddy field to 5.14 in vineyard, on average) and contents of soil organic C and total N, though not much. In the soils of the paddy field and vineyard, the inorganic–N pools were dominated with nitrate, with NH_4^+/NO_3^- being 0.26 and 0.06, respectively, and the gross N mineralization rate (mineralization of labile and recalcitrant soil organic matter) was N 3.90 mg kg^{-1} d^{-1} and 4.52 mg kg^{-1} d^{-1}, respectively. Obviously the differences between the two were not very sharp. In the paddy field, the gross NH_4^+ assimilation rate was 0.56 mg kg^{-1} d^{-1}, accounting for only 14% of the total NH_4^+ produced, while in the vineyard it was almost negligible. The gross N autotrophic nitrification rate in the vineyard was 15.85 mg kg^{-1} d^{-1}, significantly higher than that (13.65 mg kg^{-1} d^{-1}) in the paddy field, while the gross heterotrophic nitrification rate and NO_3^- assimilation rate were both negligible in both soils. Through fitting with the MCMC algorithm–based numerical optimization model, consumption of NO_3^- in the soils was found to have two pathways, namely assimilation of NO_3^- and dissimilatory reduction of NO_3^- to NH_4^+ (DNRA) . However, in both of the soils, NO_3^- assimilation was not detected, turning DNRA into the major pathway of NO_3^- consumption, moreover, the two soils did not differ much in DNRA rate. The ratio of total nitrification to gross NH_4^+ assimilation (N/NA) in the soil was 24 in the paddy field and 793 in the vineyard, indicating that ammonia oxidizing bacteria are stronger than heterotrophic nitrifiers in competition for NH_4^+, and hence autotrophic nitrification is the dominant fate of NH_4^+, especially in the vineyard. On the whole, the conversion of paddy field into vineyard significantly affects soil autotrophic nitrification, increasing the N autotrophic nitrification rate in the soil, but its influence on NH_4^+ assimilation rate was almost negligible, thus making autotrophic nitrification the only fate for NH_4^+ in the vineyard. The decreased NH_4^+ assimilation rate and the increased autotrophic nitrification rate in the vineyard enhanced NO_3^- accumulation in the soil, which may in turn increase the risk of N leaching and losing with runoff. It is recommended that nitrification inhibitor and/or organic manure high in C/N ratio should be applied to mitigate the risk.

Key words Gross soil N transformation rate; ^{15}N tracing; Land use; Soil nitrogen retention capacity

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