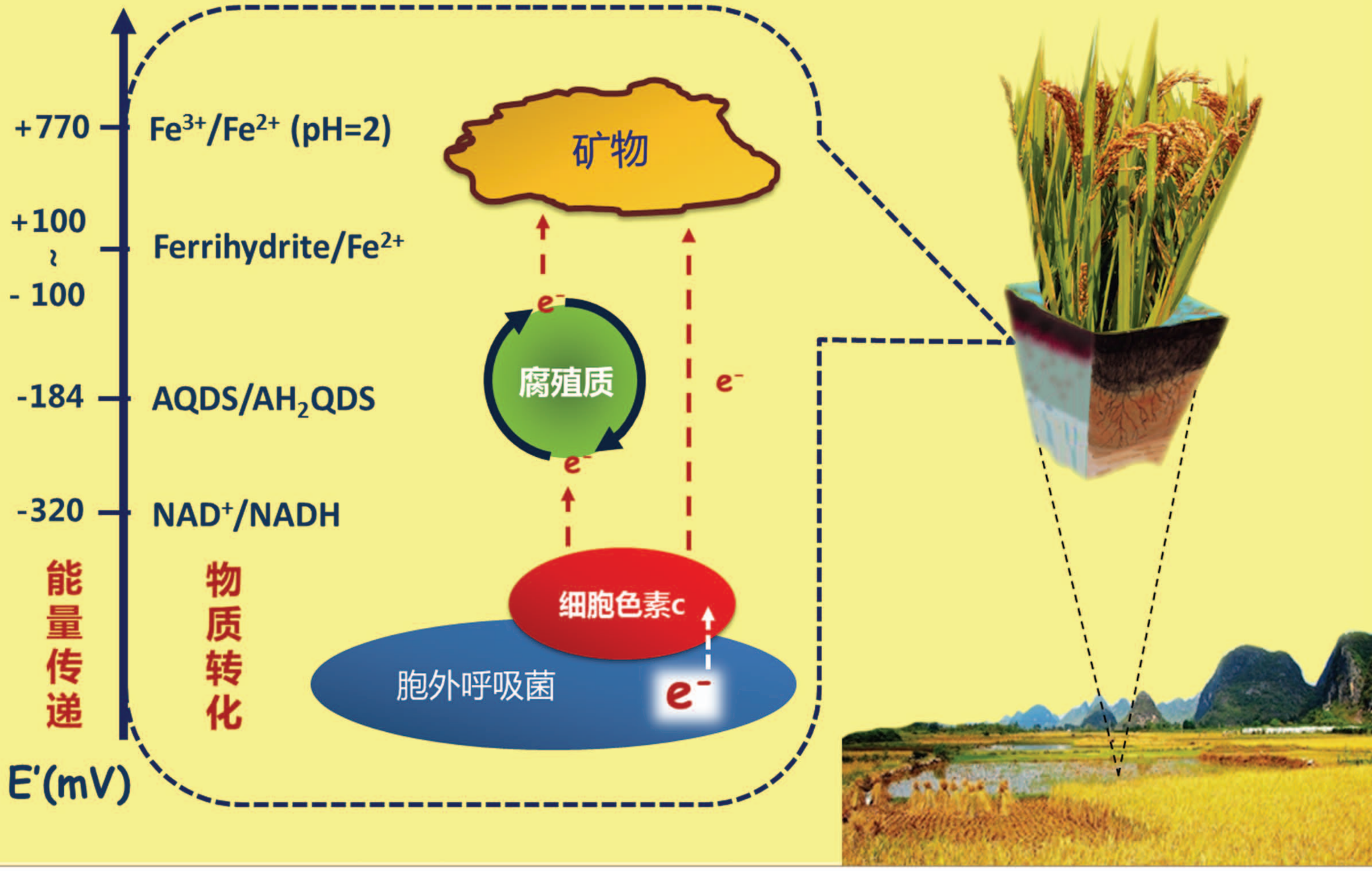
ISSN 0564-3929

Acta Pedologica Sinica 土壤学报

Turang Xuebao



中国土壤学会　主办
科学出版社　出版

2016
第53卷　第2期
Vol.53　No.2

土壤学报

（Turang Xuebao）

第53卷 第2期 2016年3月

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第 53 卷第 2 期
2016 年 3 月

土　壤　学　报
ACTA PEDOLOGICA SINICA

Vol. 53，No. 2
Mar.，2016

DOI：10.11766/trxb201507130273

长期施肥对农田土壤氮素关键转化过程的影响*

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摘　要　当前，如何合理施肥、提高作物产量、维持土壤肥力、并兼顾生态环境效应是农业研究的主要挑战之一。本文综述了长期施肥对农田土壤氮素关键转化过程的影响，主要从土壤氮转化过程的初级转化速率角度综述肥料（有机肥和化学氮肥）对土壤氮素关键转化过程的影响。土壤氮素矿化-同化循环是自然界氮循环过程中两个至关重要的环节，是决定土壤供氮能力的重要因素。总体而言，长期施用氮肥，尤其是有机肥能显著提高初级矿化-同化周转速率；长期施肥可以刺激自养硝化作用，且有机肥的刺激作用更明显；施用化学氮肥和有机肥均能提高反硝化速率，且有机肥的刺激作用高于化学氮肥。有机肥一直被提倡和实践用来改善土壤肥力和提高土壤固碳能力，无论是单施有机肥还是有机-无机配施，均能有效地减轻硝酸盐污染，改善土壤肥力并提高作物产量。但是有机肥的施用并不是多多益善，有机肥过多施用也会增加氮损失的风险。因此，本文综述了长期施肥对农田土壤氮素关键转化过程初级转化速率的影响，讨论了各个氮转化过程之间的联系，以期增强人们对长期施肥措施影响农田土壤氮素循环的理解，并为合理施用氮肥、提高氮肥利用率、减少与氮相关的环境污染提供理论依据。

关键词　长期施肥；矿化；铵态氮同化；自养硝化；反硝化
中图分类号　S154.1　　**文献标识码**　A

氮是植物生长的关键限制因子，施用氮肥是提高农作物产量的重要措施。但是，当氮肥投入超过了农作物和土壤微生物对氮的需求，不仅对提高产量无益，反而会降低氮肥利用率，同时大量盈余的氮素很容易通过径流、淋溶、氨挥发和反硝化等途径损失，引发地下水硝酸盐污染、水体富营养化及温室效应等一系列负面环境问题[1-4]。目前，单施及过度施用化学氮肥引起的与氮相关的环境问题尤为严重[5-7]，而有机-无机配施措施已被证实在提高农作物产量和改善品质的同时可以降低与氮相关的环境污染[8-10]。那么，长期施肥究竟影响哪些土壤氮素转化过程，进而影响土壤的供氮能力和保氮机制呢？长期施有机肥又是如何降低氮损失风险的呢？本文综述了长期施肥对农田土壤氮素关键转化过程的影响，以期为合理施用氮肥、提高氮肥利用率提供理论依据。

本文主要从土壤氮转化过程的初级转化速率角度综述肥料（有机肥和化学氮肥）对土壤氮素关键转化过程的影响。氮素形态之间的转化速率控制各种形态的氮在土壤中的含量变化。依据测定方法，

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* 江苏省自然科学基金项目（BK20140062）、江苏省普通高校学术学位研究生科研创新计划项目（KYZZ15_0218）和江苏高校优势学科建设工程（PAPD，164320H116）资助 Supported by the Natural Science Foundation of Jiangsu Province（No. BK20140062），the Academic Degree Graduate Student Research and Innovation Program of Jiangsu Higher Education Institutions （No. KYZZ15_0218），and the Priority Academic Program Development of Jiangsu Higher Education Institutions（PAPD，No. 164320H116）

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收稿日期：2015-07-13；收到修改稿日期：2015-11-11

土壤氮素的转化速率可分为净转化速率和初级转化速率。净转化速率是评价土壤供氮能力和环境风险的常用指标。初级转化速率指的是土壤氮从一种特定的形态转化为另一种特定形态的实际转化速率。在自然条件下，土壤中各种形态氮的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[11]。例如，当硝化作用速率与NO_3^--N的生物同化速率相等时，土壤中NO_3^--N含量保持常数，净硝化速率为零，但这不等于土壤未进行硝化作用和NO_3^--N的同化作用。因此，要阐明无机氮含量变化的过程，并进行针对性地调控，必须认识其初级转化速率。综上所述，将反映氮素各种形态含量变化的净转化速率研究推进到控制含量变化的过程初级转化速率研究，对于认识土壤氮素转化规律、合理施用氮肥、评估氮肥的环境效应等具有极其重要的意义。本文主要综述长期施肥对土壤氮素各个关键转化过程这方面的研究结果，有助于从土壤氮转化过程角度深入认识长期施肥对农田土壤氮素转化过程的影响机制。

1　长期施肥对氮素初级矿化-同化周转速率的影响

土壤氮素矿化-同化循环是自然界氮循环过程中两个至关重要的环节，是决定土壤供氮能力的重要因素[12-13]。土壤有机氮矿化速率越高，可为作物提供的有效态氮可能就越多。土壤氮素初级矿化速率大小由土壤有机碳和有机氮含量决定[14]。大量长期定位施肥试验表明，施用氮肥可以增加土壤有机碳、氮含量，进而提高土壤氮素初级矿化速率[15-16]（表1，图1a）。长期施用有机肥可以增加农作物秸秆在土壤中的残留量和根系分泌物数量，根系分泌物可以为微生物生长提供营养物质。此外，有机肥本身就含有大量的营养物质，如动物粪肥通常含有一系列易降解的有机碳、氮和无机氮化合物[16]，而作物秸秆则主要含有如木质素、纤维素和半纤维素等较稳定的有机化合物[12，17-19]。与有机肥相比，化学氮肥对土壤氮素初级矿化速率的提高程度与其对作物生长的促进作用密切相关，化学氮肥施入可以提高作物产量，进而提高土壤中根和作物残体的自然还田量，最终增加土壤有机碳、氮含量[15-16，20-21]。此外，肥料类型可以影响土壤中稳定性和不稳定性有机氮库的相对矿化速率。Zhang等[22]对封丘17年的长期定位试验研究发现，长期施用化学氮肥可以提高稳定性有机氮库的矿化速率，而有机肥则刺激了不稳定性有机氮库的矿化速率。英国希尔斯堡38年的长期定位实验数据也发现不施肥处理中铵态氮主要由稳定性有机氮库矿化而来，而牛粪处理土壤铵态氮主要来自不稳定性氮库矿化[23]。

土壤氮同化是指无机氮被微生物同化吸收进入有机氮库的过程，其中微生物同化铵态氮进入有机氮库的过程即为铵态氮同化，是评价土壤保氮能力的一个重要指标。关于长期施用化学氮肥或有机肥对铵态氮同化的影响，总体表现为有机肥对提高土壤铵态氮同化速率的能力强于化学氮肥（图1b）。长期施用有机肥提高土壤铵态氮初级同化速率可能是由于有机肥含有大量的有效碳源，可提高微生物生物量和活性，促使微生物同化更多的铵态氮进入土壤活性有机氮库[22，24]。相比而言，化学氮肥施入仅仅通过提高土壤中根和作物残体的自然还田量增加土壤有机碳含量，因而其提供的有效碳源相对有限，对提高土壤铵态氮同化速率的能力也就弱于施入有机氮肥。近期，我们对四川紫色土和太湖水稻土的研究却发现单施化学氮肥竟能抑制铵态氮同化[25-26]（表1）。

总体而言，长期施用氮肥，尤其是有机肥能显著提高初级矿化-同化周转速率。有机肥施用提高微生物利用铵态氮和硝态氮的能力，致使更多的有效态氮被微生物同化至土壤有机氮库短暂地储存起来，随后这部分氮将会通过再矿化过程转变为植物有效氮，最终提高土壤氮矿化速率并增加植物有效态氮数量，有效降低氮的损失风险[27-28]。

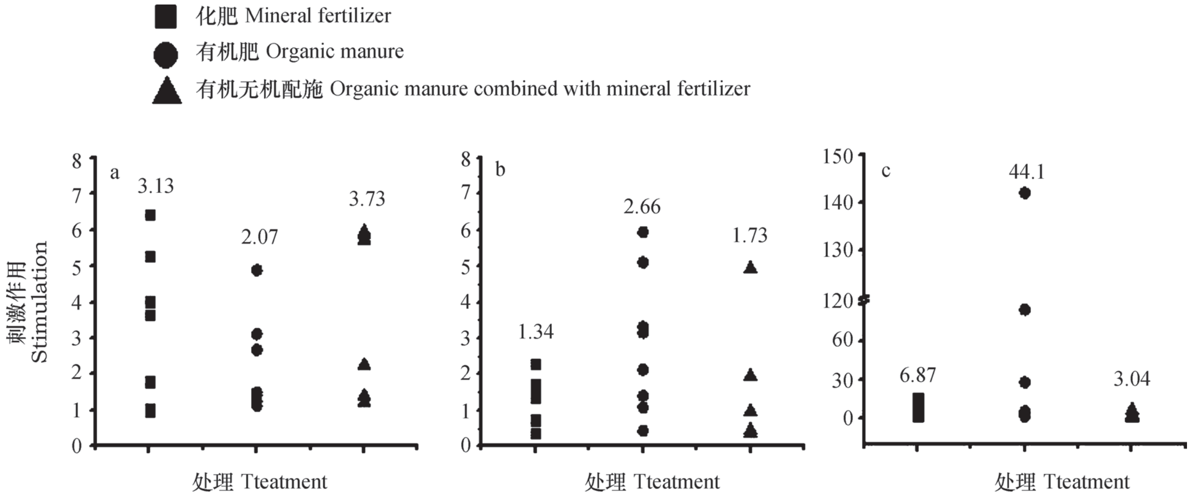
2　长期施肥对初级硝化速率的影响

硝化作用通常可分为自养硝化作用（氨氧化菌氧化铵态氮为硝态氮）和异养硝化作用（异养微生物氧化有机氮或铵态氮为硝态氮）[29]。长期施肥可以激发自养硝化作用，且有机肥的激发作用更明显（图1c），这可能归结于有机肥和化学氮肥的不同激发机制。化学氮肥不仅直接为自养硝化提供底物铵态氮，还可以激发土壤氨氧化菌的活性[22，30]。有研究表明，对于酸性土壤，长期施化学氮肥会激发AOA（ammonia oxidizing archaea，氨氧化古菌）的活性和数量[31-32]，而中性和偏碱

性土壤则是激发AOB（ammonia oxidizing bacteria，氨氧化细菌）的活性和数量[22, 30, 33-35]。此外，长期施用化学氮肥通常激发自养硝化，而自养硝化过程中产生的大量H^+可能会导致土壤酸化，土壤酸化反过来又会抑制自养硝化过程。通常情况下，土壤酸化对硝化的抑制作用会被化学氮肥对自养硝化的刺激作用完全抵消[36]，但土壤酸化到一定程度后，化学氮肥对自养硝化的激发作用就不存在了[37]。

长期施用有机肥刺激自养硝化作用的机制较为复杂。即使在等氮量施肥处理的情况下，有机肥所含的大量有效碳和其他养分还有益于改善土壤的物理化学和生物学性质[38]。有机肥中有机氮的矿化有致碱作用，且有机肥本身含有大量的盐基离子也可提高土壤pH[39-40]，而土壤pH的提高可激发自养硝化[41-42]。He等[37]对江西红壤16年的长期定位试验结果也发现，有机–无机配施不仅可以缓冲土壤pH变化，还能为氨氧化细菌（AOB）和氨氧化古菌（AOA）提供基质、养分及适宜的生存环境。此外，有研究表明有机肥处理土壤的AOB硝化潜势和AOB数量明显高于化学氮肥处理[30, 43]。因此，长期施用有机肥对自养硝化的激发作用也可能是土壤中AOB数量和活性增加的结果。有机肥料种类不同对自养硝化的刺激作用也不同，农作物秸秆对自养硝化的激发作用通常小于动物粪肥。与农作物秸秆相比，动物粪肥的C/N比较低，致使其对初级氮矿化的激发作用强于初级氮同化，这必然会为自养硝化细菌提供更多可利用的铵态氮[25]。动物粪肥本身含有的较高浓度铵态氮也会快速释放到土壤中，成为自养硝化微生物的底物[44-45]。而农作物秸秆C/N比通常较高，微生物从土壤中吸收更多的无机氮来满足自身生长需要，致使农作物秸秆施入促进了氮同化并导致自养硝化的底物减少[46-47]，农作物秸秆处理的NH_4^+-N同化/总NH_4^+-N消耗比值大于动物粪肥处理也证实了上述观点[25]。

目前，有关不同施肥措施对硝化速率影响的研究主要关注自养硝化过程，定量研究有机肥对异养硝化速率影响的报道很少。异养硝化分为有机和无机途径，即氧化有机氮和铵态氮过程。Müller等[48]发现有机肥施入促进铵态氮向硝态氮的氧化作用，这是因为提高了异养硝化的无机过程。其研究还发现，长期施用牛粪会刺激有机氮异养硝化为硝态氮[23]。Zhang等[49]的研究结果表明，有机物质的种类可以影响异养硝化的途径。加入氨基酸类有机氮化合物后，硝态氮主要来自于铵态氮和有机氮异养硝化，而对于玉米秸秆这些复杂的化合物，有机氮异养硝化是硝态氮产生的唯一途径。玉米秸秆处理的异养硝化与总硝化（即自养硝化+异养硝化）的相对比值高达80%～93%，显著高于氨基酸类的有机氮化合物处理（41%～49%）。在此基础



注：刺激作用为不同施肥处理与相应对照处理氮素初级转化速率的比值 Note：The stimulation effect refers to the ratio of fertilization rate to gross N transformation rate in the soil

图1 比较长期施用化肥、有机肥和有机无机配施对土壤初级矿化速率（a）、初级铵态氮同化速率（b）和初级硝化速率（c）的刺激作用（数据引自表1）

Fig. 1 Priming effects of long-term application of chemical fertilizer，organic manure or chemical fertilizer in combination with organic manure on soil primary N mineralization rate（a），primary NH_4^+-N assimilation rate（b），and primary nitrification rate（c）in the soil（data from Table 1）

表1　长期施肥对土壤氮素关键转化速率的影响

Table 1　Effects of long-term fertilization on key gross transformation rates of soil nitrogen（mg kg^{-1} d^{-1}）

土壤类型 Soil types	处理[1）] Treatment	施氮量 N application rate（kg hm^{-2} a^{-1}）	pH	SOC（g kg^{-1}）	TN（g kg^{-1}）	定位年限 Fixed number of years（a）	矿化 Gross mineralization	铵态氮同化 NH_4^+–N immobilization	自养硝化 Gross autotrophic nitrification	异养硝化 Gross hetetrophic nitrification	总硝化 Total gross nitrification	硝态氮同化 NO_3^-–N immobilization	参考文献 Refences
封丘潮土 Aquic Inceptisol	CK	0	8.55	4.43	0.40	17	0.67	2.74	2.22	0	2.22	0.09	[22]
	NP	300	8.39	5.43	0.65		3.53	4.71	15.75	0	15.75	4.2	
	PK	300	8.49	5.11	0.51		0.51	0.95	3.54	0	3.54	0.26	
	NK	300	8.46	4.71	0.41		2.45	6.3	11.88	0	11.88	2.54	
	NPK	300	8.38	5.61	0.70		4.30	3.77	17.14	0	17.14	4.73	
	HOM	300	8.03	7.63	0.93		3.94	5.32	14.41	0	14.41	0.01	
	OM	300	8.29	9.91	1.06		1.79	5.82	12.48	0	12.48	1.08	
Northern Ireland	CK	0	–	–	–	38	5.03	0.88	0.07	0.02	0.09	0.08	[23]
	化肥Chemical fertilizer	200	–	–	–		4.96	1.34	1.43	0.05	1.48	0.04	
	LOM	170	–	–	–		7.50	0.38	2.16	0.36	2.52	0.06	
	MOM	340	–	–	–		6.24	4.49	5.73	1.87	7.6	0.14	
	HOM	680	–	–	–		5.67	2.78	10.21	2.58	12.79	0.07	
紫色土 Purple Soil	UC	0	7.83	5.99	0.64	10	2.06	2.5	8.9	0	8.9	4.73	[25]
	NPK	280	7.83	7.48	0.84		8.26	0.92	23.53	0	23.53	6.69	
	OM	280	7.70	11.83	1.31		10.07	8.29	27.81	0	27.81	0.04	
	OM+NPK	280	7.75	10.27	1.15		11.79	12.3	26.51	0	26.51	0.03	
	RSD	112	7.76	10.48	1.05		6.41	14.84	12.64	0	12.64	0.61	
	RSD+NPK	280	7.67	11.67	1.10		12.23	14.35	22.33	0	22.33	0.01	
乌栅土 Gleyic–Stagnic Anthrosols	CK	0	7.5	19.4	2.1	23	3.62	–	–	–	3.7	–	[35]
	NPK	360	7.0	21.2	2.4		6.53	–	–	–	5.56	–	
	NPK+RSD1	387	6.9	25.0	2.5		8.13	–	–	–	4.3	–	
	NPK+RSD2	414	6.9	25.8	2.6		5.04	–	–	–	4.33	–	

续表

土壤类型 Soil types	处理[1] Treatment	施氮量 N application rate（kg hm^{-2} a^{-1}）	pH	SOC（g kg^{-1}）	TN（g kg^{-1}）	定位年限 Fixed number of years（a）	矿化 Gross mineralization	铵态氮同化 NH_4^+-N immobilization	自养硝化 Gross autotrophic nitrification	异养硝化 Gross hetetrophic nitrification	总硝化 Total gross nitrification	硝态氮同化 NO_3^--N immobilization	参考文献 Refences
Typic Melanudand	米糠 Rice husk	480	6.5	49.7	4.7	23	5.2	–	–	–	–	–	[38]
	锯屑 Sawdust	480	6.5	54.2	5.1		8.6	–	–	–	–	–	
	NPK	480	6.3	43.5	4.1		1.2	–	–	–	–	–	
水稻土 Anthrosols	CK	0	5.04	11.47	1.23	21	2.06	0.99	0.66	0.002	0.662	0.064	[26]
	NPK	207	5.08	13.86	1.52		2.17	0.73	1.32	0.001	1.321	0.03	
	NPK+OM	207	5.14	16.99	1.89		2.50	0.35	2.05	0.001	2.051	0.058	
	NPKS+RSD	207	5.10	16.68	1.88		2.68	0.44	0.58	0.002	0.582	0.073	
Typic Hapludalf（Askov，Denmark）	CK	–	–	–	2.9	12	1.3	1.2	–	–	–	–	[27]
	RSD	–	–	–	3.4		1.84	1.68	–	–	–	–	
	OM	–	–	–	3.2		1.61	1.29	–	–	–	–	
	RSD+OM	–	–	–	3.7		1.84	1.68	–	–	–	–	

1）CK，无肥对照；NPK，N肥+P肥+K肥处理；OM，有机肥处理；LOM，低量有机肥处理；MOM，中量有机肥处理；HOM，高量有机肥处理；RSD，秸秆处理 CK，control of no fertilization；NPK，mineral NPK fertilizer；OM，organic manure；LOM，low rate of organic manure；MOM，medium rate of organic manure；HOM，high rate of organic manure；RSD，straw

上，Zhang等[50]进一步发现有机酸（甘氨酸）浓度并不影响异养硝化与总硝化的相对比值，低浓度的有机酸（20 mg kg^{-1}）足以支持异养硝化作用。异养硝化过程可以提高土壤的供氮能力，同时又是土壤排放N_2O的三个主要来源之一[51]，进一步加强施肥措施对异养硝化过程的研究具有非常重要的意义。

3　长期施肥对硝态氮同化速率的影响

与铵态氮相比，微生物利用硝态氮需要消耗更多的能量[52]，且土壤铵态氮浓度高时会抑制硝态氮的转运或硝态氮还原酶的合成[53-55]，因而大多数研究均认为农田土壤不存在硝态氮同化作用。最近的研究表明，C源不足也是农田土壤微生物不利用硝态氮的重要原因[56]。Recous和Mary[57]发现，耕作土壤中只加入KNO_3时，微生物NO_3^--N同化几乎可忽略不计，而在相同KNO_3施用量的基础上加入C 500 mg kg^{-1}干土的葡萄糖时就立即发生NO_3^--N同化。同样地，在森林生态系统中，葡萄糖的加入量在C 1000 mg kg^{-1}干土以上时才会促进NO_3^--N同化[58]。但是，Shi和Norton[56]与Shi等[59]发现堆肥处理土壤仍然不能进行NO_3^--N同化，他们推测这是由于堆肥的C/N比较低（<12），有效C源不足以满足微生物的生长需求。与低C/N比的有机物料相比，高C/N比有机物料的施入则会激发异养微生物吸收更多的外源N来满足自身需求，致使微生物在利用NH_4^+-N的同时也进行NO_3^--N同化。已有研究表明，农田土壤施用小麦秸秆可以提高NO_3^--N同化[60-61]，而森林、草地和有机农田系统土壤中明显的NO_3^--N同化现象也可能是由于这些土壤中有效碳含量较高的原因[58，62-63]。

然而，利用数值模型测定土壤氮素转化速率时却发现，农田土壤也能发生微生物同化硝态氮作用（表1）。农田土壤中存在的硝态氮同化作用，可能是因为土壤中存在某些铵态氮浓度极低的微域，微生物转而利用硝态氮。例如，土壤中铵态氮有两个主要去向：一是通过自养硝化氧化为硝态氮，二是被微生物同化进入有机氮库，因此不可避免地会发生氨氧化细菌和异养微生物对铵态氮的竞争作用，而竞争的结果可能会使土壤中产生一些铵态氮不足的微域[62]。此外，底物的空间异质性也会形成铵态氮不足的微域。在这些微域中，铵态氮不能满足微生物自身生长对氮的需求，致使硝态氮成为可被微生物利用的有效氮源[63-65]。

4　长期施肥对反硝化速率和N_2O排放的影响

反硝化作用是指厌氧条件下NO_3^--N和NO_2^--N逐步还原为NO、N_2O和N_2的过程，是将活性氮转变为惰性氮（N_2）的一个重要的土壤氮循环过程[66-67]。大量长期定位施肥实验结果表明，施用化学氮肥和有机肥均能提高反硝化速率[68-69]，且有机肥的刺激作用高于化学氮肥。化学氮肥可以通过影响硝化过程间接地影响反硝化过程。首先，长期施用化学氮肥可以激发自养硝化，增加土壤中硝态氮的浓度，为反硝化提供充足的底物，最终促进反硝化过程及反硝化中间产物N_2O的排放[69-70]。其次，化学氮肥的长期施用导致农田土壤酸化[3]，pH降低会显著提高反硝化对N_2O产生的贡献[68，71]。Cheng等[71]的研究发现，控制N_2O排放途径的pH阈值约为4.4，低于该阈值时反硝化成为土壤N_2O排放的主要来源。与其他中间过程的反硝化还原酶相比，N_2O还原酶的转移与合成对低pH较反硝化过程中其他还原酶更敏感[72]，土壤pH降低可以显著抑制N_2O还原酶活性，从而导致反硝化产物中N_2O的比例增加[68，71]。亦或，与反硝化细菌需要厌氧条件相比，真菌介导的反硝化过程对O_2浓度范围的要求较宽[73-74]。主导反硝化的真菌通常缺少N_2O还原酶，N_2O成为反硝化的主要最终产物[74-75]。一般而言，酸性土壤中真菌反硝化过程较为显著[76-77]。Yamamoto等[78]发现酸性土壤中真菌介导的反硝化作用对N_2O产生的贡献量高达16.9%。因此，土壤pH的降低使得反硝化成为N_2O排放的主导过程，可能与真菌介导的反硝化过程密切相关。此外，酸性条件下化学反硝化过程可能也会对N_2O排放有一定的贡献。有研究发现化学反硝化过程在pH为4.1 ~ 4.2的酸性土壤对N_2O排放有重要贡献[79]。

与化学氮肥相比，有机肥施用影响反硝化过程的机制较为复杂。首先，有机肥作为C源，可直接为反硝化细菌提供能量和电子而促进反硝化，进而增加N_2O的产生量[80-81]。此外，有机肥施用可以激发自养硝化[37，61，59]和异养硝化[48-49]，为反硝化提供底物。再者，有机肥加入还可影响除无机N外的其他非生物因素，如有机肥激发了微生物活

性，进而加剧了土壤孔隙中O_2的耗竭，致使更多的好氧区域转变为厌氧区域[82]，导致反硝化替代硝化成为一些土壤孔隙中N_2O的主要过程，进而增加N_2O排放。这种异养微生物生长诱导的O_2耗竭可能与有机肥施入量呈正相关关系[82]。

5 基于农学和环境效应的施肥措施

有机肥一直被提倡和实践用来改善土壤肥力和提高土壤固碳能力[8，83-84]。研究表明，无论是单施有机肥还是有机-无机配施，均能有效地减轻硝酸盐污染，改善土壤肥力并提高作物产量[8-10]。Kramer等[85]间接地证明，有机肥施用可以通过增加反硝化过程中的气态氮损失，来降低苹果园土壤的NO_3^--N淋失。Wang等[25]的实验发现，有机肥施入可以增强异养微生物与氨氧化菌对铵态氮的竞争能力，进而降低NO_3^--N在土壤中的累积，并减少NO_3^--N损失。

硝化作用产生的NO_3^--N较NH_4^+-N更易迁移和淋失，因此抑制自养硝化过程是降低硝态氮损失的较好手段。目前硝化抑制剂，如双氰胺、氯甲基吡啶在减少农田氮素流失方面的应用前景广阔。此外，通过施用有机肥促进微生物对铵态氮和硝态氮的同化作用亦是降低NO_3^--N在土壤中累积的手段之一。但是有机肥的施用并不是多多益善，其过多施用也会增加氮损失的风险[86-88]。本综述的结果表明，长期施有机肥对自养硝化作用的刺激作用明显高于化学氮肥（图1c），会导致土壤中硝态氮的积累。Masaka等[86]发现，有机肥施用量超过15 t hm^{-2}时，淋溶液（深度为40 cm）中NO_3^--N浓度就超过饮用水标准（10 mg L^{-1}）的15%以上。而Maeda等[89]发现，有机肥处理1 m深土壤水中的NO_3^--N浓度只在前3年保持不变，随后则达到化学氮肥处理相同水平，表明有机肥在短期内可以减少NO_3^--N淋溶损失，长期施用下会与化学氮肥一样导致大量NO_3^--N淋溶损失。此外，有机肥还能促进土壤中可溶性有机氮的淋洗[90]。

6 结论与展望

合理施肥、在兼顾生态环境效应的前提下，提高作物产量、维持土壤肥力是农业可持续发展的必由之路，尤其是在农业面源污染日益严重的情况下，在不减产的同时降低肥料投入，提高氮肥利用率，降低氮向环境的排放是当前农业研究的热点和难点。研究长期施肥对土壤氮各个过程的影响，有助于加强我们对长期施肥对土壤供氮能力和保氮能力的影响的认识，可以为合理施用氮肥、提高氮肥利用率、减少与氮相关的环境污染提供理论依据。目前，有待深入开展以下几方面的研究：

（1）长期施化学氮肥会导致土壤酸化以及大量的氮损失，而施用有机肥可以缓解这些问题，因此有机无机配施是农业肥料投入的正确方式，但是过量的施入有机肥也会造成大量的氮损失，因此亟待明确有机肥投入的阈值以及合理的有机无机肥料投入比例。

（2）无论是有机肥还是化学氮肥投入均显著刺激硝化过程，造成土壤中大量的硝态氮累积，进而增加硝态氮损失的风险。虽然目前已经开发了硝化抑制剂来抑制或减缓自养硝化过程，并在一定程度上降低了硝态氮淋失以及N_2O排放风险。但是，如何提高土壤中微生物对硝态氮的同化则研究较少，一般认为农业土壤微生物不利用硝态氮。但有限的研究表明，通过加入一些C/N比较高的外源C很有可能促进农业土壤中硝态氮同化速率，进而把硝态氮转变为微生物生物量氮储存起来，然后通过再矿化作用缓慢释放出来，增加土壤保氮和供氮能力。但是，外源C输入亦可以提高土壤反硝化损失和N_2O排放。因此，需要加强研究能够提高硝态氮同化能力并尽可能降低反硝化损失的有效措施。

（3）虽然通过对氮各个转化过程的研究可以知晓同一体系中矿化、同化、硝化和反硝化等过程的关联作用及交互影响，但是如何整体评价长期施肥对土壤氮循环的影响亟待明确，比如长期施用有机肥可以通过增加反硝化过程中的气态氮损失，来降低苹果园土壤的NO_3^--N淋失，硝态氮淋失降低的代价是提高温室效应，这也是得不偿失的。再比如，应用硝化抑制剂可以减少农田土壤硝态氮和N_2O损失，但却可以大量提高氨挥发损失风险。因此，如何做到综合评估长期施肥下不同种类肥料及其比例对环境的综合影响也是以后研究的重点。

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Effects of Long-term Fertilization on Key Processes of Soil Nitrogen Cycling in Agricultural Soil：A Review

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Abstract　Application of synthetic nitrogen（N）fertilizer has been playing a critical role in enhancing the supply of food to an increasingly growing world population. However，large inputs of mineral N fertilizer in excess of the crop requirements may lead to low N use efficiency and cause a series of negative environmental impacts，such as eutrophication of surface waters，nitrate pollution of groundwater，soil acidification and greenhouse gas emissions. Such environmental problems are getting worse due to predictable increase in the use of mineral N fertilizer in the future. Therefore，optimal N fertilizer management strategies synchronizing N supply with crop demand should be developed to maintain crop yield and economic profit while minimizing negative environmental impact. Organic fertilizer as substitute for mineral N fertilizer has been advocated and practiced to increase soil carbon（C）sequestration and improve soil fertility. It has also been suggested that application of organic fertilizers，either alone or in combination with mineral N fertilizers，is effective in mitigating N-related pollution，improving soil fertility，and increasing crop yield. At present，how to fertilize rationally，improve crop yields，build up soil fertility and meanwhile maintain a sound ecological environment is one of the major challenges to agricultural research. Which step of N transformation in the soil would long-term application of organic manure affect thus influencing N supplying capacity and N retaining mechanism of the soil? What is the mechanism behind long-term application of organic manure decreasing N-related pollution and the increasing crop yield? This review elaborated effects of long-term fertilization on key processes of soil nitrogen cycling in agricultural soil in expectation to provide some theoretical basis for rationalization of long-term fertilization and improvement of N fertilizer utilization rate. The review proceeded from the angle of primary N transformation rate of the processes of soil nitrogen cycling to discuss effects of fertilization（mineral or organic fertilizers）on key processes of the soil nitrogen cycling. Soil N mineralization and assimilation are two crucial links in the cycling and factors that determine soil N supplying capacity. Long term application of nitrogen fertilizers could increase soil organic N and C contents and provide crops with available N slowly through mineralization of soil organic N and subsequent nitrification. Large volumes of long-term fertilization experiments demonstrate that long-term application of N fertilizers could stimulate soil primary N mineralization rate by increasing soil organic N and C contents. Long-term application of chemical N fertilizers or organic manure both have some influence on assimilation of soil ammonium nitrogen，which is reflected as a whole in better effect of organic manure raising soil ammonium assimilation rate than that of chemical fertilizer. Generally speaking，long-term application of N fertilizer，especially organic manure，could significantly increase soil N primary mineralization and assimilation turnover rate，and stimulate soil autotrophic nitrification, too, which may be attributed to the difference between chemical fertilizer and organic manure in stimulation mechanism. The experiments also demonstrate that the application of either chemical fertilizer or organic manure could increase soil denitrification rate, and the effect is more apparent with the application of organic manure. Being a substitute of chemical fertilizer, organic manure has been advocated and used to improve soil fertility and carbon sequestration capacity. Researches indicate that the application of organic manure, either singly or in combination with chemical fertilizers can effectively reduce nitrate pollution, and improve soil fertility and crop yield, but in terms of application rate, it could not be said as the more the better. Like chemical fertilizer, organic manure, if applied excessively, may also increase the risk of N loss. Rational fertilization with its impact on eco-environment taken into consideration is the only way to raise crop yield, maintain soil fertility and pursue sustainable development of the agriculture. The study on effects of long-term fertilizer on various processes of soil N cycling will help us understand how long-term fertilization affect soil N supplying and retaining capacities and lay down a scientific basis for rationalizing N fertilization.

Key words Long-term fertilization; Mineralization; NH_4^+ immobilization; Autotrophic nitrification; Denitrification

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《土壤学报》编辑委员会

土壤学报

Turang Xuebao

（双月刊，1948年创刊）

第 53 卷　第 2 期　2016 年 3 月

ACTA PEDOLOGICA SINICA

（Bimonthly，Started in 1948）

Vol. 53　No. 2　Mar.，2016

编　　辑	《土壤学报》编辑委员会 地址：南京市北京东路 71 号　邮政编码：210008 电话：025－86881237 E-mail：actapedo@ issas. ac. cn	Edited by	Editorial Board of Acta Pedologica Sinica Add：71 East Beijing Road，Nanjing 210008，China Tel：025－86881237 E-mail：actapedo@ issas. ac. cn
主　　编	史学正	Editor-in-Chief	Shi Xuezheng
主　　管	中国科学院	Superintended by	Chinese Academy of Sciences
主　　办	中国土壤学会	Sponsored by	Soil Science Society of China
承　　办	中国科学院南京土壤研究所	Undertaken by	Institute of Soil Science， Chinese Academy of Sciences
出　　版	科学出版社 地址：北京东黄城根北街 16 号 邮政编码：100717	Published by	Science Press Add：16 Donghuangchenggen North Street， Beijing 100717，China
印刷装订	北京中科印刷有限公司	Printed by	Beijing Zhongke Printing Limited Company
总 发 行	科学出版社 地址：北京东黄城根北街 16 号 邮政编码：100717 电话：010－64017032 E-mail：journal@ mail. sciencep. com	Distributed by	Science Press Add：16 Donghuangchenggen North Street， Beijing 100717，China Tel：010－64017032 E-mail：journal@ mail. sciencep. com
国外发行	中国国际图书贸易总公司 地址：北京 399 信箱　邮政编码：100044	Oversea distributed by	China International Book Trading Corporation Add：P. O. Box 399，Beijing 100044，China

国内统一连续出版物号：CN 32-1119/P　　国内邮发代号：2-560　　国外发行代号：BM45　　定价：60.00 元

国内外公开发行

ISSN 0564-3929

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