冻融条件下土壤 N_2O 排放研究进展

王风[1, 2*]，高尚宾[1]，张克强[1]，杨鹏[1]，白丽静[1]，黄治平[1]
1. 农业部环境保护科研监测所，天津 300191；2. 中国科学院遗传与发育生物学研究所农业资源研究中心，河北 石家庄 050021

摘要：随着全球气候变化以及突发性气候事件频繁发生，温室气体逐渐成为公众普遍关注的问题。作为温室气体的重要组成之一，土壤N_2O气体排放也一直都是研究的焦点。但长期以来开展的土壤N_2O监测大多在作物生长季节，随着研究的深入和领域的拓展，很多试验和数据证实冻融条件下土壤N_2O的排放不容忽视。冻融条件下土壤N_2O排放主要受土壤水分形态和分布，土壤团聚体形成或破碎，土壤微生物种群和数量，以及N_2O产生途径变化等因素影响。从以上几个方面综述了国内外冻融条件下土壤N_2O排放的研究进展。结合作者相关研究结果认为应加强以下重点领域研究：土壤团聚体形成或破碎导致微生物可利用的有机碳的包被或释放，冻融过程微生物种群变化引起对不同氮素形态的利用效率差异。解决这些问题将可以进一步丰富土壤温室气体产排领域的研究内容和理论体系。

关键词：冻融过程；土壤；氧化亚氮；排放；进展
中图分类号：S154 **文献标识码**：A **文章编号**：1674-5906（2009）05-1933-05

氧化亚氮(N_2O)是温室气体的重要组成之一，而土壤是 N_2O 的主要排放源，占全球每年排放总量的 35%左右。目前，国内关于土壤 N_2O 的研究主要集中在以下两方面：一是区域及不同农田生态系统 N_2O 的排放特征研究[1-3]；二是排放影响因素的研究，主要集中在温湿度、肥料形态和含量等方面。Hans 等[4]和 He 等[5]研究认为土壤 N_2O 的排放与施氮量和灌溉量高度相关，而不同氮肥类型对土壤 N_2O 排放也有一定影响[6-7]，通常认为硝态氮肥的施用提高土壤反硝化速率，但梁东丽等[8]发现施用铵态氮肥的土壤 N_2O 排放量显著高于硝态氮肥处理，而施用尿素的土壤 N_2O 排放量显著高于施用硫铵[9]，Gregorich 等[10]研究发现施用有机肥比液态或化学氮肥产生较少的 N_2O。以上研究多集中在作物生长季节，而忽视了冻融期土壤 N_2O 的排放[11-12]，加强对冻融过程 N_2O 排放影响因素和规律的研究能够进一步丰富土壤温室气体的产排领域的研究内容和理论体系。Teepe 等[13]通过定位监测证实土壤冻结和融化过程中存在 N_2O 的排放，且监测的 3 种土壤类型在冬季 N_2O 排放量占年排放量的 50%，因此作为普遍存在于中、高纬度及高海拔地区的自然现象[14-15]，冻融作用条件下 N_2O 排放逐渐引起人们重视。迄今为止，该领域的研究已经涉及到土壤固液态水分的含量和分布及由此形成的冰膜造成的厌氧环境，土壤团聚体形成和破碎及由此引起的有机碳氮的保存或释放，土壤微生物种群和数量及其对碳氮元素形态和数量可用性等方面，本文就冻融过程的作用机理综述土壤 N_2O 排放最新研究进展，并展望了该领域的研究重点。

1 冻融作用通过改变水分形态和分布影响 N_2O 排放

龚家栋[16]发现融冻后的土壤含水量显著提高，王风等[17]在黑土区监测到2 m土体因冻结贮水量增加73.7 mm，而冻融过程中的土壤水分处于不同的相态[18]，可以应用中子仪-TDR联合测定的方法测试冰和液态水含量[19]。冰和液态水含量会对土壤N_2O的排放产生重要影响。Van等[20]发现，融冻期含水量为39%的粘土比含水量28%时释放更多的N_2O，这个结论得到广泛的认可。也有研究表明，土壤含水量为充水孔隙度80%时，融冻后土壤具有最大的N_2O排放量[21]。冻融过程造成微域土壤颗粒表面包被冰膜[22]，使土粒处于缺氧环境，利于土壤微生物进行反硝化作用产生N_2O，但冰膜的存在也会阻碍土壤冻结阶段N_2O的释放[23]，而在土壤融冻阶段得以充分排放，出现N_2O排放高峰[24-25]，虽然Röver等[21]和Teepe等[23]认为下部土壤N_2O的扩散是该峰值的重要来源，但王风等认为表层土壤团聚体内部是冻融过程中N_2O产排的主要部位[26-27]。

2 冻融过程通过改变土壤结构影响N_2O排放

冻融作用和冻融循环影响土壤团聚体稳定性[28-29]。众多学者研究表明冻融过程降低土壤团聚体稳定性[28,30-31]，但也存在截然相反的研究结论[32-33]。王风等[34]研究表明，在田间持水量时，冻融过程增强黑土团聚体稳定性，含水量过高或过低都

基金项目："十一五"国家科技支撑计划项目(2006BAD17B02)；中央级公益性科研院所基本科研业务专项
作者简介：王风(1982 年生)，男，研究助理，博士研究生，从事农田生态研究。E-mail: wangfeng_530@163.com
*通讯作者，E-mail: wangfeng_530@163.com
收稿日期：2009-07-25

会破碎土壤团聚体稳定性，特别是在较高的含水量条件下[28,34]，而这种破碎作用对大团聚体影响更为显著[20,34]，受到破碎的大团聚体所包裹保存的新形成的活性有机碳被释放出来[35-36]，显著增强土壤微生物有效性，即使在较低的含水量条件下，通过反硝化作用产生N_2O的强度也很大[37]，Van等[20]甚至发现冻融过程土壤碳矿化作用和反硝化作用增加了95%，N_2O的排放量增加220%。

王风等[26]研究了潮土两种粒径范围（≤1 cm粒径和≤0.25 mm粒径）土壤在冻融过程中N_2O排放的特征。结果表明：冻结前，0.25 mm粒径土壤N_2O排放通量比1 cm粒径土壤平均高26.5%；在-5 ℃条件下冻结过程中，0.25 mm粒径土壤比1 cm粒径土壤较早达到稳定冻结状态（分别在冻结1 410 min和2 610 min），并且在稳定冻结状态下0.25 mm粒径土壤N_2O排放通量小于1 cm粒径土壤；融化阶段，0.25 mm粒径土壤比1 cm粒径土壤较早出现N_2O排放通量高峰（分别在融化2 670 min和2 790 min），并且其峰值小于1 cm粒径土壤。1 cm粒径土壤冻结过程、融化过程和整个冻融过程土壤平均N_2O排放量分别比0.25 mm粒径土壤多3 952.74、1 512.51和5 465.25 μg·m^{-2}，相应增加76.83%、18.65%和41.23%。

3 冻融过程通过改变土壤微生物种群和数量影响N_2O排放

冻融过程改变土壤微生物的种群结构、数量以及生存环境[38]，对不同形态的土壤氮素响应及N_2O的排放有重要影响。冻结温度、持续时间、土壤含水量和冻融循环次数均影响土壤微生物种群结构及活性[39]。弱冻对土壤微生物量碳氮影响不大[40]，但强烈的冻融循环会影响土壤溶液中氮和有机碳的数量和形态[15]。随冻结持续时间和冻融循环次数的增加融冻期N_2O的排放量增加[41-42]，可能因为冻结导致一些细菌死亡，死亡的细菌释放出碳、氮营养物质[40]，这些营养物质被存活的微生物固持、利用，增加土壤微生物的活性，增强土壤碳和氮矿化能力，因而排放更多的N_2O[43]。Teepe等[44]发现融冻期土壤微生物产生N_2O过程中的呼吸量与整个土壤的呼吸量相差很大，土壤中其它生物的呼吸依旧很强烈，说明冻融作用改变土壤中微生物种群结构和生命活动过程[38]，冻融时期土壤优势种群为真菌[45]，非冻融期则为细菌[46]。

4 通过改变产生途径而影响 N_2O 排放

土壤通过硝化作用、反硝化作用、硝态氮异化还原成铵作用和化学反硝化作用等途径产生 N_2O。其中，土壤微生物硝化作用和反硝化作用是 N_2O 产生的主要途径[46]。硝化作用分为自养硝化和异养硝化，均在好氧条件下进行。农业非冻融期土壤中自养硝化作用是产生 N_2O 的主要过程[48-49]。自养硝化细菌氧化 NH_4^+获得能量，NH_4^+经过一系列反应形成中间产物 N_2O[50]。异养硝化菌以有机碳为碳源。一般认为，真菌比细菌更易进行异养硝化过程，在冻融过程后的草地土壤上也得到相似结论[24]。土壤反硝化过程主要由异养反硝化细菌完成，其生长繁殖过程需要有机碳源[51]。厌氧条件下，异养反硝化细菌以氮氧化物为最终电子受体，有机碳为电子供体，进行电子传递氧化磷酸化作用[52-53]。冻融过程中硝化和反硝化作用产生 N_2O 能力不同。通过不同方法测试发现，反硝化作用是冻融过程中土壤 N_2O 产生的主要途径[24, 38, 54-55]，主要因为氧化亚氮还原酶在土壤融冻时活性增强[56],反硝化作用对 N_2O 的贡献达 83%[57]。

王风等[58]2009年研究了3种氮素形态（铵态氮、硝态氮和酰胺态氮）和3种浓度（40、200和800 mg N/L）对冻融过程潮土N_2O排放通量的影响。结果表明：随氮素浓度的增加，铵、硝态氮源土壤N_2O排放通量分别比对照增加17.49%、40.09%、425.67%和563.38%、915.28%和1458.6%，并且达到稳定N_2O排放通量的时间向后推移，该结论从一定程度上证实反硝化作用是冻融过程中土壤N_2O产生的主要途径。随浓度增加酰胺态氮处理土壤N_2O排放通量降低，可能是因为硝化微生物和反硝化微生物适宜的最大pH值为8[59]，供试潮土土壤基础pH值为7.98，处于土壤适宜反硝化酸碱度的临界值，有人证实尿素水解的前4天土壤pH值持续增加0.5[8]，土壤pH值的增加导致超出了最适宜的反硝化pH值范围，土壤N_2O的排放开始受到抑制，伴随尿素浓度的增大抑制效应越显著。无机态氮的施入增大了N_2O累积排放量，且施加的浓度越高累积排放量越大，酰胺态氮结果相反。

同年另外一篇文献中[60]报道了在相同氮素形态和浓度条件下，两种粒径土样（1 cm和0.25 mm）在冻融过程中N_2O的排放特征。结果表明：冻结前，除硝态氮浓度在大于200 mg·L^{-1}时，细土N_2O排放通量小于粗粒径土壤，其他氮素形态和浓度得到相反结果，说明N_2O排放通量是土粒厌氧程度和底物浓度总和作用的结果；冻结过程细土达到N_2O稳定排放通量的时间要早于粗粒径土壤；融化后细土比粗粒径土壤早出现N_2O排放峰，并且该峰值总体比粗粒径土壤小；随氮素浓度增加，粗粒径土壤3种氮素形态平均N_2O累积排放量分别比细粒径土壤多45.46%、7.81%和46.87%。建议加氮灌溉土壤应尽量避免施加硝态氮肥，尽可能施用尿素态氮代替无机态氮素，而铵态氮肥的施用应尽量考虑降低浓

度。整个冻融过程3种氮素形态和浓度条件下粗粒径土壤N_2O累积排放量较细粒径土壤多32.16%，建议在灌溉越冬水后耙碎大土块以减少N_2O排放，而铵浓度低于40 $mg \cdot L^{-1}$灌溉后无需耙地。

5 展望

目前，国外学者对冻融作用下土壤N_2O排放的物理因素、化学因素和生物因素等方面的影响因素正进行研究，并且相关文献多来源于国际杂志《Soil Biology and Biochemistry》，使得该领域的研究成为国际普遍关注的热点。然而考虑冻融过程中土壤团聚体形成或破碎，以及微生物种群和数量变化条件下碳氮元素形态、数量可用性等因素在内的土壤实际N_2O排放特征更为复杂。而且，冻融过程似乎通过改变土壤团聚体稳定性而影响N_2O排放速率，具体表现在以下3个方面。

（1）土壤团聚体形成或破碎导致微生物可利用的有机碳的包被或释放。

（2）冻结团聚体内部的厌氧环境似乎是冻融过程N_2O产生的重要部位，而并非像以往研究结果认为是下部土层的扩散。

（3）冻融过程引起微生物种群变化，从而引起对不同氮素形态的利用效率差异。

这些问题的证实和解决，将可以进一步丰富土壤学、地表重要过程以及土壤温室气体的产排等领域的研究内容和理论体系。

参考文献：

[1] 林杉, 冯明磊, 阮雷雷, 等. 三峡库区不同土地利用方式下土壤氧化亚氮排放及其影响因素[J]. 应用生态学报, 2008, 19(6): 1269-1276.
LIN Bin, FENG Minglei, RUAN Leilei, et al. Soil N_2O flux and its affecting factors under different land use patterns in Three Gorges Reservoir Area of China[J]. Chinese Journal of Applied Ecology, 2008, 19(6): 1269-1276.

[2] 邹建文, 黄耀, 宗良纲, 等. 不同种类有机肥施用对稻田CH_4和N_2O排放的综合影响[J]. 环境科学, 2003, 24(4): 7-12.
ZOU Jianwen, HUANG Yao, ZONG Lianggang, et al. Integrated effect of incorporation with different organic manures on CH_4 and N_2O emissions from rice paddy[J]. Environmental Science, 2003, 24(4): 7-12.

[3] 丁琦, 白红英, 李西祥, 等. 作物对黄土性土壤氧化亚氮排放的影响-根系与土壤氧化亚氮排放[J]. 生态学报, 2007, 27(7): 2823-2831.
DING Qi, BAI Hongying, LI Xixiang, et al. The effects of crop on N_2O emission from loess soil: roots and N_2O emission from soil[J]. Acta Ecologica Sinica, 2007, 27(7): 2823-2831.

[4] HANS J H, VOLKHARD S, JŰRGEN K. Fertiliser induced nitrous oxide emissions during energy crop cultivation on loamy sand soils[J]. Atmospheric Environment, 2008, 42(36): 8403-8411.

[5] He F F, JIANG R F, CHEN Q, et a1. Nitrous oxide emissions from an intensively managed greenhouse vegetable cropping system in Northern China[J]. Environmental Pollution, 2009, 157(5): 1666-1672.

[6] 秦晓波, 李玉娥, 刘克樱, 等. 不同施肥处理稻田甲烷和氧化亚氮排放特征[J]. 农业工程学报, 2006, 22(7): 143-148.
QIN Xiaobo, LI Yue, LIU Keying, et al. Methane and nitrous oxide emission from paddy field under different fertilization treatments[J]. Transactions of the Chinese Society of Agricultural Engineering, 2006, 22(7): 143-148.

[7] 邹建文, 黄耀, 宗良纲, 等. 不同种类有机肥施用对稻田CH_4和N_2O排放的综合影响[J]. 环境科学, 2003, 24(4): 7-12.
ZOU Jianwen, HUANG Yao, ZONG Lianggang, et al. Integrated effect of incorporation with different organic manures on CH_4 and N_2O emissions from rice paddy[J]. Environmental Science, 2003, 24(4): 7-12.

[8] 梁东丽, 方日尧, 李生秀, 等. 硝、铵态氮肥对旱地土壤氧化亚氮排放的影响[J]. 干旱地区农业研究, 2007, 25(1): 67-72.
LIANG Dongli, FANG Rirao, LI Shengxiu, et al. Effects of nitrogen types on N_2O emissions of dry-land soil[J]. Agricultural Research in the Arid Areas, 2007, 25(1): 67-72.

[9] 丁洪, 王跃思, 项虹艳, 等. 灰泥土中不同氮肥品种反硝化损失与N_2O排放量的差异[J]. 生态环境, 2004, 13(4): 643-645.
DING Hong, WANG Yuesi, XIANG Hongyan, et al. Differences of denitrification losses and N_2O emission from different nitrogen fertilizers in grey soil[J]. Ecology and Environment, 2004, 13(4): 643-645.

[10] GREGORICH E G, ROCHETTE P, VANDENBYGAART A J, et a1. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada[J]. Soil and Tillage Research, 2005, 83(1): 53-72.

[11] FREIBAUER A. Regionalised inventory of biogenic greenhouse gas emissions from European agriculture[J]. European Journal of Agronomy, 2003, 19(2): 135-160.

[12] GROFFMAN P M, HARDY J P, DRISCOLL C T, et a1. Snow depth, soil freezing and fluxes of carbon dioxide, nitrous oxide and methane in a northern hardwood forest[J]. Global Change Biology, 2006, 12(9): 1-13.

[13] TEEPE R, BRUMME R, BEESE F. Nitrous oxide emissions from frozen soils under agricultural, fallow and forest land[J]. Soil Biology and Biochemistry, 2000, 32(11-12): 1807-1810.

[14] 赵其国, 王浩清, 顾国安. 中国的冻土[J]. 土壤学报, 1993, 30(4): 341-354.
ZHAO Qiguo, WANG Haoqing, GU Guoan. Gelisols of China[J]. Acta Pedologica Sinica, 1993, 30(4): 341-354.

[15] GROGAN P, MICHELSEN A, AMBUS P, et al. Freeze-thaw regime effects on carbon and nitrogen dynamics in sub-arctic heath tundra mesocosms[J]. Soil Biology and Biochemistry, 2004, 36(4): 641-654.

[16] 龚家栋, 祁旭升, 谢忠奎, 等. 季节性冻融对土壤水分的作用及其在农业生产中的意义[J]. 冰川冻土, 1997, 19(4): 328-333.
GONG Jiadong, QI Xusheng, XIE Zhongkui, et al. Effect of seasonal freezing on soil moisture and its significance for agriculture[J]. Journal of Glaciology and Geocryology, 1997, 19(4): 328-333.

[17] 王风, 韩晓增, 邹文秀, 等. 冻融过程黑土2 m土体固液态水分含量动态特征[J]. 水科学进展, 2008, 19(3): 361-366.
WANG Feng, HAN Xiaozeng, ZOU Wenxiu, et al. Study on the dynamic characteristics of solid and liquid water in the process of freezing-thawing in black soil[J]. Advances in Water Science, 2008, 19(3):

361-366.

[18] BOND L B, WANG C K, GOWER S T. Spatiotemporal measurement and modeling of stand-level boreal forest soil temperatures[J]. Agricultural and Forest Meteorology, 2005, 131(1-2): 27-40.

[19] 王风, 韩晓增, 李海波, 等. 土壤冻融过程中固液态水含量测定技术研究[J]. 土壤通报, 2007, 38(5): 1036-1037.
WANG Feng, HAN Xiaozeng, LI Haibo, et al. A technique of distinguishing the content of solid and liquid water during freezing-thawing period[J]. Chinese Journal of Soil Science, 2007, 38(5): 1036-1037.

[20] VAN B E, PREVOST D, PELLETIER F. Effects of freeze-thaw and soil structure on nitrous oxide produced in a clay soil[J]. Soil Science Society of America Journal, 2000, 64(5): 1638-1643.

[21] RÖVER M. HEINEMEYER O, KAISER E A. Microbial induced nitrous oxide emissions from an arable soil during winter[J]. Soil Biology and Biochemistry, 1998, 30(14): 1859-1865.

[22] WANG L F, CAI Z C, YAN H. Nitrous oxide emission and reduction in a laboratory-incubated paddy soil response to pretreatment of water regime[J]. Journal of Environmental Sciences, 2004, 16(3): 353-357.

[23] TEEPE R, BRUMME R, BEESE F. Nitrous oxide emissions from soil during freezing and thawing periods[J]. Soil Biology and Biochemistry, 2001, 33(9): 1269-1275.

[24] MŰLLER C, MARTIN M, STEVENS R J, et al. Processes leading to N_2O emissions in grassland soil during freezing and thawing[J]. Soil Biology and Biochemistry, 2002, 34(9): 1325-1331.

[25] ZHU R B, LIU Y S, MA E D, et a1. Greenhouse gas emissions from penguin guanos and ornithogenic soils in coastal Antarctica: effects of freezing-thawing cycles[J]. Atmospheric Environment, 2009, 43(14): 2336-2347.

[26] 王风, 白丽静, 张克强, 等. 冻融过程不同粒径土壤 N_2O 排放特征[J]. 应用与环境生物学报, 2010, 16(1).
WANG Feng, BAI Lijing, ZHANG Keqiang, et al. Effects of soil particle sizes on the N_2O flux in the freezing and thawing process[J]. Chinese Journal of Applied and Environmental Biology, 2010, 16(1).

[27] WANG FENG, BAI LIJING, ZHANG KEQIANG, et al. Effects of nitrogen application on N_2O flux from fluvo-aquic soil subject to freezing and thawing process[J]. Agricultural Science in China, 2010.

[28] OZTAS T, FAYETORBAY F. Effect of freezing and thawing processes on soil aggregate stability[J]. Catena, 2003, 52(1): 1-8.

[29] SIGRUN H K, LILLIAN Ø. The influence of freeze-thaw cycles and soil moisture on aggregate stability of three soils in Norway[J]. Cetena, 2006, 67(3): 175-182.

[30] BAJRACHARYA R M, LAL R, HALL G F. Temporal variation in properties of an uncropped, ploughed Miamian soil in relation to seasonal erodibility[J]. Hydrological Processes, 1998, 12(7): 1021-1030.

[31] ØYGARDEN L. Soil erosion in small agricultural catchments, south-eastern Norway[D]. Agricultural University of Norway, 2000: 8.

[32] LEHRSEH G A, SOJKA R E, CARTER D L, et a1. Freezing effect on aggregate stability affected by texture, mineralogy and organic matter[J]. Soil Science Society of America Journal, 1991, 55: 1401-1406.

[33] LEHRSEH G A. Freeze-thaw cycles increase near surface aggregate stability[J]. Soil Science, 1998, 163(1): 63-70.

[34] 王风, 韩晓增, 李良皓, 等. 冻融过程对黑土水稳性团聚体含量影响[J]. 冰川冻土, 2009, 31(5): 890-900.
WANG Feng, HAN Xiaozeng, LI Lianghao, et al. The effect of freezing and thawing processes on black soil aggregate stability[J]. Journal of Glaciology and Geocryology, 2009, 31(5): 890-900.

[35] PUGET P, CHENU C, BALESDENT J. Total and young organic matter distributions in aggregates of silty cultivated soils[J]. European Journal of Soil Science, 1995, 46(3): 449-459.

[36] LI H B, HAN X Z, WANG F, et al. Impact of soil management on organic carbon content and aggregate stability[J]. Communications in Soil Science and Plant Analysis, 2007, 38(13-14): 1673-1690.

[37] WANG L F, CAI Z C, YANG L F, et a1. Effect of disturbance and glucose addition on nitrous oxide and carbon dioxide emissions from a paddy soil[J]. Soil and Tillage Research, 2005, 82(2): 185-194.

[38] SHARMA S, SZELE Z, SCHILLING R, et a1. Influence of freeze-thaw stress on the structure and function of microbial communities and denitrifying populations in soil[J]. Applied and Environmental Microbiology, 2006, 72(3): 2148-2154.

[39] 王连峰, 蔡延江, 解宏图. 冻融作用下土壤物理和微生物性状变化与氧化亚氮排放的关系[J]. 应用生态学报, 2007, 18(10): 2361-2366.
WANG Lianfeng, CAI Yanjiang, XIE Hongtu. Relationships of soil physical and microbial properties with nitrous oxide emission under effects of freezing-thawing cycles[J]. Chinese Journal of Applied Ecology, 2007, 18(10): 2361-2366.

[40] NEILSEN C B, GROFFMAN P M, HAMBURG S P, et a1. Freezing effects on carbon and nitrogen cycling in northern hardwood forest soils[J]. Soil Science Society of America Journal, 2001, 65: 1723-1730.

[41] LARSEN K S, JONASSON S, MICHELSEN A. Repeated freeze-thaw cycles and their effects on biological processes in two arctic ecosystem types[J]. Applied Soil Ecology, 2002, 21(3): 187-195.

[42] ZHU R B, LIU Y S, MA E D, et a1. Nitrous oxide flux to the atmosphere from two coastal tundra wetlands in eastern Antarctica[J]. Atmospheric Environment, 2008, 42(10): 2437-2447.

[43] PAPEN H, BUTTERBACH-BAHL K. A 3-year continuous record of N-trace gas fluxes from untreated and limed soil of a N-saturated spruce and beech forest ecosystem in Germany. I. N_2O emissions[J]. Journal of Geophysical Research, 1999, 104(15): 18487-18503.

[44] TEEPE R, VOR A, BEESE F, et a1. Emissions of N_2O from soils during cycles of freezing and thawing and the effects of soil water, texture and duration of freezing[J]. European Journal of Soil Science, 2004, 55(2): 357-365.

[45] SCHADT C W, MARTIN A P, LIPSON D A, et a1. Seasonal dynamics of previously unknown fungal lineages in tundra soils[J]. Science, 2003, 301: 1359-1361.

[46] LIPSON D A, SCHADT C W, SCHMIDT S K. Changes in soil microbial community structure and function in an alpine dry meadow following spring snow melt[J]. Microbial Ecology, 2002, 43(3): 307-314.

[47] GRANLI T, BØCKMAN O C. Nitrous oxide from agriculture[J]. Norwegian Journal of Agricultural Science, 1994, 12(supp): 1-128.

[48] TORTOSO A C, HUTCHINSON G L. Contribution of autotrophic and heterotrophic nitrifiers to soil NO and N_2O emissions[J]. Applied and Environmental Microbiology, 1990, 56(6): 1799-1805.

[49] MALJANEN M, MARTIKKALA M, HANNU T K, et a1. Fluxes of nitrous oxide and nitric oxide from experimental excreta patches in boreal agricultural soil[J]. Soil Biology and Biochemistry, 2007, 39(4):

914-920.

[50] WRAGE N, VELTHOF G L, VAN BEUSICHEM M L, et a1. Role of nitrifier denitrification in the production of nitrous oxide[J]. Soil Biology and Biochemistry, 2001, 33(12-13): 1723-1732.

[51] 王连峰, 蔡祖聪. 水分和温度对旱地红壤硝化活力和反硝化活力的影响[J]. 土壤, 2004, 36(5): 543-546.
WANG Lianfeng, CAI Zucong. Effects of temperature and water regime on nitrification and denitrification activity of upland red soils[J]. Soils, 2004, 36(5): 543-546.

[52] WANG L F, CAI Z C. Dynamics of denitrifying enzyme activity in red soils as affected by water treatment[C]// ZHU Z L, MINAMI K, XING G X. 3rd International Nitrogen Conference Contributed Papers. New York: Science Press USA Inc, 2005, 174-177.

[53] YANG L F, CAI Z C. The effect of growing soybean (*Glycine max. L.*) on N_2O emission from soil[J]. Soil Biology and Biochemistry, 2005, 37(6): 1205-1209.

[54] PREMÉ A, CHRISTENSEN S. Natural perturbations, drying-wetting and freezing-thawing cycles, and the emission of nitrous oxide, carbon dioxide and methane from farmed organic soils[J]. Soil Biology and Biochemistry, 2001, 33(15): 2083-2091.

[55] MØRKVED P T, DÖRSCH P, HENRIKSEN T M, et al. N_2O emissions and product ratios of nitrification and denitrification as affected by freezing and thawing[J]. Soil Biology and Biochemistry, 2006, 38(12): 3411-3420.

[56] MŰLLER C, KAMMANN C, ONOW J C G, et a1. Nitrous oxide emission from frozen grassland soil and during thawing periods[J]. Journal of Plant Nutrition and Soil Science, 2003, 166(1): 46-53.

[57] LUDWIG B, WOLF I, TEEPE R. Contribution of nitrification and denitrification to the emission of N_2O in a freeze-thaw event in an agricultural soil[J]. Journal of Plant Nutrition and Soil Science, 2004, 167(6): 678-684.

[58] 王风, 白丽静, 张克强, 等. 氮素调控对冻融过程中土壤N_2O排放的影响[J]. 环境科学, 2009, 30(11): 印刷中.
WANG Feng, BAI Lijing, ZHANG Keqiang, et al. Effects of nitrogen on the N_2O flux in the freezing and thawing process in fluvo-aquic soil[J]. Environmental Science, 2009, 30(11): in press.

[59] DELWIEHE C C, BRYAN B A. Denitrification[J]. Annul Review Microbiology, 1976, 30: 241-262

[60] 王风, 白丽静, 张克强, 等. 粒径对冻融过程中加氮灌溉土壤N_2O排放的影响[J]. 农业工程学报, 2009, 25(9): 69-73.
WANG Feng, BAI Lijing, ZHANG Keqiang, et al. Effects of soil particle sizes irrigated with nitrogen on the N_2O flux in the freezing and thawing process[J]. Transactions of the Chinese Society of Agricultural Engineering, 2009, 25(9): 69-73.

Progress on N_2O emission from soil in the freeze-thaw process

WANG Feng[1, 2], GAO Shangbin[1]， ZHANG KeQiang[1], YANG Peng[1], BAI LiJing[1], HUANG ZhiPing[1]

1. Institute of Agro-environmental Protection, Ministry of Agriculture, Tianjin 30019, China;

2. Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China

Abstract: With global climate change and unexpected climatic events frequent breaking out, greenhouse gases has been obviously concerned. As an important greenhouse gas, soil N_2O gas emissions have been also focusing great attention, but most scientific experiments were carried out in the crop growing season. With the development of depth and scope, some studies and data confirmed that soil N_2O emissions in the freeze-thaw process can not be ignored. soil N_2O emissions in the freeze-thaw process were affected by soil water morphology and distribution; soil aggregates formation and fragmentation; soil microbial populations and the quantity, as well as ways to producing N_2O. In this paper, the factors of N_2O emissions in the freeze-thaw process were reviewed from above four aspects. Then, author prospects the following two key areas: soil aggregates formation or fragmentation causing organic carbon coated or released differs micro-organisms activities, freeze-thaw process changing microbial populations differs nitrogen use efficiency. Solving the problems will enrich the soil greenhouse gases emission in the field of research content and theory.

Key words: freeze-thaw process; soil; N_2O; emission; progress