

DOI: 10.11766/trxb201703160104

# 营林措施对森林土壤N<sub>2</sub>O排放影响的研究进展\*

王会来<sup>1, 2, 3</sup> 刘娟<sup>1, 2, 3†</sup> 姜培坤<sup>1, 2, 3</sup> 周国模<sup>1, 2, 3</sup> 李永夫<sup>1, 2, 3</sup>  
吴家森<sup>1, 2, 3</sup>

(1浙江农林大学亚热带森林培育国家重点实验室,浙江临安 311300)

(2浙江农林大学浙江省森林生态系统碳循环与固碳减排重点实验室,浙江临安 311300)

(3浙江农林大学浙江省竹资源与高效利用协同中心,浙江临安 311300)

**摘要** 森林土壤是大气N<sub>2</sub>O重要的排放源。施肥、采伐、火烧、林下植被管理等营林措施和土地利用变化改变了土壤理化性质和土壤微气候,显著影响森林土壤N<sub>2</sub>O的产生与排放。综述了森林土壤N<sub>2</sub>O排放对不同营林措施的响应,探讨了营林措施影响土壤N<sub>2</sub>O排放的主要机理,并提出目前研究的不足和未来研究的重点。总体而言,森林转变为农田、草地后增加了土壤N<sub>2</sub>O排放,而农田和草地恢复成人工林后减弱了土壤N<sub>2</sub>O排放;天然林转换为人工林或次生林后土壤N<sub>2</sub>O排放没有明确结论;森林生态系统“氮饱和”程度使得森林土壤N<sub>2</sub>O排放对施肥呈非线性响应,即初期无明显响应、中期缓慢增加和后期急剧增加;火烧一般增加土壤N<sub>2</sub>O排放;采伐改变土壤温度、含水量、有机碳的分解和利用等,从而增强森林土壤N<sub>2</sub>O排放能力;剔除林下植被提高土壤温度,加快了表层土壤有机碳的分解矿化,促进土壤N<sub>2</sub>O排放;种植固氮植物增加了土壤有机碳和土壤氮含量,土壤N<sub>2</sub>O排放增强。今后的研究应更多地关注多种因素和气候变化对林地土壤N<sub>2</sub>O排放影响的内在机理以及氨氧化细菌、硝化细菌和反硝化细菌等微生物对各种干扰因素的响应机制。

**关键词** 土壤N<sub>2</sub>O排放; 营林措施; 土地利用变化; 施肥; 采伐; 火烧; 林下植被管理

**中国分类号** S718.5      **文献标识码** A

N<sub>2</sub>O是引起全球气候变暖的第三大温室气体,单位质量N<sub>2</sub>O的增温潜势是CO<sub>2</sub>的298倍,对全球气候变暖的贡献约为6%<sup>[1-2]</sup>。近10年来,大气N<sub>2</sub>O浓度已经超过325 μg L<sup>-1</sup>,相较于工业革命前提高了20%,目前仍以每年0.25%的速度不断递增<sup>[1-3]</sup>。土壤是N<sub>2</sub>O的主要排放源,全球N<sub>2</sub>O年释放量为16.2~20.1 Tg a<sup>-1</sup><sup>[4-5]</sup>,其中土壤N<sub>2</sub>O释放量占57%~70%<sup>[6-7]</sup>。森林是陆地生态系统的重要组成部分,森林面积占全球陆地总面积的27.7%<sup>[8]</sup>。森林土壤N<sub>2</sub>O年排放量约为2.4~5.7 Tg a<sup>-1</sup>,其中热带和温带森林土壤N<sub>2</sub>O年排放量为4 Tg a<sup>-1</sup><sup>[9]</sup>。中国N<sub>2</sub>O年排放量为0.42 Tg a<sup>-1</sup>,占全球N<sub>2</sub>O排放总

量的7%<sup>[4]</sup>。

土壤N<sub>2</sub>O主要通过硝化和反硝化过程产生。土壤N<sub>2</sub>O产生的微生物过程存在很大差异性,热带森林和亚热带森林地区由于水分饱和易形成厌氧环境,加之NO<sub>3</sub><sup>-</sup>相对富集,反硝化是土壤N<sub>2</sub>O的主要产生过程<sup>[10]</sup>,而北方森林地区水分适中、气候寒冷的环境特点有利于硝化作用的发生<sup>[11]</sup>。研究表明,北方森林因低温导致土壤氮素周转较慢,土壤中氮素相对匮乏;而热带和亚热带森林土壤中土壤氮素相对富集,从而使热带和亚热带森林土壤N<sub>2</sub>O排放量高于温带森林和北方森林<sup>[12]</sup>。参与土壤N<sub>2</sub>O排放的主要微生物群落包括:硝化细菌(氨氧

\* 国家自然科学基金项目(31700540)和浙江省自然科学基金项目(LY15C160004)资助 Supported by the National Natural Science Foundation of China (No. 31700540) and the Natural Science Foundation of Zhejiang Province (No. LY15C160004)

† 通讯作者 Corresponding author, E-mail: liujuan@zafu.edu.cn

作者简介:王会来(1991—),男,山东淄博人,硕士研究生,主要从事土壤碳汇与全球气候变化方向研究。E-mail: sjw8515@163.com

收稿日期:2017-03-16;收到修改稿日期:2017-08-22;优先数字出版日期([www.cnki.net](http://www.cnki.net)):2017-09-29

化细菌、古菌及亚硝酸盐氧化菌)和反硝化细菌以及部分菌根真菌。参与硝化过程的酶包括:氨单加氧酶(*amo*)，羟胺氧化酶(*hao*)，亚硝酸氧化还原酶(*nxr*)；参与反硝化过程的酶主要包括:硝酸盐还原酶(*narG/napA*)，亚硝酸盐还原酶(*nirK/nirS*)，一氧化氮还原酶(*nor*)和氧化亚氮还原酶(*nosZ*)。

营林措施是人工林经营管理的重要方式,通过改善土壤结构、增加土壤肥力,提高森林生产力,显著影响森林土壤N<sub>2</sub>O排放。近年来,营林措施对森林土壤N<sub>2</sub>O排放的影响开展了大量研究,但因土壤环境因子<sup>[10-12]</sup>、经营措施<sup>[13-14]</sup>、土地利用方式<sup>[15]</sup>和生态系统类型的不同,营林措施对林地土壤N<sub>2</sub>O排放的影响的研究结果存在较大差异;同一种营林措施在不同森林类型、土壤状况和气候条件下,也会产生抑制、促进和不变3种结果。本文综述了营林措施(施肥、采伐、火烧、林下植被管理和灌溉)影响林地土壤N<sub>2</sub>O排放通量的研究进展,探讨了营林措施影响土壤N<sub>2</sub>O排放的主要机理,并提出未来研究的重点,以期对全球气候变暖背景下林地的合理经营管理起到借鉴和启示作用。

## 1 土地利用变化对森林土壤N<sub>2</sub>O排放的影响

土地利用变化通过改变地表植被覆盖类型以及生物地球化学过程,显著影响了土壤N<sub>2</sub>O的排放。Cheng等<sup>[16]</sup>对马尾松林转换为农田和Álvaro-Fuentes等<sup>[17]</sup>对地中海白松林转换为大麦田的研究表明,土壤N<sub>2</sub>O排放分别增加了15.8%和99.3%(表1),其主要原因为:(1)与森林生态系统相比,农田和草地生态系统由于无机肥和有机肥的大量施用,造成土壤氮素的累积,硝化和反硝化作用增强<sup>[18]</sup>;(2)土壤氮素过多造成土壤酸化,抑制了*nosZ*的活性,从而增加土壤N<sub>2</sub>O的排放<sup>[19]</sup>;(3)土壤表层温度的升高加快了土壤微生物的代谢速率,同时土壤含水量的变化促进了土壤N<sub>2</sub>O的排放<sup>[20]</sup>;(4)森林经过开垦耕作后,土壤被压实,土壤反硝化作用的增强进一步促进了土壤N<sub>2</sub>O的排放<sup>[21]</sup>。

森林生态系统由于人为干扰较少,农田或草地转化为森林后氮肥施用的减少直接减少了土壤N<sub>2</sub>O的排放;同时土壤结构得到改善,土壤通气性

的增强减少了厌氧微生物的数量,有利于减少土壤N<sub>2</sub>O的产生<sup>[22-23]</sup>。例如:Baah-Acheamfour等<sup>[24]</sup>对农田转换为森林和Kooch等<sup>[25]</sup>对水稻田转化为罗雨松林的研究表明,土壤N<sub>2</sub>O的排放分别减少了44%和67%。但Li等<sup>[26]</sup>研究表明,草地转化为松树林后,土壤表层有机碳含量的增加使得土壤N<sub>2</sub>O排放速率增加了2倍。此外,草地或农田转化为林地后土壤N<sub>2</sub>O排放还与硝化细菌和反硝化细菌的群落组成和数量有关<sup>[22, 27]</sup>。Xue等<sup>[27]</sup>报道草地转化为柳树林和杨树林后,硝化螺旋菌数量的增加促进土壤硝酸盐的累积,从而增加了土壤N<sub>2</sub>O排放。Lammel等<sup>[22]</sup>研究表明,农田退耕还林后土壤pH等理化性质的改善显著增加了土壤反硝化细菌的数量(如*nirK*),从而促进土壤N<sub>2</sub>O排放。

林型转化是土地利用变化的重要方式,天然林转换为人工林或次生林造成森林类型结构单一,森林生产力下降,土壤碳、氮流失,显著影响了土壤N<sub>2</sub>O的产生与排放。目前林型转化对土壤N<sub>2</sub>O排放的影响还没有明确定论(表2)。Liu等<sup>[28]</sup>研究表明,亚热带常绿阔叶林转换为毛竹林后土壤N<sub>2</sub>O排放没有显著变化,但集约经营后显著提高了土壤N<sub>2</sub>O的排放。孙海龙等<sup>[15]</sup>研究表明,温带次生林转变为落叶松后土壤N<sub>2</sub>O排放增加了360%。而张睿<sup>[29]</sup>对亚热带天然林转换为人工林的研究表明,土壤有机碳含量的降低和土壤含水量的增加使得土壤N<sub>2</sub>O排放速率减少了25.4%~63.1%。Kim和Kirschbaum<sup>[18]</sup>基于模型计算表明,天然林转换为人工林初期减少了土壤N<sub>2</sub>O的排放,但随着森林生态的恢复,土壤N<sub>2</sub>O排放逐步趋于稳定。为了更深入探讨土地利用变化对土壤N<sub>2</sub>O的影响机理,未来研究需增加观测时间和观测频率,同时需将气体观测与土壤微生物群落组成测定相结合,以期从本质上解释其作用机理。

## 2 营林措施对森林土壤N<sub>2</sub>O排放的影响

### 2.1 施肥对森林土壤N<sub>2</sub>O排放的影响

研究表明,森林生态系统“氮饱和”程度使得森林土壤N<sub>2</sub>O排放对施肥呈非线性响应,即初期无明显响应、中期缓慢增加和后期急剧增加<sup>[14, 35-36]</sup>。森林土壤有效氮贫乏时,外源氮很容易被植被和土壤微生物吸收利用<sup>[14]</sup>,硝化细菌和反硝化细菌的活性受土壤有效氮的限制,导致施N肥后土壤

表1 土壤N<sub>2</sub>O排放对森林与草地或农田之间转换的响应Table 1 Responses of soil N<sub>2</sub>O emission to reclamation of forest into farmland or grassland

地点 Site	土地利用类型1 Land use 1	土地利用类型2 Land use 2	变化率 Change rate	参考文献 Reference
法属圭亚那 French Guiana	热带雨林 Rainforest	农田 Cropland	+224%	[ 30 ]
意大利 Italy	杨树林 <i>Populus</i> L. forest	农田 Cropland	+28.6%	[ 31 ]
澳大利亚 Australia	干硬叶桉树林 Drysclerophyll eucalypt forest	草地 Grassland	+55.6%	[ 32 ]
中国贵州 Guizhou, China	马尾松林 <i>Pinus massoniana</i> forest	农田 Cropland	+15.8%	[ 16 ]
西班牙 Spain	白松林 <i>Pinus halepensis</i> L. forest	农田 Cropland	+99.3%	[ 17 ]
加拿大 Canada	农田 Cropland	森林 Forest	-44%	[ 24 ]
伊朗 Iran	水稻田 Rice paddy	罗雨松林 <i>Taxodium distichum</i> plantation	-66.7%	[ 25 ]
新西兰 New Zealand	草地 Grassland	辐射松林 <i>Pinus radiata</i> plantation	+200%	[ 26 ]

表2 土壤N<sub>2</sub>O排放对天然林转换为次生林、人工林的响应Table 2 Responses of soil N<sub>2</sub>O emission to replacement of natural forest with secondary and artificial forest

地点 Site	土地利用类型1 Land use 1	土地利用类型2 Land use 2	变化率 Change rate	参考文献 Reference
中国浙江 Zhejiang, China	亚热带常绿阔叶林 Subtropical evergreen broadleaf forest	毛竹人工林 <i>Phyllostachys pubescens</i> plantation	+247%	[ 28 ]
中国贵州 Guizhou, China	天然林 Natural forest	马尾松人工林 <i>Pinus massoniana</i> forest	+17.9%	[ 16 ]
中国黑龙江 Heilongjiang, China	阔叶红松林 Broad-leaved korean pine forest	落叶松人工林 Larch forest	+360%	[ 15 ]
中国广西 Guangxi, China	红椎林 <i>Castanopsis hystrix</i> forest	马尾松林 <i>Pinus massoniana</i> forest	-24%	[ 33 ]
中国浙江 Zhejiang, China	亚热带天然阔叶林 Subtropical evergreen broadleaf forest	马尾松林和杉木林 <i>Pinus massoniana</i> and <i>Cunninghamia lanceolata</i> forest	-25.4%和63.1%	[ 29 ]
中国湖北 Hubei, China	亚热带常绿阔叶林 Subtropical evergreen broadleaf forest	桦木次生林和马尾松 <i>Betula</i> and <i>Pinus massoniana</i> forest	不变	[ 34 ]

N<sub>2</sub>O的排放没有显著变化<sup>[37-38]</sup>。与此相反, Kim等<sup>[39]</sup>对温带落叶松人工林和Krause等<sup>[40]</sup>对温带云杉林的研究表明, 有效氮富集的土壤N<sub>2</sub>O排放速率在施肥后分别增加了69%和260% (表3), 其增加的原因为: (1) 施肥促进土壤氮素的累积, 硝化和反硝化作用的增强促进土壤N<sub>2</sub>O的排放<sup>[41-42]</sup>; (2) 土壤NH<sub>4</sub><sup>+</sup>的累积降低土壤pH, 土壤酸化抑制了土壤硝化作用, 造成NO<sub>2</sub><sup>-</sup>大量累积, 亚硝酸盐的毒性作用使得氨氧化细菌将部分亚硝酸盐转化为N<sub>2</sub>O, 从而增加土壤N<sub>2</sub>O的排放<sup>[14]</sup>; (3) 施肥降低了森林土壤C/N比, 反硝化细菌利用自身碳源进行反硝化作用, 反硝化不彻底造成NO<sub>2</sub><sup>-</sup>的积累, 从而使土壤N<sub>2</sub>O排放呈上升趋势<sup>[42-43]</sup>。研究表明, 在有效氮富集的土壤中施加S肥和P肥促进了植物对土壤氮素的吸收, 改变土壤微生物的群落结构, 显著减弱土壤N<sub>2</sub>O的排放<sup>[44-45]</sup>。例如, Fan等<sup>[46]</sup>

在马尾松林混施N肥和S肥和Zhang等<sup>[47]</sup>在大叶相思林混施N肥和P肥的研究均表明, 土壤N<sub>2</sub>O排放分别减少了97%~330%和21%。

施肥对林地土壤N<sub>2</sub>O的影响还与施肥量、施肥时间、肥料类型、森林类型等因素有关。Zhang等<sup>[48]</sup>对亚热带松树林的研究表明, 高氮(150 kg hm<sup>-2</sup>a<sup>-1</sup>)促进土壤N<sub>2</sub>O排放, 低氮(50 kg hm<sup>-2</sup>a<sup>-1</sup>)对土壤N<sub>2</sub>O排放没有明显影响。Peng等<sup>[49]</sup>研究表明, 施肥1年后土壤N<sub>2</sub>O的增加只维持了2~3周, 而2年后土壤N<sub>2</sub>O持续增加。但Jassal等<sup>[38]</sup>对杉木林的研究表明, 施肥后第1年促进土壤N<sub>2</sub>O排放, 而第2年土壤N<sub>2</sub>O排放没有显著变化。肥料种类是影响林地土壤N<sub>2</sub>O排放的另一重要因素, Liu和Greaver<sup>[43]</sup>研究表明, 施加硝态氮肥后土壤N<sub>2</sub>O增加程度高于铵态氮肥。而Peng等<sup>[49]</sup>却得出相反的结果, 这可能与土壤N<sub>2</sub>O产生微生物过程的不同有关<sup>[35]</sup>。

表3 土壤N<sub>2</sub>O排放对施肥的响应

Table 3 Responses of soil N<sub>2</sub>O emission to N fertilization

地点 Site	森林类型 Forest type	肥料类型 Fertilizer type	施肥量 Application rate (kg hm <sup>-2</sup> a <sup>-1</sup> )	变化率 Change rate	参考文献 Reference
中国广东 Guangdong, China	亚热带松树林 Subtropical pine forests	NH <sub>4</sub> NO <sub>3</sub>	150	+48%	[ 48 ]
日本 Japan	温带落叶松人工林 Temperate larch forest	NH <sub>4</sub> NO <sub>3</sub>	50	+69%	[ 39 ]
瑞士 Switzerland	温带云杉林 Temperate spruce forest	NH <sub>4</sub> NO <sub>3</sub>	25	+260%	[ 40 ]
中国广东 Guangdong, China	阔叶红松林 Broad-leaved korean pine forest	NH <sub>4</sub> NO <sub>3</sub>	150	+13%	[ 45 ]
中国吉林 Jilin, China	温带针阔混交林 Temperate mixed pine and broadleaf forest	CO(NH <sub>2</sub> ) <sub>2</sub>	10~140	+264%	[ 37 ]
中国云南 Yunnan, China	橡胶林 Rubber plantation	CO(NH <sub>2</sub> ) <sub>2</sub>	75	+60%	[ 52 ]
中国江西 Jiangxi, China	马尾松林 <i>Pinus massoniana</i> forest	NaNO <sub>3</sub> 和Na <sub>2</sub> SO <sub>4</sub>	40~45	-213.5%	[ 46 ]
中国广东 Guangdong, China	尾叶桉林 <i>Eucalyptus urophylla</i> forest	NaH <sub>2</sub> PO <sub>4</sub>	50~100	-20.9%	[ 47 ]
中国吉林 Jilin, China	白桦林和杨树林 <i>Betula platyphylla</i> and <i>Populus L.</i> forest	NH <sub>4</sub> NO <sub>3</sub>	50	不变	[ 37 ]
加拿大 Canada	温带花旗松林 Temperate douglas-fir forest	CO(NH <sub>2</sub> ) <sub>2</sub>	200	不变	[ 38 ]

由于土壤有效氮含量的差异，使得不同森林类型土壤N<sub>2</sub>O排放对施肥的响应存在明显差异。Liu和Greaver<sup>[43]</sup>研究表明，热带和亚热带森林土壤N<sub>2</sub>O对施肥的敏感性高于温带森林和北方森林，这主要因为热带和亚热带森林土壤氮素富集，施肥后土壤中多余的无机氮被土壤硝化细菌和反硝化细菌利用，增加了土壤N<sub>2</sub>O排放，而温带森林和北方森林施氮后，土壤氮素很容易被植被和土壤微生物吸收利用，导致施N肥后土壤N<sub>2</sub>O的排放没有显著变化<sup>[14, 35-36]</sup>。

森林土壤N<sub>2</sub>O排放涉及的主要微生物群落对施氮存在不同的响应。例如，Schmidt等<sup>[50]</sup>对苏格兰南部有效氮富集和贫乏两种酸性云杉林的研究表明：施肥改变有效氮富集的森林土壤反硝化细菌群落组成；而施肥没有改变有效氮贫乏的森林土壤氨氧化菌群落组成。Levicnik-Hofferle等<sup>[51]</sup>研究表明，酸性森林添加铵态氮肥刺激了奇古菌对有机氮的矿化，从而影响了低NH<sub>4</sub><sup>+</sup>森林土壤铵氧化过程。目前，森林土壤氮素变化过程中土壤硝化-反硝化细菌功能群的演变特征尚不清楚，对土壤N<sub>2</sub>O排放与土壤硝化细菌和反硝化细菌数量、组成之间的耦合关系缺乏明确认识。

## 2.2 火烧对森林土壤N<sub>2</sub>O排放的影响

森林火灾对土壤N<sub>2</sub>O排放的影响主要表现在两个方面：一是火烧通过高温直接影响土壤微生物，改变土壤微生物的数量及群落组成；二是火烧改变了森林生态系统林分组成、土壤理化性质等环境因素，间接影响了土壤N<sub>2</sub>O排放<sup>[53]</sup>。马秀枝等<sup>[54]</sup>对兴安落叶松林和Morishita等<sup>[55]</sup>对西伯利亚黑云杉林的研究表明，火烧后土壤N<sub>2</sub>O排放分别增加了69.2%和354%（表4），其主要原因：（1）火烧后地表凋落物和低矮植被转化为无机物，增加了土壤氮素含量，为硝化和反硝化细菌提供丰富底物，促进土壤N<sub>2</sub>O的排放<sup>[56-57]</sup>；（2）火烧发生时土壤温度升高增强了土壤硝化和反硝化细菌的活性，增强了土壤硝化和反硝化作用<sup>[58]</sup>；（3）火烧后土壤有机碳含量的减少和土壤氮素的增加降低了森林土壤C/N，有利于土壤N<sub>2</sub>O的产生<sup>[59]</sup>。

火烧后土壤N<sub>2</sub>O排放的变化与火烧强度、火烧残留物的处理情况、森林类型以及森林火烧时间序列有关。Morishita等<sup>[55]</sup>对西伯利亚黑云杉林的研究表明，重度火烧减弱了土壤N<sub>2</sub>O的排放，但局部火烧增强了土壤N<sub>2</sub>O的排放。Kim等<sup>[60]</sup>研究表明

明，火烧产生的生物质炭干扰了硝化和反硝化作用，土壤N<sub>2</sub>O排放量减少了6.6%；而去除地上残留物后，土壤N<sub>2</sub>O排放增加了30.1%。Inclán等<sup>[61]</sup>研究表明，火烧后比利牛斯橡树林土壤含水量的增加减弱了土壤N<sub>2</sub>O的排放，而冬青栎林、欧洲赤松林土壤N<sub>2</sub>O的排放没有明显变化。研究表明，土壤N<sub>2</sub>O排放对不同火烧时间序列的响应完全不同。例如，马秀枝等<sup>[54]</sup>对兴安落叶松林的研究表明，火烧1年后土壤N<sub>2</sub>O排放相较于对照下降了37.9%，而火烧19年后土壤N<sub>2</sub>O排放与未火烧地无显著差异，28年后较对照增加了69.2%。这可能是火烧初期凋落物及土壤养分含量下降，但随着时间的增加，凋落物数量和质量以及土壤养分含量不断提高，土壤N<sub>2</sub>O排放逐渐增加<sup>[62]</sup>。但Köster等<sup>[63]</sup>对桉树林的研究表明，火烧75年后土壤表现为N<sub>2</sub>O的排放源，而155年后则表现为N<sub>2</sub>O的弱吸收汇。目前，关于不同火烧时间序列对土壤N<sub>2</sub>O排放影响的研究尚不清楚，对引起不同火烧时间森林土壤N<sub>2</sub>O排放转变的原因尚未确定。

## 2.3 采伐对森林土壤N<sub>2</sub>O排放的影响

采伐减少了森林植被，改变了森林生态系统碳、氮循环，显著影响森林土壤N<sub>2</sub>O的排放。目前有关采伐对森林土壤N<sub>2</sub>O排放的研究大多关注皆伐，而对于择伐报道较少（表5）。Mäkiranta等<sup>[65]</sup>对欧洲赤松林和Yashiro等<sup>[66]</sup>对马来西亚热带雨林的研究表明，皆伐后土壤N<sub>2</sub>O排放分别增加了368%和685%（表5），主要原因：（1）皆伐后土壤温度的提高加快了土壤氮素矿化速率，增加了土壤N<sub>2</sub>O的排放<sup>[67]</sup>；（2）大量死根的分解和皆伐后的剩余物为硝化细菌和反硝化细菌提供丰富底物，从而促进土壤N<sub>2</sub>O的排放<sup>[66]</sup>；（3）皆伐后土壤容重的增加和地下水位的上升增加了土壤厌氧微生物的数量，有利于土壤N<sub>2</sub>O的产生<sup>[67-68]</sup>。因择伐对森林土壤环境的影响较小，从而使择伐后土壤N<sub>2</sub>O排放表现为不变或者减少<sup>[69-70]</sup>。

皆伐后土壤N<sub>2</sub>O的变化与采伐残留物的处理、森林土壤恢复情况和采伐后营林措施有关。Mäkiranta等<sup>[65]</sup>对芬兰泥炭地森林研究表明，皆伐后保留残留物的土壤N<sub>2</sub>O排放量是未保留的3倍。McVicar和Kellman<sup>[74]</sup>对红皮云杉林的研究表明，皆伐2年后土壤N<sub>2</sub>O排放增加，20年后逐渐衰减，至皆伐125年后与对照没有明显差异。Pearson等<sup>[71]</sup>研究表明，皆伐地翻耕后土壤N<sub>2</sub>O的排放明

表4 土壤N<sub>2</sub>O排放对火烧的响应Table 4 Responses of soil N<sub>2</sub>O emission to burning

地点 Site	森林类型 Forest type	变化率 Change rate	参考文献 Reference
美国 USA	寒温带黑云杉林 <i>Picea mariana</i> forest	+354%	[ 55 ]
日本 Japan	白桦林 <i>Betula platyphylla</i> forest	+30.1%	[ 58 ]
中国内蒙古 Inner Mongolia, China	兴安落叶松林 <i>Larix gmelinii</i> (Rupr.) Kuzen forest	+69.2%	[ 54 ]
日本 Japan	白桦林 <i>Betula platyphylla</i> forest	-6.6%	[ 60 ]
西班牙 Spain	硬木混交林和黑松林 Hardwood and black spruce forest	-10%和-50%	[ 61 ]
美国 USA	北方森林 Boreal forest	-50%	[ 64 ]
西班牙 Spain	冬青栎林 <i>Pyrenean</i> oak forest	不变	[ 61 ]
芬兰 Finland	欧洲赤松林 <i>Pinus sylvestris</i> forest	不变	[ 63 ]

表5 土壤N<sub>2</sub>O排放对采伐的响应Table 5 Responses of soil N<sub>2</sub>O emission to felling

地点 Site	森林类型 Forest type	变化率 Change rate	参考文献 Reference
芬兰 Finland	欧洲赤松林 <i>Pinus sylvestris</i> forest	+60%	[ 71 ]
芬兰 Finland	泥炭地森林 Peat forest	+33.9%	[ 72 ]
马来西亚 Malaysia	热带雨林 Rainforest	+685%	[ 66 ]
中国内蒙古 Inner Mongolia, China	兴安落叶松林 <i>Larix gmelinii</i> (Rupr.) Kuzen forest	+74%	[ 69 ]
中国江苏 Jiangsu, China	杨树林 <i>Populus</i> L. forest	-51.5%	[ 70 ]
加拿大 Canada	温带森林 Temperate forest	-60%	[ 73 ]
加拿大 Canada	红果云杉林 Red spruce forest	不变	[ 74 ]
中国内蒙古 Inner Mongolia, China	兴安落叶松林 <i>Larix gmelinii</i> (Rupr.) Kuzen forest	不变	[ 69 ]

显高于未翻耕地。

#### 2.4 林下植被管理和灌溉对森林土壤N<sub>2</sub>O排放的影响

林下植被管理通过改变林下表层土壤水热状况和土壤氮素含量影响土壤微生物群落结构和数量，进而影响土壤N<sub>2</sub>O排放。去除林下植被降低了林下冠层郁闭度，光照的增强导致土壤温度升高和土壤水分蒸发加快，降低了土壤湿度；同时，去除林下植被显著减少了土壤根系分泌物数量，降低了细根周转速率，使土壤活性碳含量和微生物量降低，从而改变了土壤微生物群落组成、活性

[<sup>75-77</sup>]。研究表明，去除林下植被后亚硝化细菌及硝化细菌对NH<sub>4</sub><sup>+</sup>的可利用性增加，而土壤MBC和相关酶活性显著降低[<sup>76</sup>]。林下种植固氮植物后显著增加土壤无机氮含量，土壤亚硝化细菌及硝化细菌的活性增强[<sup>77</sup>]。剔除林下植被改变了表层土壤的水热条件，加快了表层土壤有机碳的分解矿化，增加了土壤N<sub>2</sub>O的排放；由于林下灌木的减少，土壤可以保存更多的有效氮，从而增强了硝化和反硝化作用[<sup>78</sup>]。此外，种植绿肥和固氮植物增加了土壤有机碳和土壤氮含量，为土壤N<sub>2</sub>O的产生提供良好的条件[<sup>79-80</sup>]。

表6 土壤N<sub>2</sub>O对林下植被管理的响应

Table 6 Responses of soil N<sub>2</sub>O emission to understory management

地点 Site	森林类型 Forest type	林下植被管理方式 Understory management	变化率 Change rate	参考文献 Reference
中国浙江 Zhejiang, China	山核桃林 <i>Carya cathayensis</i> forest	剔除林下植被 Understory removal	+120%	[ 81 ]
中国浙江 Zhejiang, China	板栗林 <i>Castanea mollissima</i> BL. forest	剔除林下植被 Understory removal	+101.3%	[ 82 ]
中国广东 Guangdong, China	尾叶桉林 <i>Eucalyptus urophylla</i> forest	剔除林下植被 Understory removal	+40.6%	[ 78 ]
中国广东 Guangdong, China	厚荚相思林 <i>Acacia crassicarpa</i> forest	剔除林下植被 Understory removal	+42.5%	[ 79 ]
中国广东 Guangdong, China	亚热带混交林 Subtropical mixed plantation	添加固氮植物 N-fixing species addition	+62.3%	[ 78 ]
中国浙江 Zhejiang, China	板栗林 <i>Castanea mollissima</i> BL. forest	添加固氮植物 N-fixing species addition	+18.9% ~ 22%	[ 82 ]

土壤水分是影响森林生长的重要因素，尤其对于干旱地区，水资源的管理尤为重要。有关灌溉对森林土壤N<sub>2</sub>O排放的研究较少，研究表明，灌溉显著增加土壤水分，从而促进土壤N<sub>2</sub>O排放，在农田和草地生态系统也得出相同的结果[<sup>83</sup>]。而Maris等[<sup>84</sup>]对油橄榄研究表明，采用滴灌制约了土壤微生物对水分的需求，从而减少了土壤N<sub>2</sub>O排放。

### 3 结论与展望

目前，国内外学者已经开展了大量关于森林土壤N<sub>2</sub>O排放的研究，但仍存在很多研究不足和不确定性，许多问题亟待解决。主要包括：1) 土壤N<sub>2</sub>O的产生过程涉及到氨氧化菌、硝化细菌和反硝

化细菌等，加之北方和南方森林土壤氮素存在明显差异，使得土壤N<sub>2</sub>O产生过程复杂化，土壤N<sub>2</sub>O对施肥的响应存在明显差异。2) 过去关于森林土壤N<sub>2</sub>O排放对营林措施响应的研究多关注与环境因子（土壤温度、含水量、NH<sub>4</sub><sup>+</sup>、NO<sub>3</sub><sup>-</sup>等），虽然近年来，部分学者利用微生物学和分子生物学研究土壤N<sub>2</sub>O排放对人为干扰过程中微生物的数量、群落、活性变化的响应，但尚未得出统一结论，对森林土壤N<sub>2</sub>O产生的微生物学机理仍然缺乏系统性研究。3) 目前，关于不同火烧时间序列对土壤N<sub>2</sub>O排放影响的研究尚不清楚，对引起不同火烧时间森林土壤N<sub>2</sub>O排放转变的具体原因尚未确定，且当前观测周期较短、频率较低，缺乏大时空尺度上的研究数据。4) 择伐可以优化森林林龄结构，改善土壤水

热条件，维持植物根系和微生物群落的稳定，是维持森林健康的重要措施。但目前有关采伐对森林土壤N<sub>2</sub>O排放的研究大多关注皆伐，而对于择伐报道较少。

因此，建议今后应加强：1) 利用<sup>15</sup>N-<sup>18</sup>O标记法明确土壤N<sub>2</sub>O来源，以不同气候带的代表性森林为研究对象，构建不同施肥时间、不同肥料类型(铵态氮肥、硝态氮肥以及酰胺态氮肥)的定位试验，明确北方森林和南方森林土壤N<sub>2</sub>O来源的差异，构建土壤N<sub>2</sub>O排放对施肥的非线性响应函数；2) 探讨氨氧化菌、硝化细菌和反硝化细菌等微生物对各种营林措施响应模式，进而揭示土壤功能微生物群落与土壤N<sub>2</sub>O排放的耦合机制；3) 延长火烧观测周期和增加观测频率，开展不同纬度、不同气候条件下森林土壤N<sub>2</sub>O排放对不同火烧时间序列响应的研究；4) 增加择伐对森林土壤N<sub>2</sub>O排放的研究，尤其是在我国森林资源丰富的东北针叶林和南方热带雨林地区。

## 参考文献

- [ 1 ] Forster P, Ramaswamy V, Artaxo P, et al. Changes in atmospheric constituents and in radiative forcing//IPCC. Climate change 2007: The physical science basis. Cambridge: Cambridge University Press, 2007: 129—234
- [ 2 ] World Meteorological Organization ( WMO ) . The state of greenhouse gases in the atmosphere based on global observations through 2012. Switzerland: WMO Greenhouse Gas Bulletin, 2013, 9: 1—4
- [ 3 ] Saikawa E, Prinn R G, Dlugokencky E, et al. Global and regional emissions estimates for N<sub>2</sub>O. Atmospheric Chemistry & Physics, 2014, 14 ( 9 ) : 4617—4641
- [ 4 ] Cai Z C. Greenhouse gas budget for terrestrial ecosystems in China. Science China Earth Sciences, 2012, 55 ( 2 ) : 173—182
- [ 5 ] Stocker T F, Qin D, Plattner G K, et al. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change//IPCC. Climate change 2013: The physical science basis. Cambridge: Cambridge University Press, 2013: 1—30
- [ 6 ] Butterbach-Bahl K, Baggs E M, Dannenmann M, et al. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? Philosophical Transactions of the Royal Society B: Biological Sciences, 2013, 368 ( 1621 ) : 91—97
- [ 7 ] Syakila A, Kroese C. The global nitrous oxide budget revisited. Greenhouse Gas Measurement & Management, 2011, 1 ( 1 ) : 17—26
- [ 8 ] Food and Agriculture Organization of the United Nations ( FAO ) . Global forest resources assessment 2015: how are the world's forests changing? Rome: Food and Agriculture Organization of the United Nations, 2015
- [ 9 ] Davidson E A, Kanter D. Inventories and scenarios of nitrous oxide emissions. Environmental Research Letters, 2014, 9 ( 10 ) : 1—12
- [ 10 ] Zhang J B, Cai Z C, Zhu T B. N<sub>2</sub>O production pathways in the subtropical acid forest soils in China. Environmental Research, 2011, 111 ( 5 ) : 643—649
- [ 11 ] Morishita T, Aizawa S, Yoshinaga S, et al. Seasonal change in N<sub>2</sub>O flux from forest soils in a forest catchment in Japan. Journal of Forest Research, 2011, 16 ( 5 ) : 386—393
- [ 12 ] Fang H J, Yu G R, Cheng S L, et al. Effects of multiple environmental factors on CO<sub>2</sub> emission and CH<sub>4</sub> uptake from old-growth forest soils. Biogeosciences, 2010, 7 ( 1 ) : 395—407
- [ 13 ] 方华军, 程淑兰, 于贵瑞, 等. 大气氮沉降对森林土壤甲烷吸收和氧化亚氮排放的影响及其微生物学机制. 生态学报, 2014, 34 ( 17 ) : 4799—4806
- [ 14 ] Fang H J, Cheng S L, Yu G R, et al. Microbial mechanisms responsible for the effects of atmospheric nitrogen deposition on methane uptake and nitrous oxide emission in forest soils: A review ( In Chinese ). Acta Ecologica Sinica, 2014, 34 ( 17 ) : 4799—4806
- [ 15 ] 方华军, 程淑兰, 于贵瑞, 等. 森林土壤氧化亚氮排放对大气氮沉降增加的响应研究进展. 土壤学报, 2015, 52 ( 2 ) : 262—271
- [ 16 ] Fang H J, Cheng S L, Yu G R, et al. Study on the responses of nitrous oxide emission to increased nitrogen deposition in forest soils: A review ( In Chinese ). Acta Pedologica Sinica, 2015, 52 ( 2 ) : 262—271
- [ 17 ] 孙海龙, 张彦东, 吴世义. 东北温带次生林和落叶松人工林土壤CH<sub>4</sub>吸收和N<sub>2</sub>O排放通量. 生态学报, 2013, 33 ( 17 ) : 5320—5328
- [ 18 ] Sun H L, Zhang Y D, Wu S Y. Methane and nitrous oxide fluxes in temperate secondary forest and larch plantation in Northeastern China ( In Chinese ). Acta Ecologica Sinica, 2013, 33 ( 17 ) : 5320—5328
- [ 19 ] Cheng J Z, Lee X Q, Zhou Z B, et al. Nitrous oxide emissions from different land use patterns in a typical karst region, Southwest China. Acta Geochimica, 2013, 32 ( 2 ) : 137—145
- [ 20 ] Álvaro-Fuentes J, Arrúe J L, Bielsa A, et al. Simulating climate change and land use effects on soil nitrous oxide emissions in Mediterranean conditions

- using the Daycent model. *Agriculture Ecosystems & Environment*, 2016, 238: 78—88
- [ 18 ] Kim D G, Kirschbaum M U F. The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates. *Agriculture Ecosystems & Environment*, 2015, 208 ( 1 ) : 114—126
- [ 19 ] Kirschbaum M U F, Saggar S, Tate K R, et al. Quantifying the climate-change consequences of shifting land use between forest and agriculture. *Science of the Total Environment*, 2013, 465 ( 6 ) : 314—324
- [ 20 ] Van Lent J, Hergoualc'H K, Verchot L V. Soil N<sub>2</sub>O and NO emissions from land use and land-use change in the tropics and subtropics: A meta-analysis. *Biogeosciences Discussions*, 2015, 12 ( 15 ) : 7299—7313
- [ 21 ] Hergoualc'H K, Verchot L V. Greenhouse gas emission factors for land use and land-use change in Southeast Asian peatlands. *Mitigation and Adaptation Strategies for Global Change*, 2014, 19 ( 6 ) : 789—807
- [ 22 ] Lammel D R, Feigl B J, Cerri C C, et al. Specific microbial gene abundances and soil parameters contribute to C, N, and greenhouse gas process rates after land use change in Southern Amazonian Soils. *Frontiers in Microbiology*, 2015, DOI: 10.3389/fmicb.2015.01057
- [ 23 ] Pierre S, Groffman P M, Killilea M E, et al. Soil microbial nitrogen cycling and nitrous oxide emissions from urban afforestation in the New York City Afforestation Project. *Urban Forestry & Urban Greening*, 2015, 15 ( 11/12 ) : 149—154
- [ 24 ] Baah-Acheamfour M, Carlyle C N, Lim S S, et al. Forest and grassland cover types reduce net greenhouse gas emissions from agricultural soils. *Science of the Total Environment*, 2016, 571: 1115—1127
- [ 25 ] Kooch Y, Moghimian N, Bayranyand M, et al. Changes of soil carbon dioxide, methane, and nitrous oxide fluxes in relation to land use/cover management. *Environmental Monitoring & Assessment*, 2016, 188 ( 6 ) : 1—12
- [ 26 ] Li C Y, Di H J, Cameron K C, et al. Effect of different land use and land use change on ammonia oxidizer abundance and N<sub>2</sub>O emissions. *Soil Biology & Biochemistry*, 2016, 96: 169—175
- [ 27 ] Xue C, Penton C R, Zhang B, et al. Soil fungal and bacterial responses to conversion of open land to short-rotation woody biomass crops. *Global Change Biology Bioenergy*, 2016, 8 ( 4 ) : 723—736
- [ 28 ] Liu J, Jiang P K, Li Y F, et al. Responses of N<sub>2</sub>O flux from forest soils to land use change in subtropical China. *The Botanical Review*, 2011, 77 ( 3 ) : 320—325
- [ 29 ] 张睿. 天然林转换为人工林后土壤温室气体排放的动态变化. 浙江临安: 浙江农林大学, 2016
- Zhang R. Dynamic changes of soil greenhouse gas emissions after conversion from natural forest to plantations ( In Chinese ). Lin'an, Zhejiang: Zhejiang A&F University, 2016
- [ 30 ] Petitjean C, Hénault C, Perrin A S, et al. Soil N<sub>2</sub>O emissions in French Guiana after the conversion of tropical forest to agriculture with the chop-and-mulch method. *Agriculture Ecosystems & Environment*, 2015, 208: 64—74
- [ 31 ] Sabbatini S, Arriga N, Bertolini T, et al. Greenhouse gas balance of cropland conversion to bioenergy poplar short-rotation coppice. *Biogeosciences Discussions*, 2015, 12 ( 10 ) : 8035—8084
- [ 32 ] Delden L V, Rowlings D W, Scheer C, et al. Urbanization-related land use change from forest and pasture into turf grass modifies soil nitrogen cycling and increases N<sub>2</sub>O emissions. *Biogeosciences Discussions*, 2016, 13 ( 21 ) : 6095—6106
- [ 33 ] Wang H, Liu S, Wang J, et al. Effects of tree species mixture on soil organic carbon stocks and greenhouse gas fluxes in subtropical plantations in China. *Forest Ecology & Management*, 2013, 300 ( 4 ) : 4—13
- [ 34 ] 菊花, 申国珍, 马明哲, 等. 北亚热带地带性森林土壤温室气体通量对土地利用方式改变和降水减少的响应. *植物生态学报*, 2016, 40 ( 10 ) : 1049—1063
- Ju H, Shen G Z, Ma M Z, et al. Greenhouse gas fluxes of typical northern subtropical forest soils: Impacts of land use change and reduced precipitation ( In Chinese ). *Chinese Journal of Plant Ecology*, 2016, 40 ( 10 ) : 1049—1063
- [ 35 ] Shcherbak I, Millar N, Robertson G P. Global meta-analysis of the nonlinear response of soil nitrous oxide ( N<sub>2</sub>O ) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences*, 2014, 111 ( 25 ) : 199—204
- [ 36 ] Cheng S L, Wang L, Fang H J, et al. Nonlinear responses of soil nitrous oxide emission to multi-level nitrogen enrichment in a temperate needle-broadleaved mixed forest in Northeast China. *Catena*, 2016, 147: 556—563
- [ 37 ] Chen Z J, Setälä H, Geng S C, et al. Nitrogen addition impacts on the emissions of greenhouse gases depending on the forest type: A case study in Changbai Mountain, Northeast China. *Journal of Soils and Sediments*, 2017, 17 ( 1 ) : 23—34
- [ 38 ] Jassal R S, Andrew Black T, Trofymow J A, et al. Soil CO<sub>2</sub> and N<sub>2</sub>O flux dynamics in a nitrogen-fertilized

- Pacific Northwest Douglas-fir stand. *Geoderma*, 2010, 157: 118—125
- [39] Kim Y S, Imori M, Watanabe M, et al. Simulated nitrogen inputs influence methane and nitrous oxide fluxes from a young larch plantation in northern Japan. *Atmospheric Environment*, 2012, 46 (1) : 36—44
- [40] Krause K, Niklaus P A, Schleppi P. Soil-atmosphere fluxes of the greenhouse gases CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O in a mountain spruce forest subjected to long-term N addition and to tree girdling. *Agricultural & Forest Meteorology*, 2013, 181 (4) : 61—68
- [41] Wang C, Houlton B Z, Dai W, et al. Growth in the global N<sub>2</sub> sink attributed to N fertilizer inputs over 1860 to 2000. *Science of the Total Environment*, 2016, 574: 1044—1053
- [42] Shrestha R K, Strahm B D, Sucre E B. Greenhouse gas emissions in response to nitrogen fertilization in managed forest ecosystems. *New Forests*, 2015, 46 (2) : 167—193
- [43] Liu L, Greaver T L. A review of nitrogen enrichment effects on three biogenic GHGs: The CO<sub>2</sub> sink may be largely offset by stimulated N<sub>2</sub>O and CH<sub>4</sub> emission. *Ecology Letters*, 2009, 12 (10) : 1103—1117
- [44] Liu L, Bengtsson C, Lapidus L, et al. Effects of phosphorus addition on soil microbial biomass and community composition in three forest types in tropical China. *Soil Biology & Biochemistry*, 2012, 44 (1) : 31—38
- [45] Zheng M H, Zhang T, Liu L, et al. Effects of nitrogen and phosphorus additions on nitrous oxide emission in a nitrogen-rich and two nitrogen-limited tropical forests. *Biogeosciences*, 2016, 13 (11) : 3503—3517
- [46] Fan J L, Xu Y H, Chen Z M, et al. Sulfur deposition suppressed nitrogen-induced soil N<sub>2</sub>O emission from a subtropical forestland in southeastern China. *Agricultural and Forest Meteorology*, 2017, 233: 163—170
- [47] Zhang W, Zhu X, Luo Y, et al. Responses of nitrous oxide emissions to nitrogen and phosphorus additions in two tropical plantations with N-fixing vs. non-N-fixing tree species. *Biogeosciences*, 2014, 11 (18) : 4941—4951
- [48] Zhang W, Mo J M, Yu G R. Emissions of nitrous oxide from three tropical forests in Southern China in response to simulated nitrogen deposition. *Plant and Soil*, 2008, 306 (1) : 221—236
- [49] Peng Q, Qi Y, Dong Y, et al. Soil nitrous oxide emissions from a typical semiarid temperate steppe in Inner Mongolia: Effects of mineral nitrogen fertilizer levels and forms. *Plant and Soil*, 2011, 342 (1/2) : 345—357
- [50] Schmidt C S, Hultman K A, Robinson D, et al. PCR profiling of ammonia-oxidizer communities in acidic soils subjected to nitrogen and sulphur deposition. *FEMS Microbiology Ecology*, 2007, 61 (2) : 305—316
- [51] Levicnik-Hofferle S, Nicol G W, Ausec L, et al. Stimulation of thaumarchaeal ammonia oxidation by ammonia derived from organic nitrogen but not added inorganic nitrogen. *FEMS Microbiology Ecology*, 2012, 80 (1) : 114—123
- [52] Zhou W J, Ji H, Zhu J, et al. The effects of nitrogen fertilization on N<sub>2</sub>O emissions from a rubber plantation. *Scientific Reports*, 2016, DOI: 10.1038/srep28230
- [53] Stephens S L, Agee J K, Fulé P Z, et al. Managing forests and fire in changing climates. *Science*, 2013, 342 (6154) : 41—42
- [54] 马秀枝, 范雪松, 舒常禄, 等. 不同时间序列林火干扰对兴安落叶松林区土壤性质及温室气体通量的影响. *生态环境学报*, 2016, 25 (6) : 939—946
- Ma X Z, Fan X S, Shu C L, et al. Effects of forest fire disturbance in different time series on soil properties and greenhouse gas flux in *Larix gmelinii* forest of cold-temperate zone (In Chinese). *Ecology and Environmental Sciences*, 2016, 25 (6) : 939—946
- [55] Morishita T, Noguchi K, Kim Y, et al. CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes of upland black spruce (*Picea mariana*) forest soils after forest fires of different intensity in interior Alaska. *Soil Science and Plant Nutrition*, 2015, 61 (1) : 98—105
- [56] Gómez-Rey M X, González-Prieto S J. Soil gross N transformation rates after a wildfire and straw mulch application for burned soil emergency stabilization. *Biology and Fertility of Soils*, 2015, 51 (4) : 493—505
- [57] Wang Y Z, Xu Z H, Zhou Q X. Impact of fire on soil gross nitrogen transformations in forest ecosystems. *Journal of Soils and Sediments*, 2014, 14 (6) : 1030—1040
- [58] Taş N, Prestat E, Mcfarland J W, et al. Impact of fire on active layer and permafrost microbial communities and metagenomes in an upland Alaskan boreal forest. *ISME Journal*, 2014, 8 (9) : 1904—1919
- [59] Wang Y Z, Xu Z H, Zheng J Q, et al. δ<sup>15</sup>N of soil nitrogen pools and their dynamics under decomposing leaf litters in a suburban native forest subject to repeated prescribed burning in southeast Queensland, Australia. *Journal of Soils and Sediments*, 2015, 15:

- 1063—1074
- [60] Kim Y S, Makoto K, Takakai F, et al. Greenhouse gas emissions after a prescribed fire in white birch-dwarf bamboo stands in northern Japan, focusing on the role of charcoal. *European Journal of Forest Research*, 2011, 130 (6) : 1031—1044
- [61] Inclán R, Uribe C, Sánchez L, et al. N<sub>2</sub>O and CH<sub>4</sub> fluxes in undisturbed and burned holm oak, scots pine and pyrenean oak forests in central Spain. *Biogeochemistry*, 2012, 107 (1) : 19—41
- [62] 杨新芳, 鲍雪莲, 胡国庆, 等. 大兴安岭不同火烧年限森林凋落物和土壤C、N、P化学计量特征. *应用生态学报*, 2016, 27 (5) : 1359—1367  
Yang X F, Bao X L, Hu G Q, et al. C: N: P stoichiometry characteristics of litter and soil of forests in Great Xing'an Mountains with different fire years (In Chinese). *Chinese Journal of Applied Ecology*, 2016, 27 (5) : 1359—1367
- [63] Köster E, Köster K, Berninger F, et al. Carbon dioxide, methane and nitrous oxide fluxes from podzols of a fire chronosequence in the boreal forests in Värriö, Finnish Lapland. *Geoderma Regional*, 2015, 5: 181—187
- [64] Kim Y, Tanaka N. Effect of forest fire on the fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O in boreal forest soils, interior Alaska. *Journal of Geophysical Research*, 2003, 108, DOI: 10.1029/2001JD000663
- [65] Mäkiranta P, Laiho R, Penttilä T, et al. The impact of logging residue on soil GHG fluxes in a drained peatland forest. *Soil Biology & Biochemistry*, 2012, 48 (4) : 1—9
- [66] Yashiro Y, Kadir W R, Okuda T, et al. The effects of logging on soil greenhouse gas (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) flux in a tropical rain forest, Peninsular Malaysia. *Agricultural & Forest Meteorology*, 2008, 148 (5) : 799—806
- [67] Becker H, Uri V, Aosaar J, et al. The effects of clear-cut on net nitrogen mineralization and nitrogen losses in a grey alder stand. *Ecological Engineering*, 2015, 85: 237—246
- [68] Trentini C P, Campanello P I, Villagra M, et al. Thinning of loblolly pine plantations in subtropical Argentina: Impact on microclimate and understory vegetation. *Forest Ecology & Management*, 2017, 384: 236—247
- [69] 任乐, 马秀枝, 范雪松. 不同经营方式及生境对大兴安岭高纬度林区生长盛季森林土壤CO<sub>2</sub>、CH<sub>4</sub>、N<sub>2</sub>O通量的影响. *生态环境学报*, 2015, 24 (3) : 378—386  
Ren L, Ma X Z, Fan X S. Effect of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> fluxes in the thriving season of *Larix gmelinii* forest in cold-temperate zone under different forest management and topographic condition (In Chinese). *Ecology and Environmental Sciences*, 2015, 24 (3) : 378—386
- [70] Fang S Z, Lin D, Tian Y, et al. Thinning Intensity affects soil-atmosphere fluxes of greenhouse gases and soil nitrogen mineralization in a lowland poplar plantation. *Forest*, 2016, DOI:10.3390/f7070141
- [71] Pearson M, Saarinen M, Minkkinen K, et al. Short-term impacts of soil preparation on greenhouse gas fluxes: A case study in nutrient-poor, clear-cut peatland forest. *Forest Ecology & Management*, 2012, 283: 10—26
- [72] Saari P, Saarnio S, Kukkonen J V K, et al. DOC and N<sub>2</sub>O dynamics in upland and peatland forest soils after clear-cutting and soil preparation. *Biogeochemistry*, 2009, 94 (3) : 217—231
- [73] Lavoie M, Kellman L, Risk D. The effects of clear-cutting on soil CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O flux, storage and concentration in two Atlantic temperate forests in Nova Scotia, Canada. *Forest Ecology & Management*, 2013, 304: 355—369
- [74] McVicar K, Kellman L. Growing season nitrous oxide fluxes across a 125+ year harvested red spruce forest chronosequence. *Biogeochemistry*, 2014, 120 (1) : 225—238
- [75] Matsushita K, Tomotsune M, Sakamaki Y, et al. Effects of management treatments on the carbon cycle of a cool-temperate broad-leaved deciduous forest and its potential as a bioenergy source. *Ecological Research*, 2015, 30 (2) : 293—302
- [76] 林贵刚, 赵琼, 赵蕾, 等. 林下植被去除与氮添加对樟子松人工林土壤化学和生物学性质的影响. *应用生态学报*, 2012, 23 (5) : 1188—1194  
Lin G G, Zhao Q, Zhao L, et al. Effects of understory removal and nitrogen addition on the soil chemical and biological properties of *Pinus sylvestris* var. *mongolica* plantation in Keerqin Sandy Land (In Chinese). *Chinese Journal of Applied Ecology*, 2012, 23 (5) : 1188—1194
- [77] Wu J P, Liu Z F, Wang X L, et al. Effects of understory removal and tree girdling on soil microbial community composition and litter decomposition in two Eucalyptus plantations in South China. *Functional Ecology*, 2011, 25 (4) : 921—931
- [78] 李海防, 夏汉平, 傅声雷, 等. 剔除林下灌草和添加翅葵决明对尾叶桉林土壤温室气体排放的影响. *植物生态学报*, 2009, 33 (6) : 1015—1022  
Li H F, Xia H P, Fu S L, et al. Emissions of soil

- greenhouse gases in response to under-story removal and *Cassia alata* addition in an *Eucalyptus urophylla* plantation in Guangdong Province, China (In Chinese). *Chinese Journal of Plant Ecology*, 2009, 33 (6) : 1015—1022
- [79] 李海防, 张杏锋. 剔除灌草和添加翅葵决明对厚英相思林土壤温室气体排放的影响. *应用生态学报*, 2010, 21 (3) : 563—568
- Li H F, Zhang X F. Soil greenhouse gases emission from an *Acacia crassicarpa* plantation under effects of under-story removal and *Cassia alata* addition (In Chinese). *Chinese Journal of Applied Ecology*, 2010, 21 (3) : 563—568
- [80] Li H F, Fu S L, Zhao H T, et al. Effects of under-story removal and N-fixing species seeding on soil N<sub>2</sub>O fluxes in four forest plantations in southern China. *Soil Science and Plant Nutrition*, 2010, 56 (4) : 541—551
- [81] 刘娟, 陈雪双, 吴家森, 等. 剔除杂草对山核桃林地土壤温室气体排放的影响. *应用生态学报*, 2015, 26 (3) : 666—674
- Liu J, Chen X S, Wu J S, et al. Effects of under-story removal on soil greenhouse gas emissions in *Carya cathayensis* stands (In Chinese). *Chinese Journal of Applied Ecology*, 2015, 26 (3) : 666—674
- [82] Zhang J J, Li Y F, Chang S X, et al. Understory management and fertilization affected soil greenhouse gas emissions and labile organic carbon pools in a Chinese chestnut plantation. *Forest Ecology and Management*, 2015, 337: 126—134
- [83] Jamali H, Quayle W C, Baldock J. Reducing nitrous oxide emissions and nitrogen leaching losses from irrigated arable cropping in Australia through optimized irrigation scheduling. *Agricultural & Forest Meteorology*, 2015, 208: 32—39
- [84] Maris S C, Teira-Esmatges M R, Arbonés A, et al. Effect of irrigation, nitrogen application, and a nitrification inhibitor on nitrous oxide, carbon dioxide and methane emissions from an olive (*Olea europaea* L.) orchard. *Science of the Total Environment*, 2015, 538: 966—978

## Advancement in Researches on Effect of Forest Management on Soil N<sub>2</sub>O Emission in Forest Soils

WANG Huilai<sup>1, 2, 3</sup> LIU Juan<sup>1, 2, 3†</sup> JIANG Peikun<sup>1, 2, 3</sup> ZHOU Guomo<sup>1, 2, 3</sup> LI Yongfu<sup>1, 2, 3</sup>  
WU Jiasen<sup>1, 2, 3</sup>

(1 State Key Laboratory of Subtropical Silviculture, ZhejiangA&F University, Lin'an, Zhejiang 311300, China)

(2 Zhejiang Provincial Key Laboratory of Carbon Cycling in Forest Ecosystems and Carbon Sequestration, ZhejiangA&F University, Lin'an, Zhejiang 311300, China)

(3 Zhejiang Provincial Coordination Center of Bamboo Resources and High Efficient Utilization, ZhejiangA&F University, Lin'an, Zhejiang 311300, China)

**Abstract** 【Objective】Nitrous oxide (N<sub>2</sub>O) is an important kind of greenhouse gas, and forest soil is the main source of atmospheric N<sub>2</sub>O, posing a great uncertainty in budgeting of atmospheric N<sub>2</sub>O. Forest management, like fertilization, felling, litter burning, understory management and land-use change in forests would affect soil properties and soil micrometeorology, and hence production and emission of N<sub>2</sub>O from forest soils significantly. This paper discussed responses of forest soil to different management practices in N<sub>2</sub>O emission, explored major mechanisms of forest management affecting soil N<sub>2</sub>O emission, and highlighted shortages of the current researches and focal points of future studies. 【Method】With reference to the databases of Scopus, Web of Science, SDOS and China National Knowledge Infrastructure (CNKI), current studies on N<sub>2</sub>O emission from forest soils were reviewed, and findings of the researches on influences of forest management on soil N<sub>2</sub>O emission in recent 20 years were systematically summarized, mechanisms of forest management affecting soil N<sub>2</sub>O emission discussed, and shortages of the current studies and prospects of the researches in this field in future described. 【Result】Reclamation of forests into agricultural land or

grassland would increase soil N<sub>2</sub>O emission, whereas the reverse course would do the other way around. How replacement of natural forest with artificial or secondary forest to soil N<sub>2</sub>O emission is still unclear. The response of N<sub>2</sub>O emission from forest soils to fertilization exhibited a nonlinear curve, consisting of no significant response at the early stage, linear increase at the middle stage, and exponential increase at the late stage, depending on degree of “N saturation” of the forest ecosystems. It was generally held that burning stimulated soil N<sub>2</sub>O emission; felling affected soil temperature, water content, organic matter decomposition and utilization, thus enhancing soil N<sub>2</sub>O emission capacity; and removing understory increased soil temperature, sped up decomposition and mineralization of organic carbon in the surface soil layer, thus promoting soil N<sub>2</sub>O emission. Planting N-fixing plants also increased soil N<sub>2</sub>O emission. 【Conclusion】 Therefore, future researches should focus on the following four aspects 1) to define sources of soil N<sub>2</sub>O in the forests of North China and of South China by means of the <sup>15</sup>N-<sup>18</sup>O labeling technique in combination of molecular biology, and workout non-linear curves of the responses of N<sub>2</sub>O emission to increased N fertilizer application, through multi-dosage multi-form (ammonium nitrogen fertilizer, nitrate nitrogen fertilizer and amide nitrogen fertilizer) N fertilizer application experiments at different latitudes and under climate conditions; 2) to use molecular biological and metagenomic methods and techniques to determine effects of forest management on abundance and composition of N<sub>2</sub>O producing bacterial communities, and quantify the coupling relationships between soil N<sub>2</sub>O emission and major soil microbial functional groups, such as nitrifiers, denitrifiers ammonia-oxidizing bacteria, etc.; 3) to extend the observation in period and frequency of soil N<sub>2</sub>O emissions after different forest fire chronosequence; and 4) to unfold research about response of soil N<sub>2</sub>O emissions to select-cutting, especially in North and South China, rich in coniferous forest and rainforest, respectively.

**Key words** Soil N<sub>2</sub>O emission; Forest management; Land-use change; Fertilization; Felling; Burning; Understory management

(责任编辑: 卢萍)