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营林措施对森林土壤N_2O排放影响的研究进展*

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摘 要 森林土壤是大气N_2O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_2O的产生与排放。综述了森林土壤N_2O排放对不同营林措施的响应，探讨了营林措施影响土壤N_2O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_2O排放，而农田和草地恢复成人工林后减弱了土壤N_2O排放；天然林转换为人工林或次生林后土壤N_2O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_2O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_2O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_2O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_2O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_2O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_2O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_2O排放；营林措施；土地利用变化；施肥；采伐；火烧；林下植被管理
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N_2O是引起全球气候变暖的第三大温室气体，单位质量N_2O的增温潜势是CO_2的298倍，对全球气候变暖的贡献约为6%[1-2]。近10年来，大气N_2O浓度已经超过325 μg L^{-1}，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[1-3]。土壤是N_2O的主要排放源，全球N_2O年释放量为16.2～20.1 Tg a^{-1}[4-5]，其中土壤N_2O释放量占57%～70%[6-7]。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%[8]。森林土壤N_2O年排放量约为2.4～5.7 Tg a^{-1}，其中热带和温带森林土壤N_2O年排放量为4 Tg a^{-1}[9]。中国N_2O年排放量为0.42 Tg a^{-1}，占全球N_2O排放总量的7%[4]。

土壤N_2O主要通过硝化和反硝化过程产生。土壤N_2O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_3^-相对富集，反硝化是土壤N_2O的主要产生过程[10]，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[11]。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_2O排放量高于温带森林和北方森林[12]。参与土壤N_2O排放的主要微生物群落包括：硝化细菌（氨氧

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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_2O排放。近年来，营林措施对森林土壤N_2O排放的影响开展了大量研究，但因土壤环境因子[10-12]、经营措施[13-14]、土地利用方式[15]和生态系统类型的不同，营林措施对林地土壤N_2O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_2O排放通量的研究进展，探讨了营林措施影响土壤N_2O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_2O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_2O的排放。Cheng等[16]对马尾松林转换为农田和Álvaro-Fuentes等[17]对地中海白松林转换为大麦田的研究表明，土壤N_2O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[18]；（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_2O的排放[19]；（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_2O的排放[20]；（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_2O的排放[21]。

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_2O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_2O的产生[22-23]。例如：Baah-Acheamfour等[24]对农田转换为森林和Kooch等[25]对水稻田转化为罗雨松林的研究表明，土壤N_2O的排放分别减少了44%和67%。但Li等[26]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_2O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_2O排放还与硝化细菌和反硝化细菌的群落组成和数量有关[22, 27]。Xue等[27]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_2O排放。Lammel等[22]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_2O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_2O的产生与排放。目前林型转化对土壤N_2O排放的影响还没有明确定论（表2）。Liu等[28]研究表明，亚热带常绿阔叶林转换为毛竹林后土壤N_2O排放没有显著变化，但集约经营后显著提高了土壤N_2O的排放。孙海龙等[15]研究表明，温带次生林转变为落叶松后土壤N_2O排放增加了360%。而张睿[29]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_2O排放速率减少了25.4%～63.1%。Kim和Kirschbaum[18]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_2O的排放，但随着森林生态的恢复，土壤N_2O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_2O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_2O排放的影响

2.1　施肥对森林土壤N_2O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_2O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[14, 35-36]。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[14]，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_2O排放对森林与草地或农田之间转换的响应

Table 1 Responses of soil N_2O 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 *Populus* 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 *Pinus massoniana* forest	农田 Cropland	+15.8%	[16]
西班牙 Spain	白松林 *Pinus halepensis*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 *Taxodium distichum* plantation	−66.7%	[25]
新西兰 New Zealand	草地 Grassland	辐射松林 *Pinus radiata* plantation	+200%	[26]

表2 土壤N_2O排放对天然林转换为次生林、人工林的响应

Table 2 Responses of soil N_2O 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 *Phyllostachys pubescen* plantation	+247%	[28]
中国贵州 Guizhou，China	天然林 Natural forest	马尾松人工林 *Pinus massoniana* 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 *Castanopsis hystrix* forest	马尾松林 *Pinus massoniana* 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 *Pinus massoniana* and *Cunninghamia lanceolata* 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 *Betula* and *Pinus massoniana* forest	不变	[34]

N_2O的排放没有显著变化[37-38]。与此相反，Kim等[39]对温带落叶松人工林和Krause等[40]对温带云杉林的研究表明，有效氮富集的土壤N_2O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_2O的排放[41-42]；（2）土壤NH_4^+的累积降低土壤pH，土壤酸化抑制了土壤硝化作用，造成NO_2^-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_2O，从而增加土壤N_2O的排放[14]；（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_2^-的积累，从而使土壤N_2O排放呈上升趋势[42-43]。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_2O的排放[44-45]。例如，Fan等[46]在马尾松林混施N肥和S肥和Zhang等[47]在大叶相思林混施N肥和P肥的研究均表明，土壤N_2O排放分别减少了97%～330%和21%。

施肥对林地土壤N_2O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[48]对亚热带松树林的研究表明，高氮（150 kg $hm^{-2}a^{-1}$）促进土壤N_2O排放，低氮（50 kg $hm^{-2}a^{-1}$）对土壤N_2O排放没有明显影响。Peng等[49]研究表明，施肥1年后土壤N_2O的增加只维持了2～3周，而2年后土壤N_2O持续增加。但Jassal 等[38]对杉木林的研究表明，施肥后第1年促进土壤N_2O排放，而第2年土壤N_2O排放没有显著变化。肥料种类是影响林地土壤N_2O排放的另一重要因素，Liu和Greaver[43]研究表明，施加硝态氮肥后土壤N_2O增加程度高于铵态氮肥。而Peng 等[49]却得出相反的结果，这可能与土壤N_2O产生微生物过程的不同有关[35]。

表3　土壤N_2O排放对施肥的响应

Table 3　Responses of soil N_2O 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^{-2} a^{-1}）	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_4NO_3	150	+48%	[48]
日本 Japan	温带落叶松人工林 Temperate larch forest	NH_4NO_3	50	+69%	[39]
瑞士 Switzerland	温带云杉林 Temperate spruce forest	NH_4NO_3	25	+260%	[40]
中国广东 Guangdong，China	阔叶红松林 Broad-leaved korean pine forest	NH_4NO_3	150	+13%	[45]
中国吉林 Jilin，China	温带针阔混交林 Temperate mixed pine and broadleaf forest	$CO(NH_2)_2$	10～140	+264%	[37]
中国云南 Yunnan，China	橡胶林 Rubber plantation	$CO(NH_2)_2$	75	+60%	[52]
中国江西 Jiangxi，China	马尾松林 *Pinus massoniana* forest	$NaNO_3$和Na_2SO_4	40～45	−213.5%	[46]
中国广东 Guangdong，China	尾叶桉林 *Eucalyptus urophylla* forest	NaH_2PO_4	50～100	−20.9%	[47]
中国吉林 Jilin，China	白桦林和杨树林 *Betula platyphylla* and *Populus* L. forest	NH_4NO_3	50	不变	[37]
加拿大 Canada	温带花旗松林 Temperate douglas-fir forest	$CO(NH_2)_2$	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_2O排放对施肥的响应存在明显差异。Liu和Greaver[43]研究表明，热带和亚热带森林土壤N_2O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_2O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_2O的排放没有显著变化[14, 35-36]。

森林土壤N_2O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[50]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[51]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_4^+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_2O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_2O排放的影响

森林火灾对土壤N_2O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_2O排放[53]。马秀枝等[54]对兴安落叶松林和Morishita等[55]对西伯利亚黑云杉林的研究表明，火烧后土壤N_2O排放分别增加了69.2%和354%（表4），其主要原因为：（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_2O的排放[56-57]；（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[58]；（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_2O的产生[59]。

火烧后土壤N_2O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[55]对西伯利亚黑云杉林的研究表明，重度火烧减弱了土壤N_2O的排放，但局部火烧增强了土壤N_2O的排放。Kim等[60]研究表明，火烧产生的生物质炭干扰了硝化和反硝化作用，土壤N_2O排放量减少了6.6%；而去除地上残留物后，土壤N_2O排放增加了30.1%。Inclán等[61]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_2O的排放，而冬青栎林、欧洲赤松林土壤N_2O的排放没有明显变化。研究表明，土壤N_2O排放对不同火烧时间序列的响应完全不同。例如，马秀枝等[54]对兴安落叶松林的研究表明，火烧1年后土壤N_2O排放相较于对照下降了37.9%，而火烧19年后土壤N_2O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_2O排放逐渐增加[62]。但Köster等[63]对桉树林的研究表明，火烧75年后土壤表现为N_2O的排放源，而155年后则表现为N_2O的弱吸收汇。目前，关于不同火烧时间序列对土壤N_2O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_2O排放转变的原因尚未确定。

2.3 采伐对森林土壤N_2O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_2O的排放。目前有关采伐对森林土壤N_2O排放的研究大多关注皆伐，而对于择伐报道较少（表5）。Mäkiranta等[65]对欧洲赤松林和Yashiro等[66]对马来西亚热带雨林的研究表明，皆伐后土壤N_2O排放分别增加了368%和685%（表5），主要原因为：（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_2O的排放[67]；（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_2O的排放[66]；（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_2O的产生[67-68]。因择伐对森林土壤环境的影响较小，从而使择伐后土壤N_2O排放表现为不变或者减少[69-70]。

皆伐后土壤N_2O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[65]对芬兰泥炭地森林研究表明，皆伐后保留残留物的土壤N_2O排放量是未保留的3倍。McVicar和Kellman[74]对红皮云杉林的研究表明，皆伐2年后土壤N_2O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[71]研究表明，皆伐地翻耕后土壤N_2O的排放明

表4　土壤N_2O排放对火烧的响应

Table 4　Responses of soil N_2O 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 *Picea mariana* forest	+354%	[55]
日本 Japan	白桦林 *Betula platyphylla* forest	+30.1%	[58]
中国内蒙古 Inner Mongolia，China	兴安落叶松林 *Larix gmelinii* (Rupr.) Kuzen forest	+69.2%	[54]
日本 Japan	白桦林 *Betula platyphylla* 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 *Pyrenean* oak forest	不变	[61]
芬兰 Finland	欧洲赤松林 *Pinus sylvestris* forest	不变	[63]

表5　土壤N_2O排放对采伐的响应

Table 5　Responses of soil N_2O 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 *Pinus sylvestris* 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 *Larix gmelinii* (Rupr.) Kuzen forest	+74%	[69]
中国江苏 Jiangsu，China	杨树林 *Populus* 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 *Larix gmelinii* (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_2O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_2O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[75-77]。研究表明，去除林下植被后亚硝化细菌及硝化细菌对NH_4^+的可利用性增加，而土壤MBC和相关酶活性显著降低[76]。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[77]。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_2O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[78]。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_2O的产生提供良好的条件[79-80]。

表6 土壤N_2O对林下植被管理的响应

Table 6 Responses of soil N_2O 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 *Carya cathayensis* forest	剔除林下植被 Understory removal	+120%	[81]
中国浙江 Zhejiang, China	板栗林 *Castanea mollissima BL.* forest	剔除林下植被 Understory removal	+101.3%	[82]
中国广东 Guangdong, China	尾叶桉林 *Eucalyptus urophylla* forest	剔除林下植被 Understory removal	+40.6%	[78]
中国广东 Guangdong, China	厚荚相思林 *Acacia crassicarpa* 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 *Castanea mollissima 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_2O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_2O排放，在农田和草地生态系统也得出相同的结果[83]。而Maris等[84]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_2O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_2O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_2O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_2O产生过程复杂化，土壤N_2O对施肥的响应存在明显差异。2）过去关于森林土壤N_2O 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_4^+、NO_3^-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_2O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_2O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_2O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_2O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_2O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$^{15}N-^{18}O$标记法明确土壤N_2O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_2O来源的差异，构建土壤N_2O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_2O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_2O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_2O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。

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Advancement in Researches on Effect of Forest Management on Soil N_2O Emission in Forest Soils

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Abstract　【Objective】Nitrous oxide (N_2O) is an important kind of greenhouse gas, and forest soil is the main source of atmospheric N_2O, posing a great uncertainty in budgeting of atmospheric N_2O. 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_2O from forest soils significantly.This paper discussed responses of forest soil to different management practices in N_2O emission, explored major mechanisms of forest management affecting soil N_2O 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_2O emission from forest soils were reviewed, and findings of the researches on influences of forest management on soil N_2O emission in recent 20 years were systematically summarized, mechanisms of forest management affecting soil N_2O 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_2O emission, whereas the reverse course would did the other way around. How replacement of natural forest with artificial or secondary forest to soil N_2O emission is still unclear. The response of N_2O 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_2O emission; felling affected soil temperature, water content, organic matter decomposition and utilization, thus enhancing soil N_2O 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_2O emission. Planting N-fixing plants also increased soil N_2O emission. 【Conclusion】 Therefore, future researches should focus on the following four aspects 1) to define sources of soil N_2O in the forests of North China and of South China by means of the ^{15}N-^{18}O labeling technique in combination of molecular biology, and workout non-linear curves of the responses of N_2O 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 matagenomic methods and techniques to determine effects of forest management on abundance and composition of N_2O producing bacterial communities, and quantify the coupling relationships between soil N_2O 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_2O emissions after different forest fire chronosequence; and 4) to unfold research about response of soil N_2O emissions to select-cutting, especially in North and South China, rich in coniferous forest and rainforest, respectively.

Key words Soil N_2O emission; Forest management; Land-use change; Fertilization; Felling; Burning; Understory management

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