



冻融循环期间土壤氧化亚氮排放影响因素

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摘 要 全球气候变化可能会提高冻融循环时间、强度以及频率, 从而可能显著影响土壤氧化亚氮(N_2O)排放。 N_2O 是一种重要的温室气体, 但目前对冻融循环期间土壤 N_2O 排放规律以及影响因素的了解还有限。为此, 该研究采用整合分析方法, 从已发表文献中收集了30篇关于冻融循环对土壤 N_2O 通量和累积排放量影响的文献, 探究冻融循环在不同生态系统对 N_2O 排放的影响, 从试验设置、土壤基本理化性质以及冻融循环格局等角度全面综合地探究其排放影响因素。该研究得出, 冻融循环能显著增加 N_2O 通量、 N_2O 累积排放量和硝化作用速率, 全球平均增幅分别为72.34%、143.25%和124.63%; 冻融循环也可增加反硝化作用速率, 全球平均增幅为162.56%; 与之相反, 冻融循环显著减少微生物生物量氮含量, 全球平均减幅为6.39%。不同生态系统土壤水热条件和基本理化性质差异可显著影响冻融循环对 N_2O 排放的影响。当年平均气温超过5 °C时, 冻融循环作用可显著提高 N_2O 通量104.13%, 显著高于年平均气温为0–5 °C (25.56%)和小于0 °C (55.29%)时; 土壤湿度大于70%时, N_2O 通量增加109.17%, 显著高于土壤湿度为50%–70% (65.67%)和小于50% (20.37%)时的通量。土壤黏粒和养分含量越高的土壤区域, 冻融循环对 N_2O 排放的提高幅度越大。在有植物存在时, 冻融循环可显著提高土壤 N_2O 通量达91.21%, 高于无植物存在时的54.43%。土壤过筛和在冻融循环期间采集土壤都会增加冻融循环对 N_2O 排放的影响。另外, 融化时间长, 冻结强度大和冻融循环频率高均可显著提高土壤 N_2O 累积排放量对冻融循环的响应。当冻结温度低于–10 °C时, 冻融循环对土壤 N_2O 排放通量的增幅可达100.73%, 显著高于在冻结温度为–10––5 °C (47.74%)和高于–5 °C (70.25%)时。主要原因是冻结强度高可促进土壤微生物和土壤结构释放更多的养分, 从而提高 N_2O 的产生和排放。该研究结果有助于更好地理解土壤 N_2O 对冻融循环的响应及其影响因素, 为更准确地预测未来全球气候变化对 N_2O 排放影响提供科学数据支撑。

关键词 冻融; 氧化亚氮(N_2O); 微生物生物量; 全球气候变化; 反硝化作用

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Influencing factors of soil nitrous oxide emission during freeze-thaw cycles

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Abstract

Aims Enhanced duration, intensity, and frequency of freeze-thaw cycles owing to global climate change may significantly affect soil nitrous oxide (N_2O) emission. N_2O is an important greenhouse gas, but our current understanding of soil N_2O emission and its influencing factors during freeze-thaw cycles is still limited.

Methods Here, we adopted the meta-analysis method and collected 30 articles on the effects of freeze-thaw cycles on soil N_2O flux and cumulative emission from peer-reviewed journal articles. Our objectives were to explore the effects of freeze-thaw cycles on N_2O emissions in different ecosystems and to comprehensively explore the influencing factors from the perspectives of experimental settings, soil physical and chemical properties, and the patterns of freeze-thaw cycles.

Important findings Results showed that freeze-thaw cycles significantly increased N_2O instantaneous emission, cumulative emission, and nitrification by 72.34%, 143.25%, and 124.63%, respectively. Freeze-thaw cycles also increased denitrification by 162.56%. Conversely, freeze-thaw cycles significantly decreased microbial biomass nitrogen by 6.39%. The effect of freeze-thaw cycles on N_2O emission was significantly affected by the variations in soil microclimate and soil physical and chemical properties in different ecosystems. When the mean annual

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temperature (*MAT*) of a site exceeded 5 °C, freeze-thaw cycles could significantly enhance the N₂O flux by 104.13%, which was significantly higher than that the effect at sites with *MAT* between 0–5 °C (25.56%) or less than 0 °C (55.29%). When soil moisture was greater than 70%, the increase of soil N₂O flux caused by freeze-thaw cycles was 109.17%, which was significantly higher than that when soil moisture was between 50%–70% (65.67%) or less than 50% (20.37%). The higher soil clay and nutrient contents were, the greater the increase in N₂O emission caused by freeze-thaw cycles became. Freeze-thaw cycles could significantly increase soil N₂O flux by 91.21% in the presence of plants, which was higher than the effect in the absence of plants (54.43%). The impact of freeze-thaw cycles on N₂O emission could be enhanced by soil sieving. In addition, soils sampled during the freeze-thaw cycling period showed more responses to freeze-thaw cycles than soils sampled during other times. The response of cumulative N₂O emissions to freeze-thaw cycles was significantly improved by longer duration of thawing, higher intensity of freezing, and higher frequency of freeze-thaw cycles. When the freezing temperature was lower than –10 °C, freeze-thaw cycles could enhance soil N₂O flux by 100.73%, which was significantly higher than the effect when the freezing temperature was between –10– –5 °C (47.74%) or more than –5 °C (70.25%). The main reason was that higher intensity of freezing could promote the release of more nutrients from soil microorganisms and soil structure, thereby increasing the production and emission of N₂O. Overall, these results can help better understand the response of soil N₂O to freeze-thaw cycles and its influencing factors, and provide scientific data for accurately predicting the impact of global climate change on N₂O emission in the future.

Key words freeze-thaw; nitrous oxide (N₂O); microbial biomass; global climate change; denitrification

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氧化亚氮(N₂O)作为一种重要温室气体, 对全球变暖贡献率可达到6%, 此外它也是破坏臭氧层的主要气体之一(Ravinshakara *et al.*, 2009; Abalos *et al.*, 2018)。全球N₂O产生和排放途径很多, 其中以土壤排放为主, 可占全球排放总量的60%左右(IPCC, 2014)。在土壤排放的N₂O中, 以冻融循环期间的排放量相对较高, 可占到土壤年排放总量的20%–90% (陈哲等, 2016; 宋阳等, 2016; Wagner-Riddle *et al.*, 2017; Congreves *et al.*, 2018)。随着未来全球气候变暖(Rogelj *et al.*, 2012), 冻融循环格局可能也会随之发生改变, 比如冻融循环时间、强度和频率增加, 这些变化可能会通过影响土壤基本理化性质及微生物特性等途径来改变土壤N₂O排放。因此, 研究土壤N₂O在冻融循环期间的排放规律以及作用机制具有重要意义。

冻融循环是由于季节或者昼夜温差引起的反复冻结和融化过程。这种现象普遍存在于自然界中, 并广泛发生在北半球高海拔、高纬度和一些温带地区, 例如, 在中国30° N以北地区中有46.3%的区域受到季节性冻融循环的影响(陈哲等, 2016)。前人通过综述和整合分析等已经证实, 冻融循环可显著增加土壤N₂O排放(Henry, 2007; Matzner & Borken, 2008; Song *et al.*, 2017; Gao *et al.*, 2018)。冻融循环作用主要通过下面几个过程来显著提高土壤可利用

养分含量: 土壤结构破坏可释放养分(Xiao *et al.*, 2019); 土壤有机或无机胶体表面吸附的养分释放(Freppaz *et al.*, 2007); 死亡的微生物可释放养分(Yanai *et al.*, 2004); 死亡的根系可释放养分(Campbell *et al.*, 2014; Reinmann & Templer, 2016); 凋落物分解释放养分(Wieder *et al.*, 2011; Pelster *et al.*, 2013)。这些由于冻融循环作用增加的可利用养分可促进土壤氮转化过程, 比如硝化和反硝化作用等, 在这些氮转过程中会产生N₂O, 从而增加了土壤N₂O排放(Dai *et al.*, 2020)。除了硝化和反硝化外, 硝酸盐的异化还原作用也可以产生N₂O, 研究得出, 可利用碳是调节硝态氮含量在反硝化和异化还原过程分配的关键因子(Fazzolari *et al.*, 1998), 可溶性碳和硝态氮含量比值大于12时, 才会有更多的硝酸盐的异化还原作用发生(Yin *et al.*, 1998)。在冻融循环过程中, 碳、氮养分的变化会不会影响N₂O产生过程, 需要进一步证实。另外, 在研究冻融循环对土壤N₂O排放中所采用的试验方法不尽相同, 比如采用室内模拟方法或室外原位研究方法以及在室内研究中采集土壤时间和处理方式以及冻融循环过程中是否有植物的存在等都有所差异, 这些试验方法和设置的差异究竟会给冻融循环期间N₂O排放带来怎样的影响, 仍需进一步探究。在不同地区研究冻融循环的时候, 其所处的水热条件是不同的, 土壤结构、

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养分含量以及微生物活性和种类也是不同的。例如,与年平均气温较高的温带地区相比,苔原和高山草甸地区土壤微生物对冻融循环的响应较高(Gao *et al.*, 2018),这可能是因为苔原和高山草甸等地区年平均气温较低,土壤微生物对低温的适应性较强(Grogan *et al.*, 2004)。土壤本身基本理化及微生物特性差异可能也会影响土壤N₂O对冻融循环响应的大小。然而,前人研究缺乏这些因素对N₂O排放的影响的综合考虑。

除了土壤本身的性质外,冻融循环格局不同也可能会影响N₂O对冻融循环的响应。前人研究结果(Oztas & Fayetorbay, 2003; Zhou *et al.*, 2011)显示,冻结强度增加,可提高其对微生物和土壤结构的影响,从而释放更多养分,进而增加土壤N₂O排放。随着冻融循环频率增加和冻融循环时间的增加,土壤可利用养分可能会通过以下方式被降低:养分被微生物不断消耗,养分的淋洗损失,养分被土壤颗粒重吸附(Grogan *et al.*, 2004; Yu *et al.*, 2010; Han *et al.*, 2018; Xiao *et al.*, 2019)。这些可利用养分的减少会导致N₂O对冻融循环的响应随之下降。相比于N₂O排放通量,冻融循环期间N₂O累积排放量的生态学意义更大。然而前人的研究都集中在N₂O排放通量,并没有探究N₂O累积排放量与冻融循环格局变化之间的关系。未来气候变化背景下,冻融循环格局也会发生相应改变,比如冻融时间延长,冻融循环的强度和频率增加等,那么这些变化会给N₂O累积排放量产生什么样的影响?前人研究并不足。

为此,本研究通过收集全球尺度不同区域冻融循环研究的数据,整合分析研究N₂O排放通量和累积排放量对冻融循环的响应,并从试验设置、土壤基本理化性质以及冻融循环格局等角度全面综合地探究其排放如何受这些因素影响。

1 材料和方法

1.1 数据收集

本研究基于Google Scholar、Web of Science以及中国知网(CNKI)等文献检索系统,收集发表在2020年12月以前关于冻融循环对土壤N₂O排放的文献。搜索关键词为“freez* thaw*” “N₂O” “nitrous oxide” “microbial biomass” “nitrification” “denitrification”以及“冻融循环”“冻融交替”“氧化亚氮”。初步收集的文献根据下面3个原则进行进一步筛选:(1)研究必

须包括冻融循环处理组和恒温对照组;(2)排除有多因素交互效应的研究;(3)所选的研究需要报道该变量的平均值和样本数。根据上述原则进行筛选,最终本研究共收集到30篇文献中的611个观察数据。

本研究收集了5个变量,分别为N₂O通量、N₂O累积排放量、微生物生物量氮含量、硝化作用速率和反硝化作用速率。除了变量本身外,本研究也收集了每个研究中与变量相关的其他信息:(1)背景信息,包括每个研究的地理位置、年降水量(MAP)、年平均气温(MAT)、植被类型以及土壤类型;(2)试验设置,包括试验方法、生态系统类型、土壤采样时间和深度、是否有植物存在、土壤处理方式以及试验前的前处理;(3)土壤基本理化性质,包括土壤质地、湿度(全文土壤湿度的表示方式是土壤孔隙含水量(WFPS))、pH、总碳含量、总氮含量、碳氮比、有机碳含量、可溶性有机碳含量、可溶性有机氮含量、硝态氮含量以及铵态氮含量;(4)冻融循环格局,包括冻结时间、融化时间、冻融循环总时间、冻结温度、融化温度以及冻融循环频率。为了便于探究不同条件下N₂O排放的差异,本研究把收集到的关于冻融循环文章进行如下分类:(1)按照年平均气温分为:<0 °C, 0–5 °C和>5 °C;(2)按照试验方法分为:室内研究和室外原位研究;(3)按照生态系统分为:森林、草地、农田、泥炭地、湿地和苔原;(4)按照室内研究对土壤处理的方式分为:土壤过筛和不过筛;(5)按照冻融循环过程中是否有植物分为:有植物和无植物;(6)按照在室内研究对采集土壤的时间不同分为:冻融循环期和非冻融循环期;(7)按照冻结温度的强弱分为:>–5 °C, –10– –5 °C和<–10 °C;(8)按照土壤湿度的大小分为:<50%, 50%–70%和>70%。

1.2 数据分析与统计

为了便于比较不同研究之间冻融循环效应的差异,本研究采用效应比值(*R*)自然对数,定义为“效应值(ln *R*)”,来计算变量对冻融循环响应大小(Hedges *et al.*, 1999)。ln *R*通过公式(1)计算:

$$\ln R = \ln \left(\frac{\bar{X}_t}{\bar{X}_c} \right) = \ln(\bar{X}_t) - \ln(\bar{X}_c) \quad (1)$$

式中, \bar{X}_t 和 \bar{X}_c 分别代表在处理组和对照条件下变量的平均值。其中在室内试验中,对照组温度为一个大于0 °C的恒定值,在室外原位研究中,对照组温度为一个大于0 °C且有波动的值。冻融循环处理

组至少包括一个冻结和融化过程。当 $\ln R > 0$ 时, 表示与对照组相比, 冻融循环处理可增加变量的响应; 当 $\ln R < 0$ 时, 表示与对照组相比, 冻融循环处理可减少变量的响应。

$\ln R$ 变异系数(v)按照公式(2)计算:

$$v = \frac{s_t^2}{n_t \bar{X}_t^2} + \frac{s_c^2}{n_c \bar{X}_c^2} \quad (2)$$

式中, s_t 和 n_t 分别代表处理组标准差(SD)和样本数; s_c 和 n_c 分别代表对照组 SD 和样本数。文献中的数据一般是以表格或者图片形式呈现, 若以表格形式呈现, 则直接读取; 若以图形形式呈现, 则利用Getdata软件(<http://www.getdata-graph-digitizer.com/index.php>)提取。本研究处理数据所用误差是 SD , 而许多研究中数据误差是以标准误(SE)形式呈现, 因此需要利用公式(3)进行转化:

$$SD = SE\sqrt{n} \quad (3)$$

式中, n 为样本数。

每个观察值权重因子(w)根据公式(4)计算:

$$w = 1/v \quad (4)$$

为了平衡来自不同研究的权重, 权衡后的权重按照公式(5)(Bai *et al.*, 2013)计算:

$$w' = w/n \quad (5)$$

式中, n 为每个研究总观测数。

最后, 通过公式(6)和(7)分别计算加权效应值

($\ln R'$)和平均效应值($\overline{\ln R'}$):

$$\ln R' = w' \times \ln R \quad (6)$$

$$\overline{\ln R'} = \frac{\sum_i \ln R'_i}{\sum_i w'_i} \quad (7)$$

式中, $\ln R'_i$ 和 w'_i 分别表示在第 i 个观测值的 $\ln R'$ 和 w' 。

本研究采用MetaWin 2.1随机效应模型分析冻融循环对土壤 N_2O 通量、 N_2O 累积排放量、微生物生物量氮含量、硝化作用以及反硝化作用速率是否具有统计显著性差异(Rosenberg *et al.*, 2000)。每个变量结果以平均值和bootstrap 95%置信区间呈现。若某个变量平均效应值的95%置信区间不跨过0, 则表示冻融循环处理对这个变量具有统计学意义上的显著正效应或负效应。反之, 则表示冻融循环处理对这个变量无显著性影响。为了便于解释, 变量的平均效应值被转化为百分数:

$$\text{变量响应的百分数}(\%) = (e^{\overline{\ln R'}} - 1) \times 100\% \quad (8)$$

为了探究在冻融循环期间影响土壤 N_2O 排放的因素, 本研究采用一元线性回归模型分析土壤基本理化性质, 冻融循环格局与土壤 N_2O 通量和累积排放量之间的相关关系, 本分析过程中使用土壤 N_2O 通量或 N_2O 累积排放量的未加权效应值($\ln R$)。使用Origin 8.6作图。

2 结果

2.1 冻融循环对土壤 N_2O 、微生物生物量氮、硝化和反硝化作用的影响

由图1可知, 冻融循环可显著增加土壤 N_2O 通量、 N_2O 累积排放量和硝化作用速率, 平均增幅分别达72.34%, 143.25%和124.63% ($p < 0.01$)。与之相反, 冻融循环可显著减少土壤微生物生物量氮含量, 平均减幅可达6.39% ($p < 0.01$)。此外, 与恒温对照相比, 冻融循环作用可提高反硝化作用速率, 平均可提高162.56%, 但其95%置信区间通过0点, 因此并没有达到统计学显著性差异。

2.2 试验设置对 N_2O 响应冻融循环的影响

表1是本研究收集的30篇关于冻融循环对土壤 N_2O 排放影响的文献。根据不同研究采用方法的差

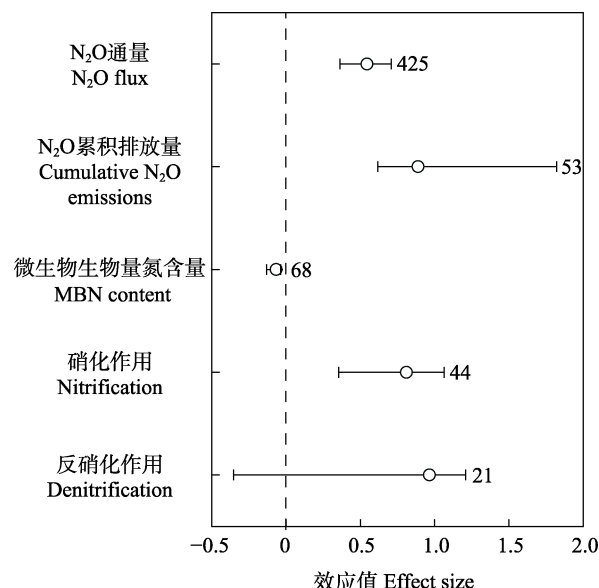


图1 冻融循环对土壤氧化亚氮(N_2O)通量、 N_2O 累积排放量、微生物生物量氮含量、硝化和反硝化作用速率的影响。误差棒表示95%置信区间, 误差棒后面数值代表变量观察数。虚线表示效应值为0。

Fig. 1 Effects of freeze-thaw cycles on soil nitrous oxide (N_2O) flux, cumulative N_2O emissions, microbial biomass nitrogen (MBN) content, nitrification, and denitrification rates. Error bars stand for 95% confidence intervals. Values next to the error bars represent the number of observations of the variable. Dashed line indicates that there is no effect.

异,可分为室内模拟培养和野外原位研究,其中有23个研究采用的是室内模拟培养,仅7个研究采用的是野外原位研究,其中原位研究的方式主要是去除雪被。根据生态系统不同可分为森林、草地、农田、湿地、泥炭地以及苔原。其中研究最多的生态系统类型是农田,其次是草地和森林。按照冻融循环研究区域,可划分为中国北部、北美、北欧以及日本(图2)。按照室内研究对于土壤的处理可分为过筛和非过筛,在室内分析中有将近40%的研究对于土壤是过筛处理的。根据室内分析采集土壤样品的时间可分为在冻融循环期间采样(即秋末到初春期间)和在非冻融循环期间采样。有些研究在试验开始前还在一定温度下进行一段时间的预培养。

由图3可知,不同试验条件和试验设置下,冻融循环作用基本上都会显著增加土壤 N_2O 通量和累积排放量,但其影响大小不同。(1)采集土壤样地的MAT大小并不影响土壤 N_2O 排放对冻融循环的正响应,但是响应大小有所差异。例如,当MAT超过5℃时,冻融循环作用可显著提高 N_2O 通量104.13%,显著高于MAT为0–5℃(增幅为25.56%)和小于0℃(增幅为55.29%)时($p < 0.01$)。在MAT小于0℃,0–5℃和超过5℃的样地,冻融循环均可显著增加 N_2O 累积排放量($p < 0.01$),增幅分别为32.78%、74.19%和55.47%,但三者之间并无统计性差异。(2)不管在室内还是在室外原位研究,冻融循环均可显著增加 N_2O 通量(室内和室外增幅分别为70.68%和91.21%)和累积排放量(室内和室外增幅分别为70.68%和91.21%)。 N_2O 通量在室外研究的平均效应值大于室内研究,尽管两者之间没有显著性差异, N_2O 累积排放量表现出截然相反的趋势。(3)在不同生态系统中,冻融循环均可显著增加 N_2O 通量($p < 0.01$),其中湿地(增幅为343.4%)和苔原(增幅为411.31%)生态系统 N_2O 通量对冻融循环的响应大于森林(增幅为96.19%)、草地(增幅为47.4%)、农田(增幅为97.03%)以及泥炭地(增幅为74.6%)等生态系统,而 N_2O 通量对冻融循环的响应在森林、草地、农田以及泥炭地之间差异并不大。与 N_2O 通量不同, N_2O 累积排放量对冻融循环的响应在不同生态系统之间差异明显,具体表现为:农田(增幅为616.92%)>草地(增幅为90.6%)>森林(增幅为7.48%)。有趣的是,在森林生态系统下,冻融循环对 N_2O 累积排放量并没有显著影响。(4)不管是 N_2O 通量还是 N_2O 累积排

放量,室内研究中土壤过筛都会提高它们对冻融循环的效应值。其中,过筛与否对于 N_2O 累积排放量影响较大,具体表现为:室内不过筛的土壤与对照相比,冻融循环提高 N_2O 累积排放量21.66%,但无统计学意义的差异;而过筛后的土壤,与对照相比,冻融循环可显著提高 N_2O 累积排放量1626.01%($p < 0.01$)。(5)有无植物的存在会改变 N_2O 对冻融循环响应的大小。比如,有植物存在的土壤 N_2O 通量响应值(增幅为91.21%)大于无植物的(增幅为54.43%),但两者之间的差异并无统计性差异。而有植物存在(增幅为80.11%)和无植物存在(增幅为74.16%)条件下, N_2O 累积排放量对冻融循环的响应并无明显差异。(6)土壤取样时间也会影响冻融循环效应。在冻融循环期间采集土壤时(N_2O 通量和 N_2O 累积排放量增幅分别为103.11%和271.69%), N_2O 通量和 N_2O 累积排放量响应冻融循环的大小均大于在非冻融循环期间取土时(N_2O 通量和 N_2O 累积排放量增幅分别为45.81%和109.03%),但两者之间并无明显差异。(7)冻融循环过程中冻结温度越低, N_2O 的排放提高幅度越大。本研究得出,在冻结温度小于–10℃时, N_2O 通量增幅可达100.73%,显著高于在冻结温度为–10––5℃(增幅为47.74%)和大于–5℃(增幅为70.25%)时。 N_2O 累积排放量也表现出相似的规律,在冻结温度小于–10℃(增幅为238.38%)和为–10––5℃(增幅为321.44%)时的 N_2O 累积排放量高于在冻结温度大于–5℃(增幅为32.78%)时。(8)与冻结温度类似,冻融循环过程中土壤湿度越高,土壤 N_2O 的排放增加幅度越大。例如,土壤湿度大于70%时, N_2O 通量增加109.17%,显著高于在土壤湿度为50%–70%(增幅为65.67%)和小于50%(增幅为20.37%)时($p < 0.01$)。土壤湿度为50%–70%(增幅为775.22%)和大于70%(增幅为240.83%)时, N_2O 累积排放量增幅也大于土壤湿度小于50%(增幅为32.78%)时。

2.3 土壤基本理化性质、硝化和反硝化作用速率及冻融循环格局与 N_2O 排放的相关性

根据冻融循环对 N_2O 通量的效应值与MAP和MAT之间的相关关系得知,冻融循环对 N_2O 通量的效应值与MAT之间呈现显著正相关关系($r = 0.68$, $p < 0.001$),而与MAP之间无相关性(图4)。

通过冻融循环对 N_2O 通量的效应值与土壤基本理化性质之间的相关关系可得:冻融循环对 N_2O 通

表1 整合分析文章的试验设置
Table 1 Experimental settings in the studies used in this meta-analysis

试验方法 Experimental method	生态系统 Ecosystem	研究地区 Study location	土壤类型 Soil type	土壤处理 Soil treatment	土层 Soil depth (cm)	取土时间 Date of sampling soils	前处理 Pre-treatment	参考文献 Reference
室内培养 Laboratory incubation	农田 Cropland	加拿大魁北克省 Quebec, Canada (45.42° N, 75.93° W)	砂壤土 Sandy loam (16% clay, 15% silt, 69% sand)	未过筛 Not sieved	0-10	1993-04-07	无前处理 No pre-treatment	Chen <i>et al.</i> , 1995
室内培养 Laboratory incubation	北方泥炭地 Boreal peatland	中国东北大兴安岭 Da Hinggan Mountain of Northeastern China (52.73° N, 122.65° E)	典型泥炭土 Typical peat soil	过4 mm筛 Pass through 4 mm sieve	0-15	2003-08	25 °C培养3天 Incubation at 25 °C for 3 days	Cui <i>et al.</i> , 2016
室内培养 Laboratory incubation	高山泥炭地/高山草甸 Alpine peatland/ Alpine meadow	中国青藏高原东部的红原县 Hongyuan County in eastern Qingzang Plateau (32.98° N, 103.67° E)	泥炭土 Peat soil	未过筛 Not sieved	0-20	2012-11	5 °C培养5天 Incubation at 5 °C for 5 days	Gao <i>et al.</i> , 2015
野外试验(雪被去除) Field experiment (Snow removal)	森林 Forest	Fichtelgebirge (NE Bavaria), Germany (50.13° N, 11.87° E)	Haplic Podsol (16% clay, 46% silt, 37% sand)	未过筛 Not sieved	—	2005-07	—	Goldberg <i>et al.</i> , 2010
室内培养 Laboratory incubation	森林 Forest	Fichtelgebirge (NE Bavaria), Germany (50.13° N, 11.88° E)	Haplic Podsol (16% clay, 46% silt, 37% sand)	未过筛 Not sieved	0-5/0-18	2005-04	5 °C培养60天 Incubation at 5 °C for 60 days	Goldberg <i>et al.</i> , 2008
野外试验(雪被去除) Field experiment (Snow removal)	森林 Forest	美国新罕布什尔州怀特山 White Mountains of New Hampshire, USA (43.93° N, 71.75° W)	粗粒壤土 Coarse-loamy, Typic Haplorthods	未过筛 Not sieved	—	1997-11-1998-01, 1998-11-1999-01	—	Groffman <i>et al.</i> , 2006
野外试验(雪被去除) Field experiment (Snow removal)	森林 Forest	美国新罕布什尔州怀特山 White Mountains of New Hampshire, USA (43.93° N, 71.75° W)	砂土 Sandy, Spodosols	未过筛 Not sieved	—	2002-11-2003-01, 2003-11-2004-01	—	Groffman <i>et al.</i> , 2011
温室培养 Greenhouse incubation	亚北极荒漠苔原 Sub-arctic heath tundra	瑞典北部的阿比斯库附近 Near Abisko in North Sweden (68.33° N, 18.83° E)	—	未过筛 Not sieved	0-14.5	1999-04-12	温室培养7个月左右 Greenhouse incubation for about 7 months	Grogan <i>et al.</i> , 2004
野外试验 Field experiment	农田/草地 Cropland/ Grassland	Field Science Center for the Northern Biosphere, Hokkaido University, Japan (42.42° N, 142.47° E)	粉砂壤土 Silt loam, Histosol/Vitric Andosol	未过筛 Not sieved	—	2004-12-8- 2005-4-19	—	Kaayanagi & Hatano, 2012
室内培养 Laboratory incubation	草地 Grassland	芬兰的东芬兰大学 University of Eastern Finland, Finland (60.02° N, 24.88° E)	砂冰碛土 Sandy till	过筛 Sieved	—	2010-06	—	Kettunen & Saarnio, 2013
室内培养 Laboratory incubation	农田 Cropland	The experimental field of the Agrifood Research Finland in Jokioinen, Southern Finland (60.82° N, 23.5° E)	泥炭土 Peat soil/砂壤土 Sandy loam, Terric Histosol/Eutric Cambisol	过5.6 mm筛 Pass through 5.6 mm sieve	0-25	2001-10-29- 2001-11-05	4 °C培养120天 Incubation at 4 °C for 120 days	Koponen <i>et al.</i> , 2006

表1 (续) Table 1 (Continued)

试验方法 Experimental method	生态系统 Ecosystem	研究地区 Study location	土壤类型 Soil type	土壤处理 Soil treatment	土层 Soil depth (cm)	取土时间 Date of sampling soils	前处理 Pre-treatment	参考文献 Reference
室内培养 Laboratory incubation	农田 Cropland	德国哥廷根附近 Near Göttingen, Germany (51.53° N, 9.9° E)	粉粒土 Silt soil, Haplic Luvisol (16% clay, 78% silt, 6% sand)	未过筛 Not sieved	0-10	-	-	Ludwig <i>et al.</i> , 2004
野外试验(雪被去除) Field experiment (Snow removal)	草地 Grassland	芬兰东部 Eastern Finland (60.15° N, 27.33° E)	Dystic Regosol (6% clay, 15% silt, 71% sand)	未过筛 Not sieved	-	2004-10-2005-06	-	Maljanen <i>et al.</i> , 2007
野外试验(雪被去除) Field experiment (Snow removal)	农田 Cropland	芬兰东部马尼卡 Maaninka, Eastern Finland (63.15° N, 27.33° E)	Dystic Regosol (6% clay, 15% silt, 71% sand)	未过筛 Not sieved	-	2005-05	-	Maljanen <i>et al.</i> , 2009
室内培养 Laboratory incubation	农田 Cropland	Institute for Energy Technology, Kjeller, Norway (59.15° N, 11.07° E)	Mollic gleysol (13% clay, 68% silt, 19% sand)	过筛 Sieved	-	-	-	Mørkved <i>et al.</i> , 2006
室内培养 Laboratory incubation	森林 Forest	美国新罕布什尔州怀特山 White Mountains of New Hampshire, USA (43.93° N, 71.75° W)	砂土 Sandy, Typic Haplothods	未过筛 Not sieved	-	1997-06	-	Neilsen <i>et al.</i> , 2001
室内培养 Laboratory incubation	农田 Cropland	加拿大魁北克市附近的拉瓦尔大学 实验农场 Laval University Experimental Farm near Saint-Augustine-Desmaures, Canada (46.73° N, 71.52° W)	粉黏粒 Silty clay, Gleyed Melanic Brunisol (43.2% clay, 40.5% silt, 16.3% sand)	过<6 mm筛 Pass through <6 mm sieve	0-20	2010-11	-	Pelster <i>et al.</i> , 2013
室内培养 Laboratory incubation	农田 Cropland	加拿大魁北克市附近的拉瓦尔大学实验农场 Laval University Experimental Farm near Saint-Augustine-Desmaures, Canada (46.73° N, 71.52° W)	粉黏粒 Silty clay, Gleyed Melanic Brunisol (43.2% clay, 40.5% silt, 16.3% sand)	过<6 mm筛 Pass through <6 mm sieve	0-20	2010-11	4 °C培养42天 Incubation at 4 °C for 42 days	Pelster <i>et al.</i> , 2019
室内培养 Laboratory incubation	草地/森林/农田 Grassland/Forest/Cropland	德国、瑞典、芬兰 Germany (48.67° N, 11.07° E), Sweden (58.33° N, 13.5° E), Finland (62.52° N, 29.38° E)	-	未过筛 Not sieved	0-19	1999-12	-	Priemé & Christensen, 2001
室内培养 Laboratory incubation	森林 Forest	美国新罕布什尔州怀特山 White Mountains of New Hampshire, USA (43.93° N, 71.75° W)	砂土 Sandy, Base-poor spodosols	未过筛 Not sieved	0-5	2009-03	无前处理 No pre-treatment	Reinmann <i>et al.</i> , 2012
野外试验(雪被去除) Field experiment (Snow removal)	农田 Cropland	美国密西根州西南部的洛格生物站 Kellogg Biological Station, Southwest Michigan, USA (42.4° N, 85.4° W)	壤土 Loamy, Typic Hapludalfs (19% clay, 38% silt, 43% sand)	未过筛 Not sieved	-	2011-12-2012-03	-	Ruan & Robertson, 2017

表1 (续) Table 1 (Continued)

试验方法 Experimental method	生态系统 Ecosystem	研究地区 Location	土壤类型 Soil type	土壤处理 Soil treatment	土层 Soil depth (cm)	取土时间 Date of sampling soils	前处理 Pre-treatment	参考文献 Reference
室内培养 Laboratory incubation	农田 Cropland	德国慕尼黑北部农业生态系统研究站 The research station Scheyern of the Munich Research Alliance on Agroecosys- tem, north of Munich, Germany (42.42° N, 142.47° E)	Dystic Eutrochrept (20% clay, 51% silt, 20% sand)	过2 mm筛 Pass through 2 mm sieve	0-10	2001-04	4 °C培养17天 Incubation at 4 °C for 17 days	Selty <i>et al.</i> , 2004
室内培养 Laboratory incubation	农田 Cropland	加拿大魁北克省 Quebec, Canada (45.42° N, 75.93° W)	黏土 Clay, Orthic Humic Gleysol	未过筛 Not sieved	0-5	1995-10-05, 1995-11-27	5 °C培养5天 Incubation at 5 °C for 5 days	van Bochove <i>et al.</i> , 2000
室内培养 Laboratory incubation	农田 Cropland	加拿大新不伦瑞克省弗雷德里克顿 Fredericton, New Brunswick, Canada (45.87° N, 66.52° W)	壤土 Loam (11.5% clay, 39.5% silt, 49% sand)	过4.75 mm筛 Pass through 4.75 mm sieve	0-15	2010-10	4 °C培养14天 Incubation at 4 °C for 14 days	Wertz <i>et al.</i> , 2016
室内培养 Laboratory incubation	草地 Grassland	中国内蒙古 Nei Mongol, China (43.97° N, 116.72° E)	栗钙土 Chestnut soil (14.1% clay, 21.4% silt, 64.5% sand)	未过筛 Not sieved	0-40	2009-07	4 °C培养 Incubation at 4 °C	Wu <i>et al.</i> , 2014a
室内培养 Laboratory incubation	草地 Grassland	中国内蒙古大兴安岭西部呼伦贝尔草原 Hulun Buir Grassland, Western Da Hinggan Mountains, Nei Mongol, China (47.08°-53.33° N, 115.52°-126.07° E)	Chernozem and kastanozem (8.9% clay, 12.8% silt, 78.3% sand)	未过筛 Not sieved	0-40	2005-09	4 °C培养 Incubation at 4 °C	Wu <i>et al.</i> , 2020a
室内培养 Laboratory incubation	草地 Grassland	中国内蒙古 Nei Mongol, China (43.97° N, 116.72° E)	栗钙土 Chestnut soil (14.1% clay, 21.4% silt, 64.5% sand)	未过筛 Not sieved	0-40	2009-07	5 °C培养10天 Incubation at 5 °C for 10 days	Wu <i>et al.</i> , 2014b
室内培养 Laboratory incubation	草地 Grassland	中国青海省玛沁县 Maqên County, Qinghai Province, China (34.47° N, 100.2° E)	亚高山草甸土 Subalpine meadow soil (17% clay, 65% silt, 18% sand)	未过筛 Not sieved	0-20	2016-09	4 °C培养14天 Incubation at 4 °C for 14 days	Wu <i>et al.</i> , 2020b
室内培养 Laboratory incubation	草地/森林/农田 Grassland/Forest/ Cropland	日本东京大学 Tokyo University, Japan (36° N, 140° E)	砂壤土 Sandy loam, Andosol/Cambisol/Acrisol	过2 mm筛 Pass through 2 mm sieve	0-10	2002-03, 2002-09	28 °C培养7天 Incubation at 28 °C for 7 days	Yanai <i>et al.</i> , 2007
室内培养 Laboratory incubation	草地/湿地 Grassland/Wetland	中国内蒙古锡林河流域 The Xilin River catchment, Nei Mongol, China (43.43°-44.65° N, 115.53°-117.2° E)	(8.4% clay, 12.3% silt, 79.3% sand)/ (3.2% clay, 4.9% silt, 91.9% sand)	未过筛 Not sieved	0-40	2007-07	4 °C培养 Incubation at 4 °C	Yao <i>et al.</i> , 2010

clay, 黏粒; sand, 砂粒; silt, 粉粒。 “-”表示这个参数没有报道。

“-” indicates that this parameter was not reported.



图2 本研究所选冻融循环试验在全球的分布图。•, 样点。
Fig. 2 The distribution of the freeze-thaw cycles experiments selected in this meta-analysis in the world. •, site.

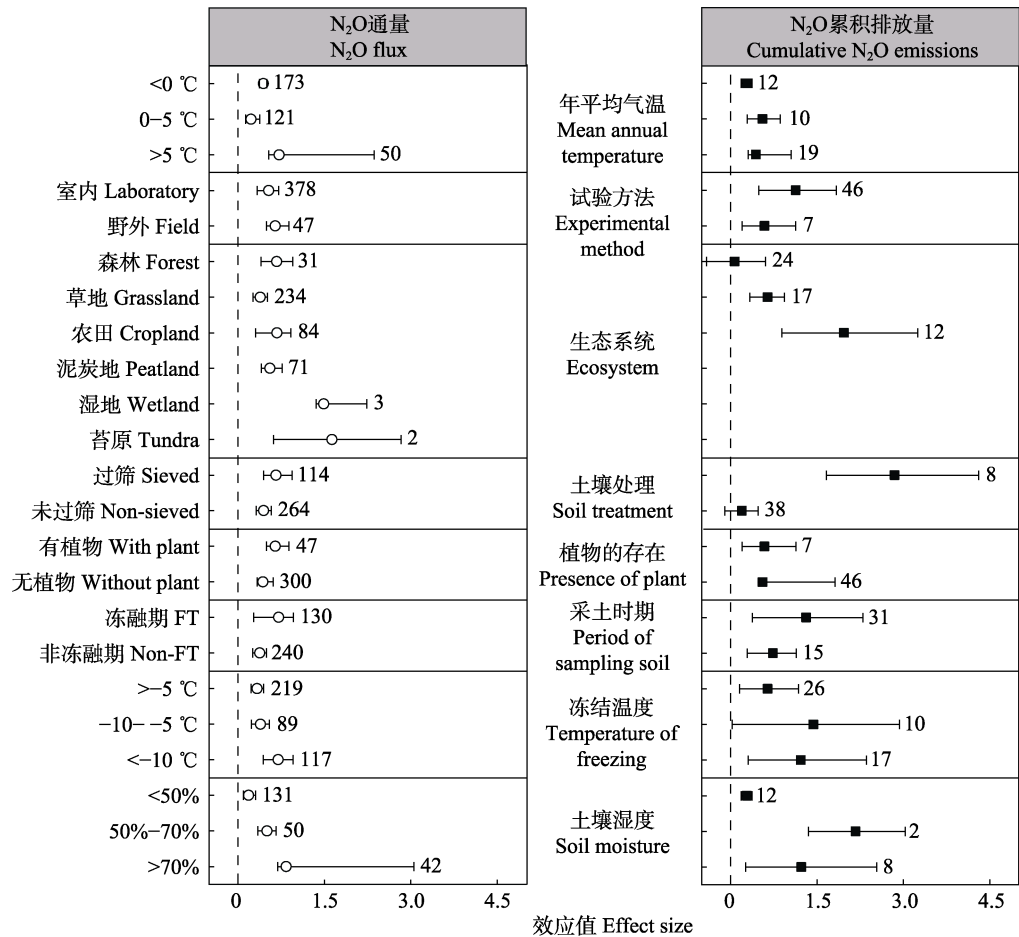


图3 冻融循环对土壤氧化亚氮(N₂O)通量和N₂O累积排放量的影响。这些变量被分成不同组, 包括年平均气温、试验方法、生态系统类型、土壤处理、植物的存在、采土时期、冻结温度以及土壤湿度。误差棒表示95%置信区间, 误差棒后面数值代表变量观察数。虚线表示效应值为0。
Fig. 3 Effects of freeze-thaw cycles on soil nitrous oxide (N₂O) flux and cumulative N₂O emissions. The variables are categorized into different groups according to mean annual temperature, experimental method, ecosystem type, soil treatment, presence of plant, period of sampling soil, temperature of freezing, and soil moisture. Error bars stand for 95% confidence intervals. The values next to the error bars represent the number of observations of the variable. Dashed line indicates that there is no effect. FT represents the freeze-thaw period.

量的效应值与土壤质地有一定相关性, 比如与土壤黏粒含量呈正相关关系($r = 0.27, p < 0.001$), 与土壤砂粒含量呈负相关关系($r = -0.22, p < 0.001$), 而与土壤粉粒含量无显著相关关系(图5; 附件I)。在土壤

养分中, 冻融循环对 N_2O 通量的效应值只与土壤硝态氮含量呈现显著正相关关系($r = 0.42, p < 0.001$), 而与土壤pH、有机碳含量、总碳含量、总氮含量、碳氮比、铵态氮含量、可溶性有机碳含量、可溶性

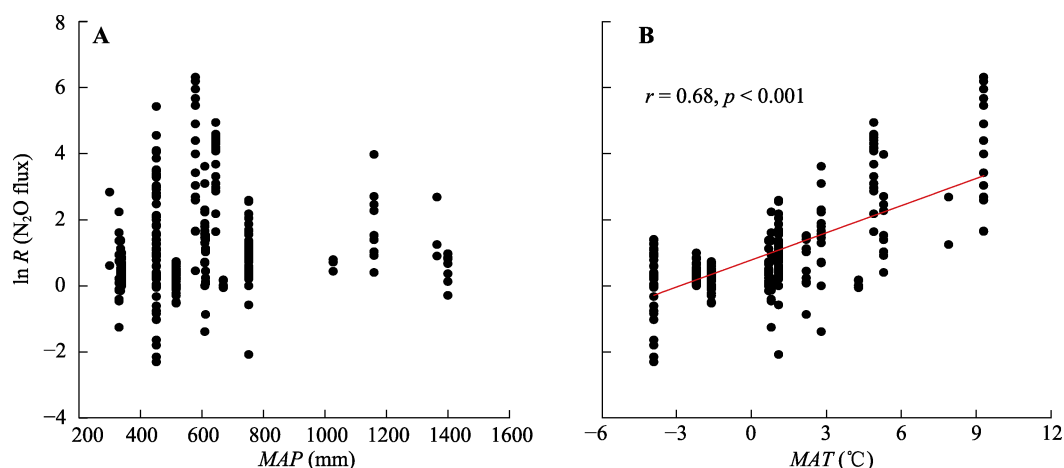


图4 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R (\text{N}_2\text{O} \text{ flux})$)与年降水量(MAP)(A)和年平均气温(MAT)(B)之间的相关关系。

Fig. 4 Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R (\text{N}_2\text{O} \text{ flux})$) and mean annual precipitation (MAP)(A) and mean annual temperature (MAT)(B).

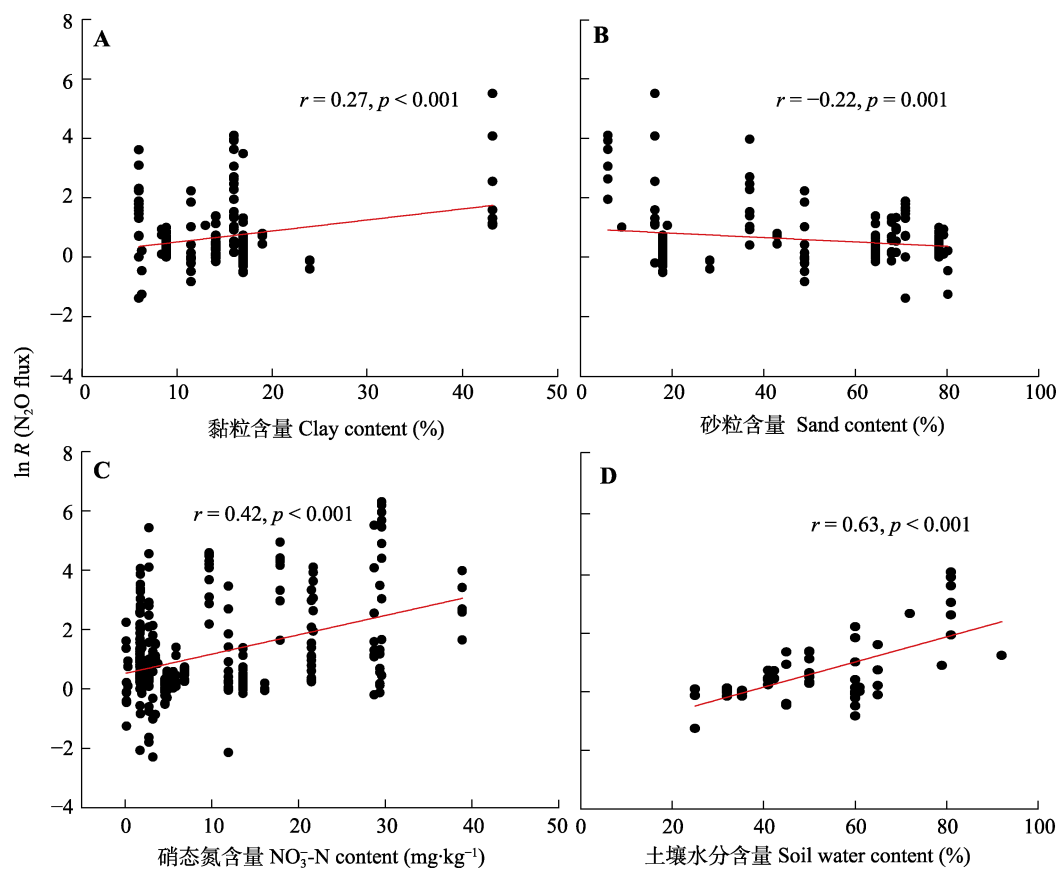


图5 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R (\text{N}_2\text{O} \text{ flux})$)与土壤基本理化性质之间的相关关系。本图只列出有显著相关关系的理化性质, 没有相关关系的见附件I。

Fig. 5 Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R (\text{N}_2\text{O} \text{ flux})$) and basic physical and chemical characteristics of soils. Those with significant relationships were shown in this figure, but those with non-significant relationships were shown in Appendix I.

有机碳与硝态氮含量比值无显著相关性。另外, 冻融循环对 N_2O 通量的效应值也与土壤湿度呈现极好的线性正相关关系($r = 0.63, p < 0.001$)。

由图6可得, 冻融循环对 N_2O 通量的效应值与冻融循环对反硝化作用速率的效应值呈显著正相关关

系($r = 0.72, p < 0.001$), 而与冻融循环对硝化作用速率的效应值无明显相关性。

冻融循环时间, 温度以及频率也会影响 N_2O 排放。根据图7可知, 冻融循环过程中土壤融化时间与冻融循环对 N_2O 通量效应值($r = 0.15, p = 0.003$)和

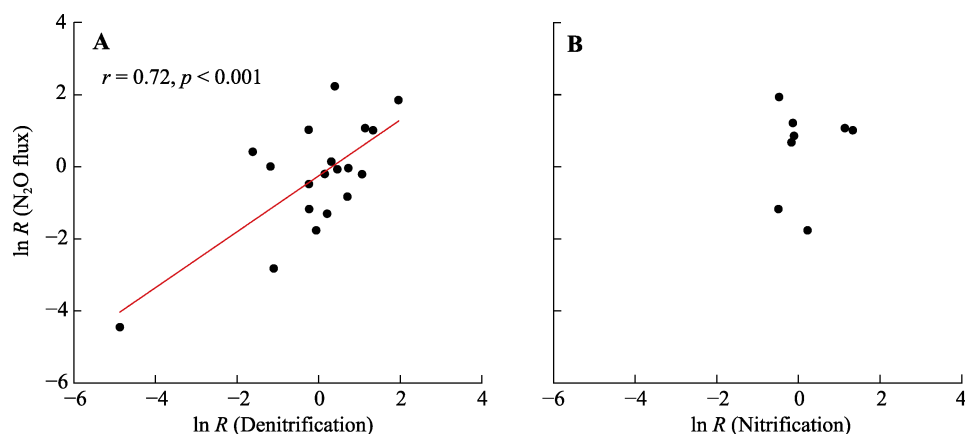


图6 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R(\text{N}_2\text{O flux})$)与冻融循环对反硝化作用速率的效应值($\ln R(\text{Denitrification})$)(A)和冻融循环对硝化作用速率的效应值($\ln R(\text{Nitrification})$)(B)之间相关关系。

Fig. 6 Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R(\text{N}_2\text{O flux})$) and the effect size of freeze-thaw cycle on denitrification rate ($\ln R(\text{Denitrification})$)(A) and the effect size of freeze-thaw cycles on nitrification rate ($\ln R(\text{Nitrification})$)(B).

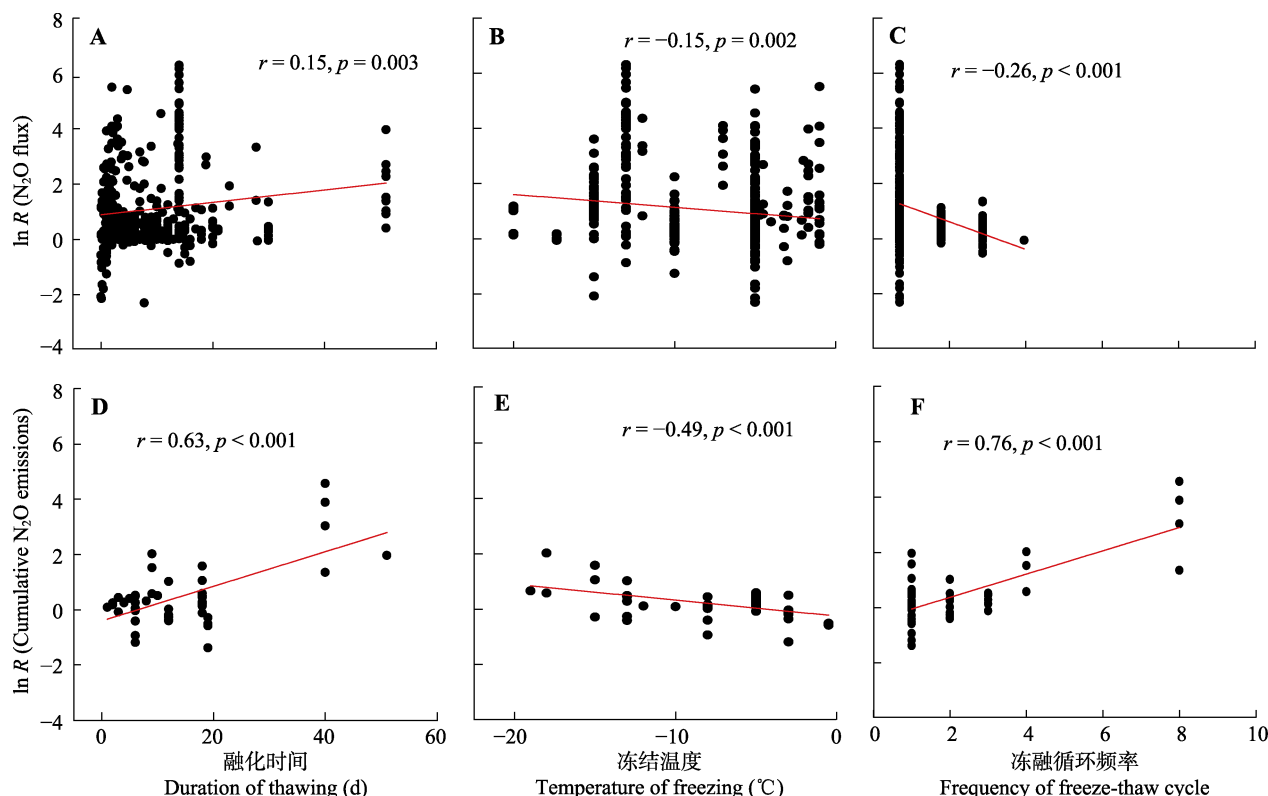


图7 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R(\text{N}_2\text{O flux})$)(A, B, C)和 N_2O 累积排放量的效应值($\ln R(\text{Cumulative N}_2\text{O emissions})$)(D, E, F)与冻融循环时间、温度以及频率之间的相关性。本图只列出有显著相关关系的理化性质, 没有相关关系的见附件II。

Fig. 7 Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R(\text{N}_2\text{O flux})$)(A, B, C) and cumulative N_2O emissions ($\ln R(\text{Cumulative N}_2\text{O emissions})$)(D, E, F) and the duration, temperature, and frequency of freeze-thaw cycles. Those with significant relationships were shown in this figure, but those with non-significant relationships were shown in Appendix II.

N_2O 累积排放量效应值($r = 0.63, p < 0.001$)均呈现显著线性正相关关系。与此相反, 冻结温度与冻融循环对 N_2O 通量效应值($r = -0.15, p = 0.002$)和 N_2O 累积排放量效应值($r = -0.49, p < 0.001$)均呈现显著线性负相关关系。另外, 冻融循环频率与冻融循环对 N_2O 通量效应值和累积排放量效应值的相关关系相反, 即分别为显著负相关关系($r = -0.26, p < 0.001$)和显著正相关关系($r = 0.76, p < 0.001$)。而其他冻融循环参数与 N_2O 排放之间并没有统计学意义上的显著相关性(附件II)。

3 讨论

本研究结果表明, 冻融循环可显著增加 N_2O 通量和累积排放量, 平均增幅达72.34%和143.25% (图1)。冻融循环主要通过破坏土壤结构, 杀死微生物和根系细胞以及破坏凋落物等途径促进土壤可利用性养分的释放(Yanai *et al.*, 2004; Freppaz *et al.*, 2007; Pelster *et al.*, 2013; Campbell *et al.*, 2014; Reinmann & Templer, 2016; Xiao *et al.*, 2019)。本研究也证实, 冻融循环可显著减少微生物生物量氮含量, 减幅可达6.39% (图1)。这些可溶性养分的增加, 一方面可为存活的微生物提供养分, 提高其活性; 另一方面这些养分可为氮转化过程提供充足的底物, 使土壤硝化作用和反硝化作用速率增强(图1), 在这些氮转化过程中会产生 N_2O , 从而增加了土壤 N_2O 的排放。在不同研究区域和冻融循环格局下, 土壤 N_2O 对冻融循环的响应有所差异, 下面探究这些差异是如何影响 N_2O 对冻融循环响应的。

3.1 不同区域土壤 N_2O 排放对冻融循环的响应不同

不同区域水热条件的差异会显著影响 N_2O 排放的效应值。比如, 本研究得出, 土壤水分与 N_2O 通量的效应值呈显著正相关关系(图5)。更进一步, 土壤 N_2O 通量在土壤湿度超过70%时最大, 其次是土壤湿度为50%–70%之间, 最后是其小于50%时。研究认为, 当土壤湿度在50%–70%之间时, 土壤以硝化作用为主, 超过75%时, 以反硝化作用为主(Seitzinger *et al.*, 2006)。在初春时期雪被的融化导致土壤水分含量过高, 因此冻融循环过程中 N_2O 的产生主要是反硝化作用的贡献(Gao *et al.*, 2018)。本研究也得出土壤 N_2O 的排放与反硝化作用速率呈显著正相关关系(图6)。主要原因是因为土壤水分增加一

方面可促使厌氧环境的形成, 有利于增强反硝化能力, 从而提高 N_2O 产生的潜力; 另一方面, 过多水分增加了冻融循环对土壤结构的破坏作用。因为水分在固态状态下体积会增加, 土壤晶格和团聚体在反复冻融过程中受到较大破坏(杨红露等, 2010), 导致其释放的养分增加, 从而提高了 N_2O 的产生。另外, 本研究还得出, 年平均气温也与 N_2O 排放通量效应值呈显著正相关关系(图4)。在 MAT 超过5 °C的样地, 土壤 N_2O 排放通量显著高于 MAT 低于5 °C的样地; 而土壤 N_2O 累积排放量并没有因采集土壤样品 MAT 的不同表现出差异(图2)。主要可能是因为 MAT 不同的地区土壤微生物适应性也不同。在 MAT 较低的地区, 土壤微生物对于低温适应性较强, 而 MAT 较高的环境下土壤微生物适应性较弱(Nottingham *et al.*, 2019), 冻融循环后, 微生物大量死亡而释放较多可利用性养分, 从而可暂时提高 N_2O 排放通量, 但是 N_2O 累积排放量并没有增加。

除了研究区域间的水热条件外, 土壤本身的理化性质也会影响土壤 N_2O 排放对冻融循环的响应。本研究结果显示, 土壤 N_2O 通量的效应值与土壤黏粒含量呈正比, 而与土壤砂粒含量呈反比(图5)。原因可能主要归功于两个方面: 一方面, 在特定的土壤温度下, 黏粒含量较高的土壤中所含液态水含量较高。例如, 在土壤温度为-5 °C时, 沙土中液体水含量可忽略不计, 而黏土中液体水可达 $0.15 \text{ cm}^3 \cdot \text{cm}^{-3}$ (Congreves *et al.*, 2018)。这种液态水的存在可为微生物在土壤冻结条件下继续保持一定的活性, 从而产生 N_2O 气体。另一方面, 黏粒含量高的土壤, 其养分含量也高, 这就为 N_2O 的产生提供充足底物。这一点也被本研究进一步证实, 即土壤硝态氮含量越高, N_2O 通量的效应值越大(图5)。有趣的是, 本研究得出 N_2O 排放的效应值只与硝态氮含量呈显著正相关关系, 而与铵态氮等其他有机、无机养分含量无显著相关性, 主要原因是与冻融循环期间 N_2O 产生途径有关。土壤 N_2O 气体产生途径包括硝化细菌的硝化作用、硝化细菌的反硝化、反硝化作用、联合反硝化作用和异化还原作用(Sánchez-García *et al.*, 2014; Hu *et al.*, 2015)。在冻融循环期间, 前人通过同位素标记技术(Ludwig *et al.*, 2004; Wagner-Riddle *et al.*, 2010), 控制氧分压(Öquist *et al.*, 2004), 乙炔抑制(Priemé & Christensen, 2001; Mørkved *et al.*, 2006)等方法均证实了反硝化作用是

冻融循环期间 N_2O 显著增加的主要贡献过程,其过程产生的 N_2O 可占总排放量的80%以上。主要原因是由于雪被的融化导致冻融循环期间水分较高,当土壤湿度超过75%时,土壤以反硝化作用为主(Seitzinger *et al.*, 2006),硝态氮是反硝化作用的重要底物之一,因此土壤 N_2O 排放的效应值与硝态氮含量表现出显著正相关关系。另外,反硝化的异化还原过程也可产生 N_2O ,可利用碳是调节硝态氮在反硝化和异化还原过程分配的关键因子(Fazzolari *et al.*, 1998),可溶性碳和硝态氮含量比值大于12时,才会有更多的硝酸盐的异化还原作用发生(Yin *et al.*, 1998)。前人通过整合分析也发现,冻融循环作用可显著增加土壤可溶性有机碳含量(Song *et al.*, 2017),有机碳源通过分解产生的电子被硝酸根或者亚硝酸根接受还原为 N_2O 和 N_2 。因此,可溶性碳和硝态氮含量共同决定了 N_2O 的排放。然而,本研究并没有发现可溶性有机碳和可溶性有机碳含量与硝态氮含量比值与 N_2O 排放有明显的相关性(附件I),可能是相关数据报道较少限制了揭示可溶性有机碳含量与 N_2O 排放之间的相关性或者可能是反硝化的异化还原过程产生的 N_2O 在冻融循环过程中的贡献较小。

虽然在不同研究地区冻融循环均会显著促进土壤 N_2O 的排放,然而土壤 N_2O 累积排放量在不同生态系统表现出明显差异,具体表现为农田>草地>森林(图3)。原因可能是农田生态系统土壤硝态氮含量高于其他生态系统,较高的硝态氮含量可为反硝化作用产生 N_2O 提供充足底物(Congreves *et al.*, 2018)。这点也间接被本研究结论所支持,即土壤硝态氮含量与土壤 N_2O 排放通量的效应值呈显著正相关关系(图5)。本研究还指出,在苔原或者湿地生态系统,冻融循环对 N_2O 排放通量的影响较其他生态系统下的大,主要原因可能是这些地区含有高的有机质和铵态氮含量,有利用异氧硝化和反硝化真菌的作用,从而产生更多 N_2O (蔡延江等, 2012)。一般养分含量较高的地区在冻融循环期间土壤 N_2O 排放会偏高,比如在农业系统中,每年30%–90%的 N_2O 排放归因于土壤冻融循环作用(Yanai *et al.*, 2011; Abalos *et al.*, 2016),因此在未来模型模拟预测全球农田 N_2O 排放时,需要特别考虑冻融循环作用的影响,否则会低估农田生态系统17%–28%的 N_2O 排放(Wagner-Riddle *et al.*, 2017)。

3.2 不同冻融循环格局的效应不同

冻融循环格局的改变也会显著影响土壤 N_2O 对冻融循环响应的大小。土壤融化时间与 N_2O 排放呈显著正相关关系(图7)。随着土壤融化时间的增加,反硝化细菌活性逐渐恢复,从而可能增加反硝化强度,进而增加 N_2O 产生与排放。随着冻结温度降低,土壤 N_2O 排放的效应值随之增加(图7)。当冻结温度低于 $-10\text{ }^{\circ}\text{C}$ 时,土壤 N_2O 排放通量要高于冻结温度大于 $-10\text{ }^{\circ}\text{C}$ 时(图3)。主要原因是冻结强度较高会增加土壤团聚体结构和微生物破坏(Fitzhugh *et al.*, 2001; Oztas & Fayetorbay, 2003; Zhou *et al.*, 2011),从而促进了可溶性有机碳和无机氮的释放,这些可溶性碳、氮含量的增加可促进硝化作用和反硝化作用速率,进而增加了土壤 N_2O 产生。另外,本研究结果表明,冻融循环频率与土壤 N_2O 通量呈显著负相关关系(图7)。随着冻融循环频率增加,土壤养分可通过微生物利用、淋洗损失以及土壤颗粒重吸附等方式降低(Grogan *et al.*, 2004; Yu *et al.*, 2010; Han *et al.*, 2018; Xiao *et al.*, 2019),使氮转化过程减慢,从而导致 N_2O 排放通量随之减少。有趣的是,本研究发现冻融循环频率与土壤 N_2O 累积排放量反而呈显著正相关关系(图7)。虽然随着冻融循环频率增加, N_2O 通量随之降低,这种降低是相对于第一次的 N_2O 通量值,而相对于对照组, N_2O 通量仍然是增加的。只是随着冻融循环频率增加,这种增加幅度在降低。因此,土壤 N_2O 累积排放量会随着冻融循环频率增加而增加。在未来气候变暖背景下,可能会减少雪被厚度和雪被存在时间(Groffman *et al.*, 2011),由于雪被起到隔热层作用,因此这些变化可能引起冻融格局发生改变,比如冻融循环时间、强度以及频率都会增加(杨开军等, 2017),这种改变可能会加剧土壤 N_2O 累积排放量,从而加剧全球气候温室效应和臭氧层破坏。

本研究得出,试验方法的差异并没有改变土壤 N_2O 排放对冻融循环的响应(图3)。前人在室内模拟冻融循环试验布局并不合理,比如土壤体积较小,冻融循环强度大,温度变化速率较快,采集土壤样品的时间不对等(Henry, 2007; Matzner & Borken, 2008; Song *et al.*, 2017; Gao *et al.*, 2018),这些与室外条件不切合的因素会导致土壤微生物在最初的冻融循环过程后超过半数的微生物死亡(Koponen *et al.*, 2006; Walker *et al.*, 2006; Sawicka *et al.*, 2010),

以及土壤团聚体受到破坏较大,从而使养分在最初的冻融阶段被大量释放出来,进而导致在冻融循环初期 N_2O 的排放通量陡然增加。然而随着冻融循环频率和时间的增加,养分很快被消耗, N_2O 排放通量表现出明显的下降趋势,甚至会低于对照条件下(Wu *et al.*, 2020b)。而在室外原位条件下,虽然在冻融循环初期, N_2O 排放通量增加幅度没有室内那么大,但在冻融循环过程中不断有养分供应,比如死亡的植物根系释放(Campbell *et al.*, 2014; Reinmann & Templer, 2016)和凋落物分解释放(Wieder *et al.*, 2011; Pelster *et al.*, 2013; 陈文静等, 2018)。这点也被本研究所证实,在有植物存在的条件下,土壤 N_2O 排放通量对冻融循环的响应大于在无植物存在的条件下(图3)。因此,随着冻融循环频率和时间的增加,在室外条件下 N_2O 排放通量表现为较为稳定的水平,而在室内培养条件下 N_2O 排放量表现为先增加后降低的趋势。最后计算两种条件在不同频率和时间的平均 N_2O 通量时,可能导致两种方法的平均 N_2O 通量并没有明显差异。

在室内研究中,土壤采样的时间和土壤的处理方式也会影响 N_2O 排放对冻融循环响应的大小(图3)。比如,与非冻融循环期间采集的土壤相比,在冻融循环期间采集的土壤 N_2O 排放效应值较大。原因可能与微生物特性和养分含量有关。在冻融与非冻融期间土壤微生物群落结构和微生物适应性是不同的(Zhang *et al.*, 2014)。在秋末至初冬,土壤反硝化细菌的数量明显高于夏季(Mergel *et al.*, 2001)。由于冻融循环期间土壤 N_2O 的产生主要是通过反硝化作用,因此反硝化细菌数量增多可提高反硝化作用速率,从而增加 N_2O 产生的量。相比于夏季,冬季土壤微生物对于温度的适应性较强(Zhang *et al.*, 2014),在经历温度的降低和升高时,仍然能保持较高的微生物活性,从而提高 N_2O 的产生。另外,土壤微生物量往往是冬季大于夏季(Alvarez *et al.*, 1995; Zhang *et al.*, 2014),在冻融循环过程中微生物死亡可释放更多可利用性养分,这就为冻融循环过程中 N_2O 的产生提供充足的底物。除了采集土壤的时间外,土壤处理方式也会影响 N_2O 排放对于冻融循环的响应。本研究得出,与土壤不过筛相比,土壤过筛会显著增加 N_2O 排放对冻融循环的响应(图3)。主要原因是过筛会破坏土壤结构。一方面土壤团聚体晶格结构的破坏会释放更多可利用性养分进入土壤(Xiao

et al., 2019),另一方面土壤过筛也会导致土壤胶体表面吸附的养分离子释放出来(Freppaz *et al.*, 2007),这些可利用性养分的增加可为 N_2O 产生提供充足的底物。在非冻融循环期间采集土壤和土壤过筛处理可能会分别导致冻融循环效应被低估和高估,因此为了得到真实的数据和探究其真正地内在机制,今后在室内研究冻融循环试验时,应尽量模拟原位条件。比如在真正野外冻融循环期间采集土壤样品以及野外采集的土壤样品不要过筛。

4 结论

本研究得出,冻融循环可显著增加 N_2O 排放通量、 N_2O 累积排放量和硝化作用速率,而显著减少了微生物量氮含量。另外,冻融循环也可增加反硝化作用速率,但不显著。土壤硝态氮含量越高,冻融循环对土壤 N_2O 排放的影响越大,主要是因为冻融循环中反硝化作用在 N_2O 排放中起主导作用。年平均气温、水分含量以及土壤黏粒含量等指标的增加都会促进 N_2O 对冻融循环的响应,主要原因是这些因素可显著促进土壤微生物和土壤结构释放更多养分,从而增加 N_2O 的产生。另外,融化时间长,冻结强度大和冻融循环频率高均可显著提高土壤 N_2O 累积排放量对冻融循环的响应。未来气候变暖可增加冻融循环的时间、强度和频率,从而可能会增加 N_2O 排放,尤其是对于养分含量和年平均气温较高的生态系统影响可能较大。因此在今后关于 N_2O 的排放模型预测研究中,需要考虑这些因素对于其排放的影响。为了准确预测土壤 N_2O 排放对冻融循环的响应,未来试验应侧重于室外原位研究或者在室内模拟试验中对土壤的处理方式尽量保持接近野外原位的状况。

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附件I 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R$ (N_2O flux))与土壤基本理化性质之间相关关系

Appendix I Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R$ (N_2O flux)) and basic physical and chemical characteristics of soils

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2021.0040-A1.pdf>

附件II 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R$ (N_2O flux))和 N_2O 累积量排放($\ln R$ (Cumulative N_2O emissions))与冻融循环的总时间、冻结时间以及融化温度之间相关关系

Appendix II Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R$ (N_2O flux)) and the effect size of freeze-thaw cycles on cumulative N_2O emissions ($\ln R$ (Cumulative N_2O emissions)) and the total duration, the duration of freezing, and temperature of thawing

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2021.0040-A2.pdf>

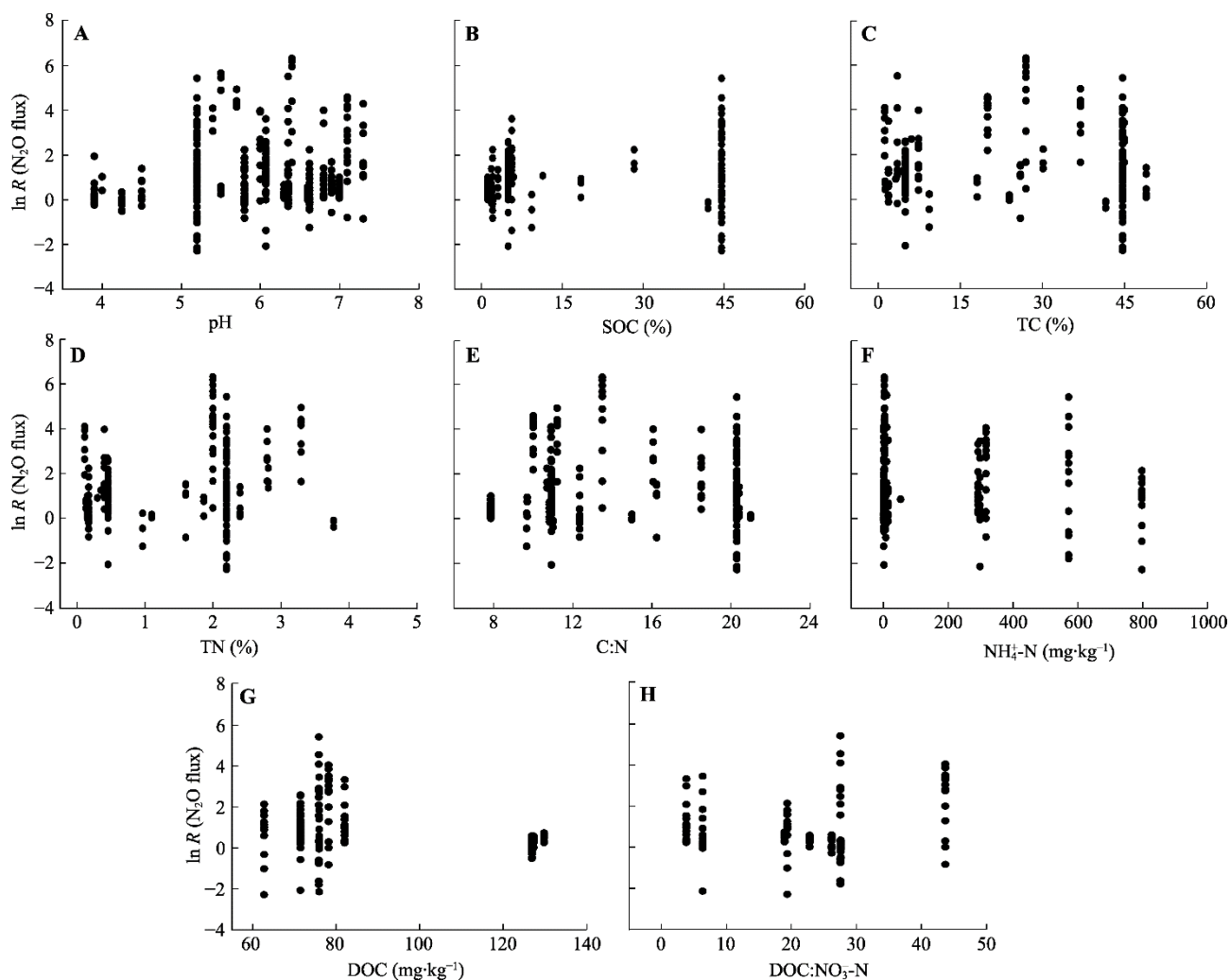
高德才, 白娥 (2021). 冻融循环期间土壤氧化亚氮排放影响因素. 植物生态学报, 45, 1006-1023. DOI: 10.17521/cjpe.2021.0040

Gao DC, Bai E (2021). Influencing factors of soil nitrous oxide emission during freeze-thaw cycles. *Chinese Journal of Plant Ecology*, 45, 1006-1023. DOI: 10.17521/cjpe.2021.0040

<https://www.plant-ecology.com/CN/10.17521/cjpe.2021.0040>

附件I 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R(\text{N}_2\text{O flux})$)与土壤基本理化性质之间相关关系

Appendix I Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R(\text{N}_2\text{O flux})$) and basic physical and chemical characteristics of soils



C:N, 土壤总碳与总氮比值; DOC, 可溶性有机碳; DOC:NO_3^- , 可溶性有机碳与硝态氮比值; NH_4^+ , 铵态氮; SOC, 土壤有机碳; TC, 土壤总碳; TN, 土壤总氮。

C:N, the ratio of soil total carbon to nitrogen; DOC, dissolved organic carbon; DOC:NO_3^- , the ratio of dissolved organic carbon to nitrate; NH_4^+ , ammonium; SOC, soil organic carbon; TC, soil total carbon; TN, soil total nitrogen.

高德才, 白娥 (2021). 冻融循环期间土壤氧化亚氮排放影响因素. 植物生态学报, 45, 1006-1023. DOI: 10.17521/cjpe.2021.0040

Gao DC, Bai E (2021). Influencing factors of soil nitrous oxide emission during freeze-thaw cycles. *Chinese Journal of Plant Ecology*, 45, 1006-1023. DOI: 10.17521/cjpe.2021.0040
<https://www.plant-ecology.com/CN/10.17521/cjpe.2021.0040>

附件II 冻融循环对土壤氧化亚氮(N_2O)通量的效应值($\ln R$ (N_2O flux))(A, B, C)和 N_2O 累积量排放($\ln R$ (Cumulative N_2O emissions))(D, E, F)与冻融循环的总时间、冻结时间以及融化温度之间相关关系

Appendix II Relationships between the effect size of freeze-thaw cycles on soil nitrous oxide (N_2O) flux ($\ln R$ (N_2O flux))(A, B, C) and the effect size of freeze-thaw cycles on cumulative N_2O emissions ($\ln R$ (Cumulative N_2O emissions))(D, E, F) and the total duration, the duration of freezing, and temperature of thawing

