

西北旱区农田土壤 N_2O 排放空间变化特征及影响因素探讨

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摘 要: 旱地农田土壤被认为是重要的 N_2O 排放源, 但排放通量及影响因素仍存在不确定性。对西北干旱半干旱地区农田土壤 N_2O 的排放分析表明, 全区 N_2O 排放通量相对较低, 20 世纪 80—90 年代呈波动式增长。 N_2O 排放的空间格局总体呈现从东南向西南逐渐减少的趋势。陕西地区排放量为 $75.58 \text{ t} \cdot \text{a}^{-1}$, 贡献了全区 50% 的 N_2O 排放。过量的氮肥施用、较高的降水量以及明显的增温效应是陕西南部 N_2O 排放增强的主要原因。

关键词: 农田土壤; N_2O ; 干旱半干旱地区

Spatial variation and influence factors of cropland N_2O emission in the Northwest Arid Area

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Abstract: *Background, aim, and scope* Upland soil is considered as an important source of N_2O emissions. At present there are many research about the field influence factors on N_2O emissions. However, in traditional rainfed agricultural region of Northwest China, it still lack of in-depth discussion about how these factors affect N_2O emissions synthetically at regional scale. In this study the change trend of N_2O emissions and its influence factors under climate fluctuation and management change were discussed based on regional simulation to support the future prediction of change of cropland N_2O emissions. *Materials and methods* Daily weather data for simulation were taken from the Modern-Era Retrospective Analysis for Research and Application (MERRA). Soil property data were collected from the national soil survey and the Chinese Soil Atlas. Crop parameters, fertilizer application rates were described in the database using agricultural census data and other sources. Twenty years simulation about the N_2O emissions of cropland in Northwest China were made based on these database. *Results* The analysis of the cropland N_2O emission in arid and semi-arid areas of Northwest China show that the regional N_2O flux is relatively low and reduced gradually from southeast to southwest with the

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decreasing precipitation and temperature overall. The lowest emissions appeared in Ningxia, which account for only 5% of total N_2O emissions. Shaanxi has the highest N_2O emission, accounting for 50% of the total N_2O emissions of the region. There showed significant regional difference and the highest flux appeared in southern Shaanxi. Through the 20 years average N_2O flux was $0.016 \text{ kgN}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$ and increased fluctuantly in Northwest China in the 1980s and 1990s. **Discussion** Fertilizer rate has decisive effect to the spatial distribution of N_2O emissions. High N_2O emissions value concentrated in southern Shaanxi and Guanzhong regions mainly due to excessive nitrogen fertilization application in these areas. In addition, this high N_2O emissions could be strengthened in southern Shaanxi because of the increased soil moisture caused by higher level of precipitation. However it should also be noticed that southern Shaanxi have higher temperature and is warming fastest. The increasing of soil temperature can promote N_2O emissions. Rising temperature can also promote soil water loss and inhibits N_2O emission when soil moisture is too low. The influence of climate factor on N_2O emissions changed according to different hydrothermal condition. **Conclusions** Cropland N_2O emissions in the Northwest Arid Area was relatively low. N_2O emissions reduced gradually from southeast to southwest. Excessive fertilization lead to high N_2O emissions in southern Shaanxi. High precipitation and significant warming can further enhance N_2O emissions. **Recommendations and perspectives** In the future strengthen the management and effective utilization of chemical fertilizer and water resource to reduce N_2O emissions should be the focus of northwest dryland farming management.

Key words: cropland soil; N_2O ; arid and semi-arid area

氧化亚氮 (N_2O) 是一种重要的温室气体。虽然 N_2O 含量低于 CO_2 , 但由于存留时间长 (Crutzen, 1970; Prather, 1998), 增温潜能高 (辐射强迫 $0.48 \text{ W}\cdot\text{m}^{-2}$) 等特点 (IPCC, 2007), 被认为是主要的温室气体。观测数据表明: 大气 N_2O 含量的增加主要是源于农业活动 (IPCC, 2007)。在中国, 农业源 N_2O 排放占排放总量的 92.43%, 其中 79.83% 为农田排放 (国家发展与改革委员会, 2004)。因此, 对各类农业系统中 N_2O 排放通量的分布及影响因素研究就成为了核心问题之一 (Smith, 1997)。

旱作农业是中国主要的农业系统之一 (信乃谄, 2002), 据估算旱地农田 N_2O 排放约占到全国农业排放总量的 78% (邢光熹和颜晓元, 2000)。中国西北地区作为传统的旱作农业区 (席承藩, 1984) 也就成为广受关注的区域。目前对 N_2O 排放的区域估算和田间影响因素已有大量研究, 表明土壤理化性质、氮素养分、温湿度变化等都会影响土壤 N_2O 排放通量 (徐文彬和洪业汤, 2000; Zheng et al, 2004; 王立刚等, 2008)。然而针对旱作农业, 在中国区域尺度这些因素综合作用如何, 会如何影响区域 N_2O 的排放变化还没有过多探讨。

DNDC (Denitrification-Decomposition Model) 模型主要模拟农田 (DNDC) (Li et al, 1994; Zhang et al, 2015)、森林 (PnET-DNDC) (Li et al, 2000; Stange et al, 2000) 和湿地 (Wetland-DNDC) (Zhang et al, 2002) 生态系统土壤碳、氮循环。模型根据气象、土壤、植被、土地利用和管理等模拟植物-土壤系统中各种环境因子的动态变化, 进而计算微生物参与的硝化、反硝化以及发酵等过程的反应速率, 从而追踪土壤物质的积累和转化。该模型已在世界范围得到广泛的验证和应用 (Cai et al, 2003; Babu et al, 2006; Beheydt et al, 2007), 在土壤生态系统的氮循环过程模拟上具有较强的可靠性 (Frolking et al, 1998; Brown et al, 2002; Grant et al, 2004)。

本文通过 DNDC 模型估算了我国西北地区旱作农田土壤 N_2O 排放的时空变化特征, 结合气象资料讨论了气候和管理措施变化背景下 N_2O 排放的变化趋势和可能影响因素, 旨在为未来区域尺度农田土壤 N_2O 的排放变化预测提供支持。

1 研究资料与方法

1.1 研究区域

本研究区域位于东经 $73^{\circ}41'$ — $111^{\circ}14'$, 北纬 $31^{\circ}43'$ — $49^{\circ}10'$, 包括陕西、甘肃、宁夏、青海、

新疆五省区的全部。区内地貌复杂,植被类型多样,地域差异明显。气候资源随海拔、纬度分配严重不均,总体热量不足、降水少、干旱问题突出。研究区内农业植被主要以一年制旱地作物和蔬菜为主,仅陕南及内陆少部分灌区有水稻种植(张小燕和杨改河,2005)。

1.2 研究资料

模拟所需气象资料包括1981—2000年日最高、最低温度和降水。降水采用MERRA数据(Rienecker et al, 2011)。土壤理化性质数据来源于全国土壤普查资料(全国土壤普查办公室,1993—1997)和中国土壤图集(1:14000000)(中国科学院南京土壤研究所,1986)。植被管理数据来源于农业普查和各种文献资料(崔读昌等,1984;刘巽浩和陈阜,2005)(<http://data.cma.gov.cn>)。基于西北地区典型耕作方式对西北地区农田土壤进行了20年模拟。模型参数中秸秆量估算据李长生等(2003),数据库中基肥施用量及灌溉参数来源自国家农业共享数据中心(<http://www.agridata.cn>)。

1.3 模型框架

DNDC模型含土壤气候、植物生长和有机质分解以及硝化、脱氮和发酵等模块。在区域模拟中,

首先利用西北地区的气象、土壤、植被、土地利用和农田耕作管理等数据建立基础数据库,其后调用数据库模拟植物-土壤系统中诸环境因子的动态变化,实现追踪农田土壤碳氮循环。数据库建立以及参数设置详见Zhang et al (2006)。

2 结果与讨论

2.1 西北地区农田 N_2O 排放的空间分布

西北地区气候资源分布地域性差异显著,热量资源以陕西南部、关中和新疆中部地区最高,日均温高于 10°C ,青海、新疆南部部分地区热量资源不足,年均温度较低。降水资源基本从东南部的陕西、甘肃向西北部的新疆地区过渡性减少(图1)。全区农田 N_2O 排放分布格局总体呈现从东南部向西南部随降水和温度降低而逐渐减少的趋势(图2)。宁夏地区排放最低,年排放量 $7\text{ t}\cdot\text{a}^{-1}$,仅占全区总排放的5%。青海和新疆地域面积广阔,但水热资源不协调,耕地仅占全区耕地总面积的26.64%, N_2O 排放基本低于 $20\text{ t}\cdot\text{a}^{-1}$ 。陕西地区最高,排放量为 $75.58\text{ t}\cdot\text{a}^{-1}$,耕地面积占全区的31%,但贡献了50%的 N_2O 排放,并且表现出显著的南北差异。陕西南部地区水热资源丰富,西北地区的水田作物及二熟、三熟作物主要种植在该地区,并有大面积的蔬菜种植, N_2O 排放系数较高。

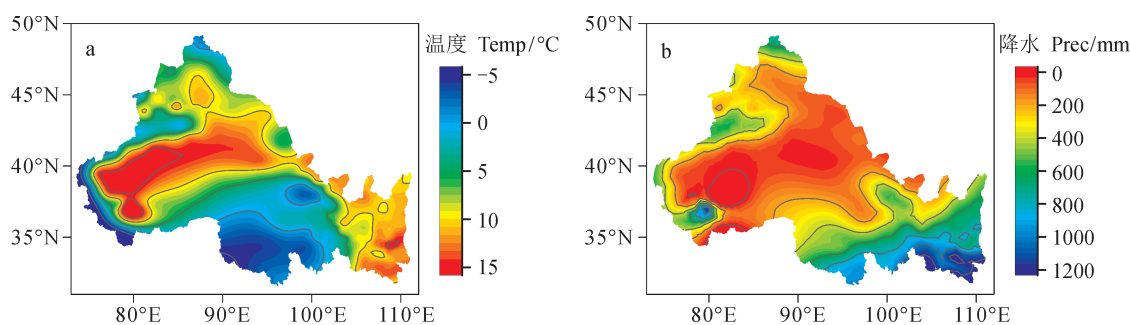


图1 西北地区年均温度及年均降水分布

Fig.1 Distribution of average annual temperature and precipitation in Northwest China

2.2 西北地区农田 N_2O 排放的时间序列变化

20世纪80—90年代整个西北地区 N_2O 排放总量呈波动式增长,20世纪80年代年平均排放总量为 $137.5\text{ t}\cdot\text{a}^{-1}$,90年代为 $163.7\text{ t}\cdot\text{a}^{-1}$,增幅19%(图3),20年平均 N_2O 排放通量为 $0.016\text{ kgN}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$ 。陕西地区年际变化明显,20年间平均排放通量为 $0.078\text{ kgN}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$,20世纪80年代排放通量为

$0.069\text{ kgN}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$,20世纪90年代增加了24%,达到 $0.086\text{ kgN}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$ 。甘肃地区20年间有微弱的 N_2O 排放增加,而宁夏、青海、新疆没有显著变化。

2.3 西北地区农田 N_2O 排放的影响因素

旱作农业区氮肥的施用会对 N_2O 排放具有明显促进作用,因此各省施肥量差异对西北地区 N_2O

排放的空间分布有决定性作用。全区排放量结果显示(图2)陕西年均排放通量较高,西北地区最高值集中出现在陕西南部 and 关中地区。1980年至2000年间,陕西地区是西北区氮肥用量最高的省份,总量达到77.8万吨,远高于其他省份(刘全清等,2005)。其中,关中地区施肥量严重过量,小麦田过量施用氮肥达 $55 \text{ kg} \cdot \text{hm}^{-2}$,玉米田间过量施肥 $56 \text{ kg} \cdot \text{hm}^{-2}$ (同延安等,2004)。笔者认为过量的氮肥施用是该地区 N_2O 排放明显较高的主要原因。由于我国农业肥料的平均利用率还较低(国家发展与改革委员会,2013),大量的氮肥施用还会进一步加剧土壤面源污染问题(张维理,2004)。因此该地区合理的化肥施用比例也是农业生态管理的重要问题。

各类田间试验的结果还显示,温度、降水的变化会影响 N_2O 排放(Magg and Vinther, 1996; Smith et al, 1998)。因此除施肥等管理条件的影响外,区域 N_2O 排放量变化还与气候变化相关。对降水而言,绝大多数西北地区属于干旱、半干旱气候,降水很少且季节性明显(丁一汇等,2013)。由于在土壤低湿度情况下, N_2O 排放与

降水量存在正相关性(郑循华等,1996;徐文彬等,2002;Zheng et al, 2004;张小燕和杨改河,2005)。在西北地区降水相对较高的陕西南部,这一因素可能加强了由于过量氮肥施用而导致的 N_2O 排放。降水和氮肥的综合效应使得该地区成为西北地区 N_2O 排放高值集中出现的区域。

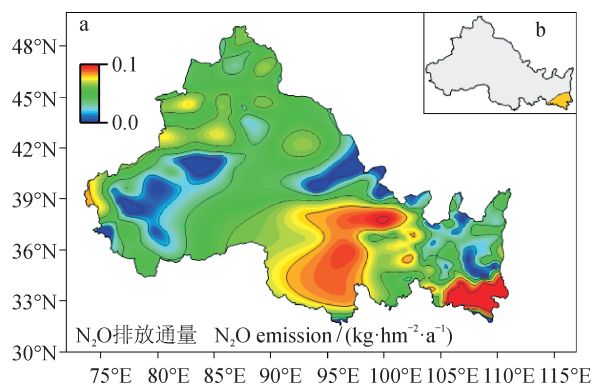


图2 西北地区农田土壤 N_2O 排放通量分布

a. 全区排放通量分布;

b. N_2O 排放和年际温度变化呈显著正相关区域

Fig.2 N_2O emission flux in cropland soil in Northwest China

a. N_2O emission flux; b. The area of significant correlation between temperature and annual N_2O emissions

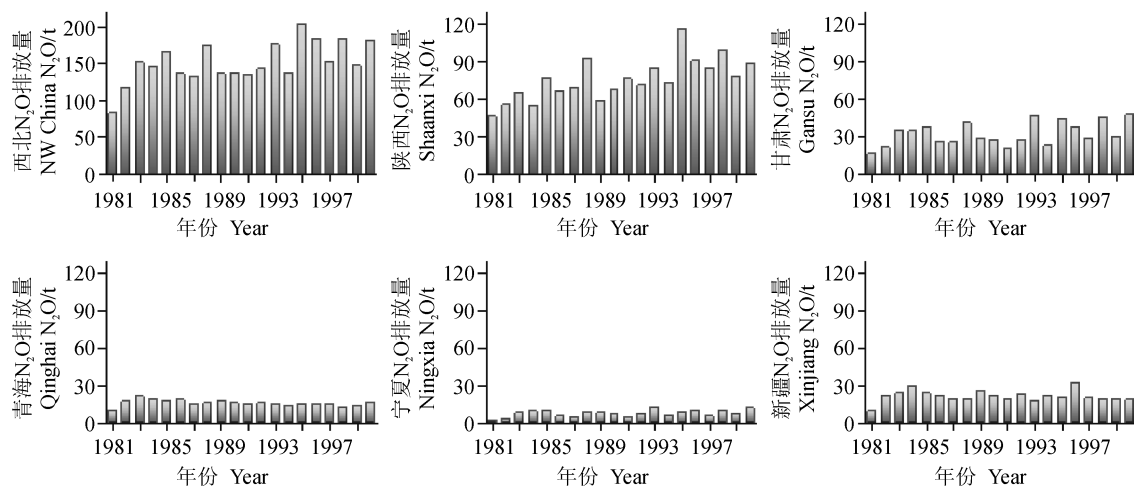


图3 西北地区1981—2000年农田土壤 N_2O 排放

Fig.3 N_2O emission in cropland soil in Northwest China from 1981 to 2000

但降水对 N_2O 年际变化的影响并不明显。从372个研究点的逐县相关分析结果看,仅甘肃中南部以及青海个别县的 N_2O 排放量与年降水表现出显著的正相关($p < 0.05$)。比如20世纪90年代在青海东南部地区、甘肃中南部降水略有减少

(刘德祥等,2005;时兴合等,2007),这一时段 N_2O 排放都有所降低。20世纪80年代青海地区 N_2O 排放量为 $0.029 \text{ kgN} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$,20世纪90年代下降为 $0.025 \text{ kgN} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ 。但在西北地区绝大多数区域,降水的年际变化与 N_2O 排放并没有

表现出确定的相关关系。在20世纪80—90年代西北降水整体表现为平稳的年际波动,时间上的变化幅度远小于各区域的空间差异,这可能是年际降水对N₂O排放影响不明显的主要原因。

对温度而言,适度的升温可以加强微生物活动,从而促进土壤硝化反硝化作用,因此温度一直被认为是农田N₂O排放的主要控制因子(陈卫卫等,2007;王立刚等,2008)。从N₂O排放量与年均温度的相关分析看,表现出显著正相关($p < 0.05$)的区域集中在整体高排放量的陕西南部地区(图2b)。由于20世纪80—90年代西北地区气温在20年间呈整体上升趋势(于淑秋等,2003),其中陕西南部整体温度较高且升温最快。因此这一区域土壤温度对N₂O排放具有很强的促进效应。但同时也应该注意到,温度升高会加剧土壤水分的散失,当土壤湿度过低时又会抑制N₂O排放。因此在其他低降水的区域,N₂O的排放并没表现出与温度的显著相关。低降水区域的温度对N₂O排放的促进可能被升温导致的干旱所抵消。因此气候因子对N₂O排放变化的影响根据不同的水热组合而具有区域差异。

3 结论

对西北干旱半干旱地区农田土壤N₂O排放估算分析表明,西北地区农田N₂O排放相对较低。农田土壤N₂O平均排放通量为 $0.016 \text{ kgN} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$,N₂O排放分布格局总体呈现从东南部向西南部逐渐减少的趋势。在西北地区,陕西南部N₂O排放量最高,过量的氮肥施用为主要原因。同时陕西南部较高的降水量以及明显的增温效应也会进一步增强N₂O排放。因此加强对农业氮肥和水资源的控制及合理有效利用,降低N₂O的排放潜力,应成为未来西北旱作农业的重点管理环节。

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