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若尔盖高原湿地不同微地貌区甲烷排放通量特征

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摘 要 若尔盖高原是我国泥炭沼泽湿地的主要分布区、青藏高原的主要甲烷(CH_4)排放中心。为了研究湿地微地貌环境对高原湿地CH_4排放通量的影响, 2014年5–10月, 采用静态箱和快速温室气体分析仪原位测量若尔盖高原湖滨湿地3种泥炭沼泽5种微地貌环境下的CH_4排放通量特征。结果表明: (1)常年性淹水泥炭湿地洼地(P-hollow)和草丘(P-hummock)生长季平均CH_4排放通量为68.48和40.32 $mg \cdot m^{-2} \cdot h^{-1}$, 季节性淹水的泥炭湿地洼地(S-hollow)和草丘(S-hummock)平均CH_4排放通量为2.38和0.63 $mg \cdot m^{-2} \cdot h^{-1}$, 而无淹水平坦地(Lawn)平均$CH_4$排放通量为3.68 $mg \cdot m^{-2} \cdot h^{-1}$; (2)湿地5种微地貌区$CH_4$排放通量为(23.10 ± 30.28) $mg \cdot m^{-2} \cdot h^{-1}$ (平均值±标准偏差)), 变异系数为131%。分析显示这5种微地貌区CH_4排放通量的平均值与其水位深度平均值存在显著的线性正相关关系(R^2 = 0.919, p < 0.01), 表明水位深度是控制湿地微地貌区CH_4排放通量空间变化的主要因子; (3) P-hummock、P-hollow和S-hummock的CH_4排放通量存在显著的季节变化, Lawn和S-hollow无明显的季节性变化, 但5种微地貌区在夏季或秋季均观测到CH_4排放通量峰值, 其影响因子可能与水位深度、土壤温度和凋落物输入密切相关; (4) P-hollow可能时常发生冒泡式CH_4排放, 这可能导致过去低估了若尔盖高原湿地的CH_4排放量。

关键词 甲烷排放通量; 草丘; 洼地; 平坦地; 若尔盖高原湿地

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Characteristics of methane emission fluxes in the Zoigê Plateau wetland on microtopography

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Abstract

Aims The Zoigê Plateau, as a very important wetland distribution region of China, was the major methane (CH_4) emission center of the Qinghai-Xizang Plateau. The objective of this study is to study the effects of microtopographic changes on CH_4 emission fluxes from five plots across three marshes in the littoral zone of the Zoigê Plateau wetland.

Methods CH_4 emission fluxes were measured in five plots across three marshes in Zoigê Plateau wetland using the closed chamber method and Fast Greenhouse Gas Analyzer from May to October in 2014.

Important findings During the growing season, mean CH_4 emission fluxes from the permanently flooded hollow (P-hollow) and hummock (P-hummock) in the Zoigê Plateau wetland were 68.48 and 40.32 $mg \cdot m^{-2} \cdot h^{-1}$, while mean CH_4 emission fluxes from the seasonally flooded hollow (S-hollow) and hummock (S-hummock) were 2.38 and 0.63 $mg \cdot m^{-2} \cdot h^{-1}$. CH_4 emission fluxes from non-flooded lawn was 3.68 $mg \cdot m^{-2} \cdot h^{-1}$. Mean CH_4 emission fluxes from five plots across three sites was 23.10 $mg \cdot m^{-2} \cdot h^{-1}$, with a standard deviation of 30.28 $mg \cdot m^{-2} \cdot h^{-1}$ and the coefficient of variation was 131%. We also found that there was a significant and positive correlation between mean CH_4 emission fluxes and mean water table depth in the five plots across three sites (R^2 = 0.919, p < 0.01), indicating that water table depth was controlling the spatial variability of CH_4 emission fluxes from the Zoigê Plateau wetland on microtopography. CH_4 emission fluxes in the P-hollow, P-hummock, and S-hummock showed an obvious seasonal pattern, which was not observed in the lawn and S-hollow. However, CH_4 emission peaks were observed in all the plots during summer and/or autumn, which could be closely related to the water table depth, soil temperature, and the magnitude of litter mass. In addition, we found that the CH_4 emission flux in the P-hollow was much higher than the other four plots in the Zoigê Plateau wetland, suggesting

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that CH_4 in the P-hollow could be often transported to the surface by ebullition and CH_4 emission from the Zoigê Plateau wetland may be under estimated in the past.

Key words CH_4 emission flux; hummock; hollow; lawn; Zoigê Plateau wetland

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甲烷(CH_4)是一种重要的温室气体, 它比CO_2活跃, 其单分子的增温效应为CO_2的28倍(IPCC, 2013)。由于人类活动的影响, 大气中的CH_4含量已从1750年的0.722 μmol·mol^{-1}上升到2011年的1.803 μmol·mol^{-1}, 升高了约2.5倍(IPCC, 2013)。虽然在1999–2006年大气中的CH_4含量趋于稳定, 但从2007年开始, 大气CH_4含量再次升高(Rigby *et al*., 2008; Kirschke *et al*., 2013), 这主要是由于湿地、稻田和生物质燃烧排放的CH_4增加(Chen & Prinn, 2006; Kirschke *et al*., 2013)。因此, CH_4的源/汇问题仍是目前研究的热点, 加强CH_4源/汇问题的研究对于认识和预测CH_4在全球气候变暖过程中的作用具有重要意义。

自然湿地是大气CH_4的重要排放源, 年排放量为177–284 Tg (1 Tg = 10^{12} g), 约占全球CH_4排放量的26%–42% (IPCC, 2013), 排放量的不确定, 一是由于不同湿地的CH_4排放存在时空变化格局(Whalen & Reeburgh, 1992; Huttunen *et al*., 2003; Inubushi *et al*., 2005; Chen *et al*., 2008; Glagolev *et al*., 2011; 黄璞祎等, 2011; McEwing *et al*., 2015; Song *et al*., 2015), 二是因为气候变化(IPCC, 2013; Munir & Strack, 2014)。湿地CH_4排放经由厌氧条件下产CH_4菌生成CH_4和需氧条件下氧化CH_4菌氧化CH_4两种微生物过程, 以扩散、冒泡和植物传输3个过程排放CH_4 (Le Mer & Roger, 2001; 王智平等, 2003; Lai, 2009; McEwing *et al*., 2015)。这3个过程受许多环境因子(温度、水位深度、底物活性和植物类型)影响(Mikkelä *et al*., 1995; 丁维新和蔡祖聪, 2002; Inubushi *et al*., 2005; McEwing *et al*., 2015; Wei *et al*., 2015)。由于湿地(如泥炭地)形成了多种生态系统及其系统内异质性地貌(Lai, 2009; Glagolev *et al*., 2011; Munir & Strack, 2014; Song *et al*., 2015; Wei *et al*., 2015), 不同水位深度条件下, 植被和土壤温度具有差异, 进而导致CH_4排放通量存在时空变化(Dise, 1993; 王智平等, 2003; Hirota *et al*., 2004; Wei *et al*., 2015)。目前, 国外有关泥炭地微地貌区CH_4排放的研究较多(Dise, 1993; Mikkelä *et al*., 1995; Waddington & Roulet, 1996; Glagolev & Shnyrev, 2008; Kalyuzhnyi *et al*., 2009; Munir & Strack, 2014), 而国内有关这方面的研究鲜有报道(Wei *et al*., 2015)。因此, 进一步研究有助于人们深刻理解不同空间湿地CH_4排放对环境变化的响应机制和精确预算区域湿地CH_4排放量。

若尔盖高原(101.60°–103.50° E, 32.33°–34.00° N, 平均海拔为3 400 m)泥炭沼泽面积约为4 038 km^2, 是我国面积最大的高原泥炭沼泽分布区(王德宣等, 2002), 也是青藏高原东部边缘的CH_4排放源(Jin *et al*., 1999)。近10年来, 国内专家研究若尔盖高原泥炭沼泽湿地CH_4排放特征(王德宣等, 2002; Ding *et al*., 2004; Hirota *et al*., 2004; Chen *et al*., 2008; 王德宣, 2010; 李丽等, 2011; Song *et al*., 2015), 取得了一定的成果, 为理解高原湿地碳循环和CH_4排放机理提供了一定理论基础。然而, 若尔盖高原泥炭沼泽微地貌区(草丘和洼地) CH_4排放的时空变化格局鲜有报道。Wei等(2015)报道了青藏高原两种海拔高度(4 758和4 320 m)的湿地微地貌区(草丘和洼地) CH_4排放特征, 结果表明其影响因子较多, 存在时间和空间上的差异, 区域CH_4排放量仍存在较大的不确定性, 这将不利于我们深刻理解高原湿地CH_4排放对环境变化和气候变化的响应机制, 以及精确预算我国高原湿地CH_4排放量。

1 研究区概况和研究方法

1.1 研究区概况

本研究地点(33.92° N, 102.82° E, 海拔为3 441 m)位于若尔盖湿地自然保护区。若尔盖湿地2008年被列入《湿地公约》的国际重要湿地名录。该地属于寒温带湿润气候, 11月至次年4月受西伯利亚和蒙古的冷空气控制, 5至10月受西南季风控制, 年平均气温为1 ℃, 最暖月7月平均气温为10.7 ℃, 最冷月1月平均气温–10.3 ℃ (王智平等, 2003; Ding *et al*., 2004)。年降水量650 mm, 降水集中在6–9月, 相

对湿度78% (王智平等, 2003)。

研究地点位于花湖湖泊边缘，有3种水位深度的泥炭湿地: 常年性淹水、季节性淹水和地表无淹水。在这3种泥炭湿地，常年性淹水泥炭湿地位于湖泊边缘，季节性淹水泥炭湿地位于湖泊外围，地表无淹水泥炭湿地位于前两个样地之间的过渡带。常年性淹水和季节性淹水泥炭湿地均形成了微地貌草丘(hummock)和洼地(hollow)，这两种微地貌面积所占比例约为55%和45%。共有5种微地貌，其植物类型如下: (1)常年性淹水草丘(P-hummock)主要植物为木里薹草(*Carex muliensis*); (2)常年性淹水洼地(P-hollow)主要植物为沉水植物小眼子菜(*Potamogeton pusillus*)和狸藻(*Utricularia vulgaris*)，伴生稀疏的木里薹草; (3)季节性淹水草丘(S-hummock)主要植物为西藏嵩草(*Kobresia tibetica*)，伴生具刚毛荸荠(*Eleocharis valleculosa*)、蕨麻(*Potentilla anserina*)和花葶驴蹄草(*Caltha scaposa*); (4)季节性淹水洼地(S-hollow)主要植物为木里薹草; (5)过渡带平坦地(lawn)主要植物为西藏嵩草和花葶驴蹄草。土壤类型为泥炭沼泽土，土壤理化性质见表1。

1.2 研究方法

1.2.1 样地设置

2014年4月下旬，在花湖湖滨湿地5种微地貌区各建立3个标准样地(20 m × 20 m)，在5种微地貌区各安装静态箱底座3个(n = 3)，共15个。底座由不锈钢制作(规格为50 cm × 50 cm × 20 cm)，底座上口四周有5 cm高度的水槽，下口插入土壤15 cm，底座永久保留在实验地土壤中。同时，在常年性淹水样地，用直径15 cm的原木搭建栈道，通过铁钉固定，防止取样时人为对土壤的干扰。

1.2.2 CH_4气体测量

通过静态箱法(Chen *et al*., 2008; McEwing *et al*., 2015)采集CH_4。静态箱由底座、中箱(50 cm × 50 cm × 50 cm)和顶箱(50 cm × 50 cm × 50 cm)组成(孙晓新等, 2009)。常年性淹水P-hollow采用底座、中箱和顶箱测量CH_4气体，其他微地貌区采用底座和顶箱测量CH_4气体。中箱和顶箱由薄的铝材料制成，中箱上口四周有5 cm高度的水槽，防止气体泄露，为了使箱内温度稳定，中箱和顶箱外包装塑料泡沫，顶箱内部有2个5 cm × 5 cm的风扇，顶箱上部中央附有直径为2 cm的2个橡皮塞小圆孔，连接快速温室气体分析仪器(Model GGA-24EP, Los Gatos Research, San Jose, USA)的2根附有橡皮塞的透明导气管,长度4 m (内径为4 mm)(Mastepanov *et al*., 2008; McEwing *et al*., 2015)，仪器通过12 V蓄电池供电，数据采集设置为1 Hz (Mastepanov *et al*., 2008)。启动仪器后，测量CH_4排放通量时，静态箱与底座水槽密闭后，密闭箱内空气进入分析仪，并通过2根透明导气管来回在分析仪器内无损坏地循环分析CH_4浓度变化。每次气体测量之前，在底座水槽注满水，启动仪器，等待仪器启动显示的顶箱内部大气CH_4浓度稳定为当地环境气体CH_4浓度($8.04×10^{-8}$ mol·L^{-1})时，将静态箱扣在底座或中箱上，密闭测量3–5 min，然后揭开静态箱置于开放状态，约为2 min，然后密闭测量下一个静态箱底座，循环操作以上过程。测量时间为2014年5–10月北京时间9:00–11:30，观测频率为每月2次。CH_4排放通量是以封闭箱内顶部的CH_4浓度随时间变化的直线斜率计算(Mastepanov *et al*., 2008; McEwing *et al*., 2015)，回归方程决定系数$R^2 \geqslant 0.90$；当$R^2 < 0.90$时，

表1 若尔盖高原湿地5种微地貌土壤理化性质(平均值±标准偏差)
Table 1 Soil physical and chemical properties from the Zoigê Plateau wetland on five microtopography (mean ± *SD*)

样点 Plot	pH (0–10 cm depth)	土壤有机碳含量 Soil organic carbon content (0–30 cm depth) (g·kg^{-1})	土壤容重 Bulk density (0–30 cm depth) (g·cm^{-3})	总氮 Total nitrogen (0–10 cm depth) (g·kg^{-1})	地上生物量 Aboveground biomass (g·m^{-2})
P-hummock	7.6 ± 0.1	210.38 ± 47.29	0.29 ± 0.09	15.20 ± 3.50	127.16 ± 8.11
P-hollow					279.34 ± 35.54
Lawn	7.5 ± 0.3	143.21 ± 10.03	0.52 ± 0.08	18.05 ± 0.00	142.28 ± 95.61
S-hummock	7.5 ± 0.2	151.74 ± 74.15	0.40 ± 0.16	8.91 ± 3.85	189.74 ± 72.79
S-hollow					194.01 ± 50.07

Lawn, 常年性淹水与季节性淹水点之间的过渡带平坦地; P-hollow, 常年性淹水洼地; P-hummock, 常年性淹水草丘; S-hollow, 季节性淹水洼地; S-hummock, 季节性淹水草丘。
Lawn, transitional zones between permanently flooded and seasonally flooded sites; P-hollow, permanently flooded hollow; P-hummock, permanently flooded hummock; S-hollow, seasonally flooded hollow; S-hummock, seasonally flooded hummock.

数据不作为CH_4排放通量计算, 其比例为3.8% (包含P-hollow的两个瞬时值过大(592.44和327.82 mg·m^{-2}·h^{-1}), 尽管$R^2 > 0.90$)。CH_4排放通量的计算公式(孙晓新等, 2009; McEwing *et al*., 2015)如下:

$$F = \frac{d_c}{d_t} \times \frac{M}{V_0} \times \frac{P}{P_0} \times \frac{T}{T_0} \times \frac{V}{A}$$

式中: F为CH_4排放通量(mg·m^{-2}·h^{-1}); M为被测气体的摩尔质量, V为箱内空气体积; A为静态箱底面积(0.25 m^2); d_c/d_t代表CH_4浓度随时间变化的直线斜率; V_0、T_0和P_0分别为标准状态下的CH_4气体摩尔体积(22.4 L·mol^{-1})、空气绝对温度(273.15 K)和气压(1 013.25 hPa); P为采样地点的气压; T为采样时箱内的绝对温度。

测量CH_4排放通量时, 采用数字温度计测量6种深度(5、10、15、20、30和45 cm)的土壤温度。通过在静态箱附近挖井约70 cm测量土壤水位深度, 而常年性淹水点直接测量地表水位深度值, 2014年8月中旬测量地上生物量, 采集3个重复样方面积为50 cm × 50 cm的地上生物量, 运输到实验室恒温箱70 ℃烘干至恒质量, 称量。另外, 在3种类型的泥炭沼泽中取0–30 cm深度土壤测量土壤理化性质(表1)。

1.2.3　数据统计

采用t检验比较3种湿地5种微地貌区之间的CH_4排放通量差异; 采用单因素多重配对Duncan分析CH_4排放通量的季节性变化; 采用Pearson相关系数评价CH_4排放通量与土壤温度、水位深度和地上生物量的相关关系。所有数据采用SPSS 18.0软件包进行分析; 图表中数据为平均值±标准偏差(mean ± *SD*)。显著水平$p = 0.05$; 极显著水平$p = 0.01$。

2　结果和分析

2.1　若尔盖高原湿地微地貌区CH_4排放通量的时空变化

若尔盖高原湿地5种微地貌区CH_4排放通量如图1所示。2014年5–10月CH_4排放通量观测期间, 湿地3种微地貌区(P-hummock、P-hollow和S-hummock) CH_4排放通量存在极显著的季节性变化($p < 0.01$), 而湿地Lawn和S-hollow两种微地貌区CH_4排放通量无显著季节变化($p > 0.05$)。P-hummock的CH_4排放通量曲线为单峰, 5月初排放通量较低(14.44 mg·m^{-2}·h^{-1}), 随后大幅升高(32.73–56.52 mg·m^{-2}·h^{-1}), 在9月初达到峰值(76.86 mg·m^{-2}·h^{-1}),

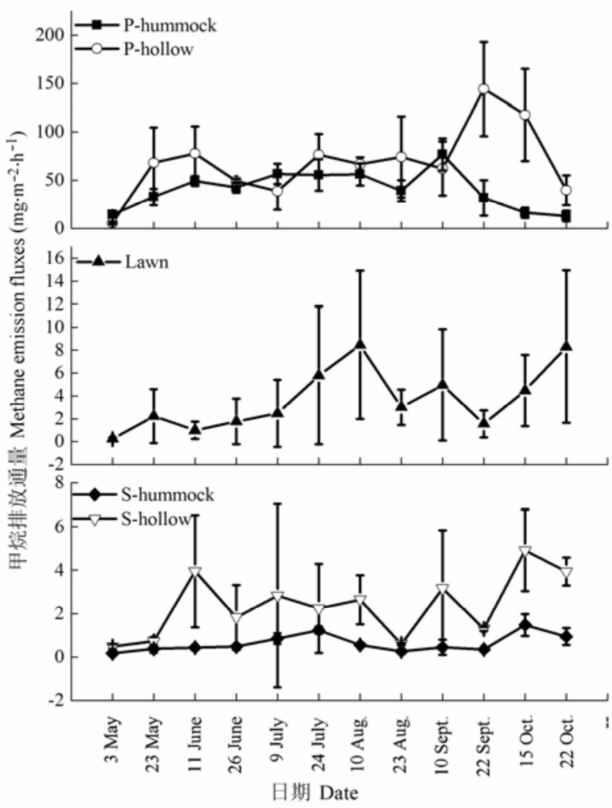

图1　若尔盖高原湿地5种微地貌区2014年CH_4排放通量季节性变化(平均值±标准偏差)。Lawn, 常年性淹水与季节性淹水点之间的过渡带平坦地; P-hollow, 常年性淹水洼地; P-hummock, 常年性淹水草丘; S-hollow, 季节性淹水洼地; S-hummock, 季节性淹水草丘。

Fig. 1　Seasonal variations of CH_4 emission fluxes from Zoigê Plateau wetland on five microtopography in 2014 (mean ± *SD*). Lawn, transitional zones between permanently flooded and seasonally flooded sites; P-hollow, permanently flooded hollow; P-hummock, permanently flooded hummock; S-hollow, seasonally flooded hollow; S-hummock, seasonally flooded hummock.

10月底达到最低值; P-hollow的CH_4排放通量曲线为3峰, 5月初最低值为5.78 mg·m^{-2}·h^{-1}, 随后也大幅增加, 6月11日和7月24日出现2个小峰值, 9月底达到最大峰值(144.43 mg·m^{-2}·h^{-1}), 10月底回到较低水平。S-hummock的CH_4排放通量曲线为双峰型, 5月初排放通量最低(0.17 mg·m^{-2}·h^{-1}), 直到7月底达到次峰值(1.24 mg·m^{-2}·h^{-1}), 随后降低, 10月中旬达到最大峰值(1.48 mg·m^{-2}·h^{-1}); Lawn和S-hollow生长季CH_4排放通量无明显的季节变化, 曲线为双峰型, 峰值出现在6月初、8月初或秋末, 排放通量范围分别为0.23–8.45和0.48–4.91 mg·m^{-2}·h^{-1}。

若尔盖高原湿地5种微地貌区P-hummock、P-hollow、Lawn、S-hummock、S-hollow生长季CH_4

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排放通量分别为(40.32 ± 19.78)、(68.48 ± 36.23)、(3.68 ± 2.73)、(0.63 ± 0.41)、(2.38 ± 1.45) $mg \cdot m^{-2} \cdot h^{-1}$ (平均值±标准偏差), 中值依次为40.81、67.51、2.74、0.46和2.44 $mg \cdot m^{-2} \cdot h^{-1}$, 它们之间的$CH_4$排放通量平均值存在显著差异($p < 0.05$)。P-hollow的$CH_4$排放通量最高, 是S-hummock的108倍, Lawn和S-hollow之间的CH_4的排放通量倍数相差最小, 但也达1.6倍。为了准确地预算区域CH_4排放量, 常年性淹水湿地生长季CH_4排放通量(草丘和洼地面积比例55: 45)为(52.99 ± 19.57) $mg \cdot m^{-2} \cdot h^{-1}$ (平均值±标准偏差); 季节性淹水湿地生长季CH_4排放通量(草丘和洼地面积比例55:45)为(1.42 ± 0.82) $mg \cdot m^{-2} \cdot h^{-1}$ (平均值±标准偏差)。

2.2 若尔盖高原湿地微地貌区CH_4排放通量与土壤温度和水位深度的相关性

Pearson相关性分析表明P-hummock与5–30 cm土壤温度显著相关(n =12, $p < 0.05$)或极显著相关(n = 12, $p < 0.01$), 其他4种微地貌区CH_4排放与土壤温度不显著相关($p > 0.05$), 但S-hummock剔除10月份数据后, CH_4排放通量与10–30 cm土壤温度显著相关(n = 10, $p < 0.05$)(表2)。5种微地貌区生长季CH_4排放通量与水位深度存在极显著线性正相关关系(n = 5, $p < 0.01$) (表2)。

3 讨论和结论

3.1 若尔盖高原湿地微地貌区CH_4排放通量的季节性变化

除了本研究湿地常年性淹水P-hollow CH_4排放通量范围(5.78–144.3 $mg \cdot m^{-2} \cdot h^{-1}$)稍大于其他研究(见表3列出的参考文献)的高原湿地CH_4通量范围(–0.81–86.78 $mg \cdot m^{-2} \cdot h^{-1}$)以外, 其他4种微地貌区$CH_4$排放通量范围(0.17–76.86 $mg \cdot m^{-2} \cdot h^{-1}$)均在其他研究的高原湿地$CH_4$通量范围内(表3)。

本研究湿地5种微地貌区CH_4排放通量峰值出现在夏季(6–8月)或秋季(9–10月)(图1), 与以往研究结果(Dise, 1993; Chen *et al*., 2008; 孙晓新等, 2009; 黄璞祎等, 2011; Wei *et al*., 2015)一致。夏季CH_4排放通量高的原因可能是夏季温度较高(图2), 促进湿地植物的生长、分蘖, 为CH_4产生提供充足的有机底物和传输通道(宋长春等, 2006; 孙晓新等, 2009; 黄璞祎等, 2011); 同时, 土壤微生物活性增强, 加快土壤中氧的消耗, 降低了氧化还原电位, 有利于产CH_4菌的生长(孙晓新等, 2009; 黄璞祎等, 2011)。秋季CH_4排放通量高的原因可能是大量有机碳输入, 当年植物生长的根开始分解或凋落物输入增加(孙晓新等, 2009; 邓昭衡等, 2015), 使可利用活性有机底物增加, 促进产CH_4菌产生CH_4; 另外, 秋季水位深度增加(图2), 湿地土壤厌氧条件增多, 有利于产CH_4菌产生CH_4和减少氧化CH_4菌氧化CH_4 (Moore *et al*., 1994; 黄璞祎等, 2011; Wei *et al*., 2015)。

然而, 湿地CH_4排放是土壤中CH_4的生成、氧化、传输与释放过程相互作用的结果(Whalen & Reeburgh, 1992; Le Mer & Roger, 2001; 孙晓新等, 2009), 受到一系列因子(包含水位深度、温度、植物和土壤性质等)影响, 使得生长季CH_4排放通量与土壤温度和水位深度的相互关系更加复杂。本研究发

表2 CH_4排放通量与土壤温度和水位深度的相关性
Table 2 Correlation between CH_4 emission fluxes and soil temperature or water table depth

样点 Plot	回归方程 Regression equation	变量 Variable	变量范围 Variable range	R^2	p	n
CH_4排放通量平均值 Mean CH_4 emission fluxes	$y = 1.07x + 32.79$	*WTD*	–39.7–29.5 cm	0.919	0.006	5
P-hummock	$y = 5.07x – 10.38$	T_5	5.6–17.9 ℃	0.747	0.000	12
	$y = 4.60x – 5.00$	T_{10}	4.0–14.6 ℃	0.694	0.012	12
	$y = 4.21x – 2.08$	T_{15}	3.2–14.5 ℃	0.698	0.012	12
	$y = 4.12x – 1.49$	T_{20}	3.0–15.0 ℃	0.737	0.006	12
	$y = 3.63x + 5.93$	T_{30}	1.7–15.1 ℃	0.670	0.017	12
S-hummock	$y = 0.07x – 0.27$	T_{10}	4.0–14.6 ℃	0.407	0.028	10
	$y = 0.07x – 0.23$	T_{15}	3.2–14.5 ℃	0.448	0.020	10
	$y = 0.06x – 0.19$	T_{20}	3.0–15.0 ℃	0.429	0.024	10
	$y = 0.05x – 0.07$	T_{30}	1.7–15.1 ℃	0.346	0.043	10

T_5, 5 cm土壤温度; T_{10}, 10 cm土壤温度; T_{15}, 15 cm土壤温度; T_{20}, 20 cm土壤温度; T_{30}, 30 cm土壤温度。*WTD*, 水位深度。
T_5, soil temperature at 5 cm depth; T_{10}, soil temperature at 10 cm depth; T_{15}, soil temperature at 15 cm depth; T_{20}, soil temperature at 20 cm depth; T_{30}, soil temperature at 30 cm depth. *WTD*, water table depth.

表3　不同地区高原泥炭地生长季CH_4排放通量比较

Table 3　Comparison of CH_4 emission fluxes in various plateau peatlands during the growing season

位点 Location	主要植被 Main vegetation	水位深度 water table depth (cm)	CH_4排放通量平均值 Mean CH_4 emission fluxes ($mg \cdot m^{-2} \cdot h^{-1}$)	范围 Range ($mg \cdot m^{-2} \cdot h^{-1}$)	研究时间 Study period	参考文献 Reference
若尔盖高原若尔盖县 Zoigê County of Zoigê Plateau			23.10 ± 30.28	0.17–144.43	May to Oct. 2014	本研究 This study
P-hollow	小眼子菜和狸藻 *Potamogeton pusillus* and *Utricularia vulgaris*	29.5	68.48	5.78–144.43		本研究 This study
P-hummock	木里薹草 *Carex muliensis*	7.5	40.32	12.93–76.86		本研究 This study
Lawn	西藏嵩草和花葶驴蹄草 *Kobresia tibetica* and *Caltha scaposa*	–21.6	3.68	0.23–8.45		本研究 This study
S-hollow	木里薹草 *Carex muliensis*	–21.1	2.38	0.48–4.91		本研究 This study
S-hummock	西藏嵩草 *Kobresia tibetica*	–39.7	0.63	0.17–1.48		本研究 This study
若尔盖高原红原县 Hongyuan County of Zoigê Plateau	乌拉草 *Carex meyeriana*	ND	4.51	0.36–10.04	May to Sept. 2001	Wang *et al*., 2002
若尔盖高原红原县 Hongyuan County of Zoigê Plateau	木里薹草 *Carex muliensis*	ND	2.87	0.51–8.21	May to Sept. 2001	Wang *et al*., 2002
若尔盖高原红原县 Hongyuan County of Zoigê Plateau	乌拉草 *Carex meyeriana*	ND	3.24	0.86–8.93	May to Oct. 2002	Ding *et al*., 2004
若尔盖高原红原县 Hongyuan County of Zoigê Plateau	木里薹草 *Carex muliensis*	ND	1.24	0.16–5.75	May to Oct. 2002	Ding *et al*., 2004
若尔盖高原红原县 Hongyuan County of Zoigê Plateau	木里薹草和乌拉草 *Carex muliensis* and *Carex meyeriana*	ND	2.43	0.02–12.01	May to Oct. 2003	Wang, 2010
若尔盖高原若尔盖县 Zoigê County of Zoigê Plateau	西藏嵩草和木里薹草 *Kobresia tibetica* and *Carex muliensis*	–18.36–10.66	14.45	0.17–86.78	June to Sept. 2005	Chen *et al*., 2008
若尔盖高原若尔盖县 Zoigê County of Zoigê Plateau	木里薹草 *Carex muliensis*	–53.94– –4.74	9.83	0.06–39.5	June to Sept. 2009	Li *et al*., 2011
青藏高原 Qinghai-Xizang Plateau	藏北嵩草和签草 *Kobresia littledalei* and *Carex doniana*	ND	2.80 ± 0.80	ND	July to Aug. 1996	Wei *et al*., 2015
青藏高原 Qinghai-Xizang Plateau	毛柄水毛茛 *Batrachium trichophyllum*	ND	0.27	–0.81–2.64	April to Sept. 1997	Jin *et al*., 1999
青藏高原 Qinghai-Xizang Plateau	杉叶藻 *Hippuris vulgaris*	10–120	1.46	–0.24–7.85	April to Sept. 1997	Jin *et al*., 1999
青藏高原 Qinghai-Xizang Plateau	薹草属 *Carex allivescers*	12	8.19	1.91–10.58	July to Sept. 2002	Hirota *et al*., 2004
青藏高原 Qinghai-Xizang Plateau	帕米尔薹草 *Carex pamirensis*	0.2	5	2.88–6.91	May to Sept. 2012	Song *et al*., 2015
青藏高原 Qinghai-Xizang Plateau	帕米尔薹草 *Carex pamirensis*	0.6	6.11	4.61–13.25	May to Sept. 2013	Song *et al*., 2015
美国科罗拉多州弗兰特山脉 Colorado Front Range, USA	薹草 *Carex scopulorum*	ND	0.35	0.05–1.10	June to Sept. 1992	West *et al*., 1999
北美洲落基山脉 Rocky Mountains, North America	薹草 *Carex aquatilis*	ND	11.45	0.04–20.41	May to Oct.1996	Wickland *et al*., 1999

ND, 无有效数据。Lawn, 常年性淹水与季节性淹水点之间的过渡带平坦地; P-hollow, 常年性淹水洼地; P-hummock, 常年性淹水草丘; S-hollow, 季节性淹水洼地; S-hummock, 季节性淹水草丘。

ND, no data available. Lawn, transitional zones between permanently flooded and seasonally flooded sites; P-hollow, permanently flooded hollow; P-hummock, permanently flooded hummock; S-hollow, seasonally flooded hollow; S-hummock, seasonally flooded hummock.

现湿地微地貌区(P-hummock、P-hollow和S-hummock) CH_4排放通量季节性变化存在极显著差异($p < 0.01$), Lawn和S-hollow CH_4排放通量季节变化不显著($p > 0.05$)。Pearson相关性分析表明整个生长季仅发现常年性淹水P-hummock与土壤温度(5–30 cm)存在显著线性正相关关系($p < 0.05$)(表2), 这表明土壤温度是影响该微地貌区CH_4排放通量存在显著季节变化的主控因子, 与其他报道的北方湿地CH_4排放与温度显著相关通常局限于常年性淹水湿地(Whalen & Reeburgh, 1992; 孙晓新等, 2009)吻合。但常年性淹水P-hollow没有发现这一规律, 说明还有其他因子影响湿地CH_4排放, 诸如水位深度和植物类型。常年性淹水P-hollow整个生长季水位深度超过土壤地表20 cm (图2); 另外, 植被类型以沉水植物小眼子菜和狸藻为主要植物群落, 它们不像维管植物通气组织(尤其是莎草科)的传输促进了CH_4从土壤向大气的输送, 进而增加CH_4排放(McEwing *et al*., 2015), 如P-hummock样点以莎草科

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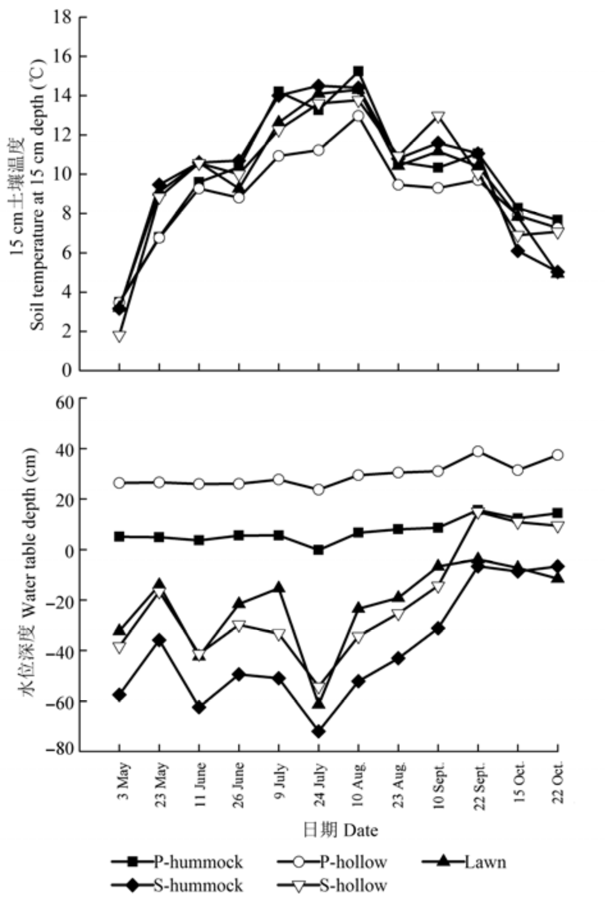

图2 2014年若尔盖高原湿地5种微地貌区15 cm土壤温度和水位深度。Lawn, 常年性淹水与季节性淹水点之间的过渡带平坦地; P-hollow, 常年性淹水洼地; P-hummock, 常年性淹水草丘; S-hollow, 季节性淹水洼地; S-hummock, 季节性淹水草丘。

Fig. 2 Soil temperature at 15 cm depth and water table depth from the Zoigê Plateau wetland on five microtopography in 2104. Lawn, transitional zones between permanently flooded and seasonally flooded sites; P-hollow, permanently flooded hollow; P-hummock, permanently flooded hummock; S-hollow, seasonally flooded hollow; S-hummock, seasonally flooded hummock.

植物木里薹草为优势种。这种水位深度和植被类型因子的变化，可能使湿地土壤-大气CH_4交换方式发生改变。许多研究表明湖泊湿地或泥炭湿地淹水小池塘水-大气界面CH_4交换方式以冒泡式(ebullition)为主(>95%)(Keller & Stallard, 1994; Casper *et al*., 2000)，其CH_4排放通量极高(Keller & Stallard, 1994; Mikkelä *et al*., 1995)，进而影响区域CH_4排放预算(Walter *et al*., 2006; Tokida *et al*., 2007)，这可能导致CH_4排放通量与温度或水位深度的关系趋于复杂。例如，在9月底和10月观测到P-hollow CH_4排放通量的最高值为592.44和327.82 mg·m^{-2}·h^{-1}。在北极圈河流阶地水淹洼地CH_4排放通量的最高值为559 mg·m^{-2}·h^{-1} (van Huissteden *et al*., 2005)。北极圈湖泊解冻后，冒泡式CH_4排放通量达到300 mg·m^{-2}·h^{-1} (Walter *et al*., 2006)。S-hummock生长季CH_4排放通量随温度增加而逐渐增加, 7月底出现次峰(图1)，秋季水位深度升高(图2)和凋落物输入，出现最大峰值，可能掩盖了温度对CH_4排放的作用。剔除10月份数据后，S-hummock CH_4排放通量与土壤(10–30 cm)温度显著线性正相关(表2)，暗示秋季水位深度升高或凋落物输入促进了湿地CH_4排放。

Lawn和S-hollow CH_4排放通量无明显的季节变化，这可能与该微地貌区水位深度(平均值为–21.6 cm和–21.1 cm)条件下的产CH_4菌和氧化CH_4菌的竞争有关(Hirota *et al*., 2004; Sun *et al*., 2011)。通常湿地土壤表层CH_4氧化潜力较大(王长科等, 2004; Lai, 2009)，水位深度下降后，CH_4氧化加强，CH_4排放通量降低，导致无明显高CH_4排放通量，可能使得观测期间CH_4排放通量无明显的季节变化(Sun *et al*., 2011)。水位深度下降还导致下层土壤温度增加，进而促进产CH_4菌生成CH_4，促进了CH_4排放。在这两种微地貌区观测期间CH_4排放变异系数较大(7.2%–149.3%，变异系数>40%的比例占75%)(图1)，进而推测标准偏差过大可能也使得CH_4排放通量无明显的季节性变化，这与Mikkelä等(1995)研究发现的北方泥炭地微地貌区小池塘CH_4排放通量无明显日变化格局的结果类似。但是，这两种微地貌区在夏季或秋季具有较高CH_4排放通量(图1)，说明温度、水位深度和凋落物输入对湿地CH_4排放影响较大。

3.2 若尔盖高原湿地微地貌区CH_4排放通量的空间变化

若尔盖高原湿地5种微地貌区CH_4排放通量大小顺序为：P-hollow > P-hummock > Lawn> S-hollow > S-hummock，这与其他研究的湿地不同微地貌区CH_4排放通量规律吻合，即水位深度较高的微地貌区CH_4排放通量较高(Clymo *et al*., 1995; Kutzbach *et al*., 2004; Glagolev *et al*., 2011; Wei *et al*., 2015)。许多研究表明不同湿地生态系统内，特别是泥炭地微地貌区的CH_4排放通量存在显著的空间变化(Moore *et al*., 1994; Clymo *et al*., 1995; Mikkelä *et al*., 1995; Waddington & Roulet, 1996; Glagolev & Shnyrev, 2008; Kalyuzhnyi *et al*., 2009;

Glagolev *et al*., 2011; Munir & Strack, 2014)。本研究湖滨湿地的5种微地貌区之间CH_4排放通量的平均值存在显著的空间差异性(表3), 变异系数为131%。Pearson相关性分析表明5种微地貌区CH_4排放通量的平均值与水位深度平均值存在极显著的线性正相关关系(表2), 表明影响该湖滨湿地微地貌区CH_4排放通量存在空间差异的主控因子是水位深度, 这与其他报道的北方湿地的研究结果(Moore *et al*., 1994; Ding *et al*., 2003; Huttunen *et al*., 2003) 一致。究其原因: 一方面可能是草丘(hummock)的水位深度较低, 产CH_4菌生成的CH_4大部分被氧化(Moore *et al*., 1994; Clymo *et al*., 1995; Lai, 2009; Wei *et al*., 2015), 进而减少了CH_4排放; 另一方面, 洼地CH_4排放通量高于草丘, 可能是由于较高水位深度, 产CH_4菌生成CH_4和温度升高后, 促进了CH_4排放(Waddington & Roulet, 1996; Lai, 2009; Wei *et al*., 2015), 这表明水位深度在调控湿地CH_4排放通量中发挥着极其重要的作用。如果不考虑这种差异, 可能会低估或高估区域CH_4排放量。例如, P-hollow CH_4排放通量最高, 它是S-hummock CH_4最低排放通量的108倍, Lawn和S-hollow CH_4排放通量倍数相差最小, 也达1.6倍。因此, 研究湿地生态系统内部微地貌区CH_4排放特征具有重要意义, 量化其数值, 进一步通过与高精度分辨率的遥感或地理信息系统数据结合, 将有助于精确地预算若尔盖高原湿地的CH_4排放量。

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