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银川市典型湖泊沉积物细菌群落结构及其对重金属的响应关系

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摘要: 湖泊湿地是极其重要而又特殊的生态系统, 在区域水资源调蓄、环境保护和生物多样性维持等方面具有重要意义. 沉积物细菌是湖泊生态系统重要的组成部分, 是湖泊生物地球化学循环的主要驱动力. 为探明银川市典型湖泊沉积物细菌的群落结构及其影响因素, 选取银川市3个典型湖泊(阅海湖、鸣翠湖和犀牛湖)为研究对象, 于2021年1月、4月、7月和10月采集表层沉积物, 应用16S rDNA高通量测序技术研究沉积物细菌群落组成, 并探究其与重金属之间的响应关系. 结果表明, 银川市3个典型湖泊沉积物重金属生态危害系数远小于40, 生态危害指数远小于150, 危害程度均为生态轻微危害. 3个湖泊的细菌群落多样性无显著差异, 但各湖泊不同季节多样性有显著变化, 群落组成也存在显著差异. 阅海湖、鸣翠湖和犀牛湖的优势种菌门(相对丰度排名前3)均为: 变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)和绿弯菌门(Chloroflexi), 优势下级阶元为 γ -变形菌纲(Gammaproteobacteria)、 α -变形菌纲(Alphaproteobacteria)和 δ -变形菌纲(Deltaproteobacteria). 银川市典型湖泊门水平分类上出现的主要差异物种为变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)、广古菌门(Euryarchaeota)、厚壁菌门(Firmicutes)、放线菌门(Actinobacteria)和酸杆菌门(Acidobacteria). 阅海湖沉积物细菌群落结构与Cu、Fe、Mn、Zn、As和Pb显著相关, 鸣翠湖沉积物细菌群落结构与Fe、Pb和Cr显著相关, 犀牛湖沉积物细菌群落结构与重金属相关关系不显著. 沉积物重金属的种类和含量对银川市阅海湖和鸣翠湖沉积物细菌群落结构有显著影响, 是引起湖泊沉积物细菌群落结构变化的重要环境因子.

关键词: 沉积物; 细菌; 群落结构; 重金属; 响应; 高通量测序

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Bacterial Community Structure of Typical Lake Sediments in Yinchuan City and Its Response to Heavy Metals

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Abstract: Lake wetlands are extremely important and special ecosystems, which are important for regional water resource storage, environmental protection, and biodiversity maintenance. Sediment bacteria are an important component of lake ecosystems and are a major driver of biogeochemical cycling in lakes. In order to investigate the community structure of bacteria in typical lake sediments in Yinchuan City and their influencing factors, three typical lakes in Yinchuan City (Yuehai Lake, Mingcui Lake, and Xiniu Lake) were selected for the study and surface sediments were collected in January, April, July, and October 2021. The composition of the sediment bacterial community was examined using 16S rDNA high-throughput sequencing technology, and the response relationships between them and heavy metals were explored. The results showed that the ecological hazard coefficient for heavy metals in the sediments of three typical lakes in Yinchuan City was far less than 40, and the ecological hazard index was far less than 150, all of which indicated a minor ecological hazard. There were no significant differences in bacterial community diversity among the three lakes, but there were significant variations in diversity among the lakes in different seasons and significant differences in community composition. The dominant phyla (top three in terms of relative abundance) in Yuehai Lake, Mingcui Lake, and Xiniu Lake were Proteobacteria, Bacteroidetes, and Chloroflexi. The dominant lower orders were Gammaproteobacteria, Alphaproteobacteria, and Deltaproteobacteria. The main divergent species that occurred at the phylum level in typical lakes in Yinchuan were Proteobacteria, Bacteroidetes, Euryarchaeota, Firmicutes, Actinobacteria, and Acidobacteria. The sediment bacterial community structure of Yuehai Lake was significantly correlated with Cu, Fe, Mn, Zn, As, and Pb; the sediment bacterial community structure of Lake Mingcui was significantly correlated with Fe, Pb, and Cr; and the sediment bacterial community structure of Xiniu Lake was not significantly correlated with heavy metals. The types and contents of sediment heavy metals had a significant effect on the bacterial community structure of sediments in Yinchuan Yuehai Lake and Mingcui Lake and were important environmental factors that caused changes in the bacterial community structure of lake sediments.

Key words: sediment; bacteria; community structure; heavy metals; response; high-throughput sequencing

湖泊沉积物是氮磷等营养元素的附着场所, 也是各种细菌的栖息地^[1]. 沉积物中的碳、氮、磷和硫

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循环等地球化学过程影响着细菌群落结构及其多样性^[2], 而细菌对水生生态系统中物质的降解、转化以及能量流动起着关键作用, 参与营养元素循环及湖泊进化演替过程^[3]. 并且由于细菌群落对外界干扰的敏感性, 群落结构在一定程度上能够反映水生态环境状况, 可作为一项重要指标用于评估河湖水生态环境状况^[4]. 因此, 研究湖泊沉积物细菌多样性并揭示其与各理化因子之间的关系, 对了解水生态系统物质循环及能量流动有重要意义.

随着水生态系统研究的不断深入及高通量宏基因组学技术的飞速发展, 水生态系统微生物群落组成、多样性及其影响因素逐渐引起关注, 在河流、湖泊和海洋等领域的研究均取得了一些重要进展^[5, 6], 例如, 竹兰萍等^[7]分析了工程干扰、支流干扰、采砂干扰、垦殖干扰和无干扰断面嘉陵江河道沉积物细菌的群落组成和功能变化; 张雨晴等^[8]研究了内蒙古岱海流域入湖河流、湖水及沉积物细菌多样性及群落组成; Mori等^[9]分析了季节性缺氧海湾表层沉积物细菌的潜在耗氧动态及其群落组成; Sauer等^[10]研究了沉积物-水界面细菌群落组成及多样性. 目前, 对于西北内陆湖泊沉积物细菌群落的相关研究仍十分有限, 尤其是其群落结构对于重金属的响应机制尚不甚明晰.

银川市湖泊数量众多, 主要分布于黄河冲积平原和洪积平原, 湖泊补给水源主要来自引黄渠道补水和少量农业灌溉退水. 本文以银川市阅海湖、鸣翠湖和犀牛湖为研究对象, 共采集湖泊表层沉积物4个采样期的64个样本, 通过高通量测序技术(high-throughput sequencing)分析沉积物细菌的群落特征和多样性, 探讨细菌群落结构与沉积物重金属因子之间的关系, 旨在为银川市湖泊水生态环境保护提供依据.

1 材料与方 法

1.1 研究区域概况

阅海湖(YH)位于宁夏银川市金凤区偏北, 总面积占地8 km², 是目前银川市面积最大、地貌保持最完整的一个生态湖泊^[11], 也是我国西部地区鸟类迁徙的中转站之一^[12]. 鸣翠湖(MC)位于宁夏银川市兴庆区东侧, 西距市区9 km, 东临黄河3 km, 平均海拔为1 100 m, 总面积6.67 km²^[13]. 犀牛湖(XN)位于西夏区同庄公路以东, 芦花排洪沟以南, 新南公路以西、西大沟以北, 水域面积约1.8 km²^[14]. 3个湖泊面积均在1.5 km²以上, 具有典型代表性. 随着人类活动的加剧和经济社会的快速发展, 湖泊资源逐渐透支, 环境压力增大, 水环境容量减小, 富营养化

程度加重等因素导致湖泊生态功能不断削弱.

1.2 样点布设和采样时间

根据水域特征确定阅海湖6个采样点(YH1~YH6), 鸣翠湖6个采样点(MC1~MC6), 犀牛湖4个采样点(XN1~XN4), 共16个采样点(如图1), 采样时间为2021年1月、4月、7月和10月.

1.3 样品采集及分析方法

使用采泥器采集湖泊表层沉积物, 去除砂石等杂质后, 一部分样品分装至50 mL无菌离心管及一次性采样袋中, 低温保存并于4 h内送回实验室, 将离心管放入-80℃的冰箱中冷冻保存用于提取DNA. 另一部分样品置于烘箱中烘干, 研钵磨碎后过筛, 保存于干燥器中待测.

1.4 沉积物重金属的测定

重金属As和Hg含量采用原子荧光法(HJ 680-2013), Pb、Cr、Cu和Zn含量采用火焰原子吸收分光光度法(HJ 491-2019), Cd和Mn含量采用电感耦合等离子体质谱法(HJ 803-2016)检测^[15].

1.5 DNA提取及高通量测序

使用NucleoSpin 96 soi (MACHEREY-NAGEL, Germany)提取样品DNA. 338F(5'-ACTGCTACGG GAGGCAGCA-3')和806R(5'-GGACTACHVGGGT WTCTAAT-3')作为引物集对16S(V3+V4)区域进行PCR扩增^[16]. 扩增产物按等摩尔比混合, 使用Monarch DNA凝胶提取试剂盒(new england biolabs, MA, USA)纯化, 并用于高通量测序^[17]. 测序由Biomarker有限公司(北京, 中国)使用Illumina MiSeq 2500平台和PE250策略进行.

配对后的reads使用FLASH(version 1.2.11)^[18]连接, 合并后的reads使用QHIME 1.9.1^[19]处理. 在用Cutadapt(version 1.9.1)^[20]检测和裁剪引物序列之前, 用Trimmomatic(version 0.33)^[21]对原始序列进行去噪、排序和分离. 将嵌合物UCHIME(version 8.1)^[22]过滤后, 剩余序列用USEARCH(version 10.0)^[23]聚类成OTUs(>97%序列相似度), OTUs的阈值为所有序列计数^[24]的0.005%. 使用Silva参考数据库^[25]确定每个OTU代表性序列的分类特性. 利用Mothur(version 1.3.0)^[26]计算 α 多样性.

1.6 数据分析方法

原始数据进行标准化处理. 利用Matlab 2020对沉积物重金属富集系数及潜在生态风险系数进行可视化, 利用Origin 2017对沉积物细菌多样性进行可视化, 利用R“ggplot2”软件包(版本4.2.1)对沉积物细菌群落构成可视化. 采用基于Bray-Curtis距离的非度量多维标度(NMDS)排序研究沉积物细菌群落组成的相似性或差异性. 使用R中的“vegan”包



图 1 采样点地理位置分布示意

Fig. 1 Sampling sites of the typical lakes in Yinchuan

(4.1.2 版本)做相似性分析(ANOSIM), 得到的 R 值用于量化不同湖泊细菌群落不同时间的差异程度, R 值越大, 组间差异程度越高. 利用“vegen”软件包(版本 4.1.2)中的 Mantel test 函数, 计算环境变量与沉积物细菌总群落的相关关系, 再结合水环境变量构建的 Pearson 相关矩阵, 将银川市典型湖泊沉积物细菌群落组成与环境变量的关系可视化. 采用 Kruskal-Wallis 检验分析银川市典型湖泊沉积物门类上细菌群落的差异性. 并使用 Origin 2017 对其结果进行可视化. 利用“pheatmap”软件包(版本 4.1.2)对银川市典型湖泊沉积物差异性物种及重金属相关性进行可视化.

将样品中重金属的测量值与环境背景值进行比较, 利用富集系数法分析确定重金属的污染程度^[27], 通过潜在生态风险指数(RI)评估湖泊重金属的污染状况^[28].

2 结果与分析

2.1 重金属污染水平评估

由于缺乏宁夏黄河流域湖泊周边环境土壤这 8 种重金属的背景值, 本文采用 Lars Hankanson 提出的现代工业化前正常颗粒沉积物中重金属含量的最高背景值为参比值(表 1)来反映湖泊重金属的实际污染程度. 各采样点重金属富集系数的计算结果见图 2.

表1 常见重金属背景值

Table 1 Background values for common heavy metals

| 元素 | $\omega/\text{mg}\cdot\text{kg}^{-1}$ | | | | | | 文献 |
|---------|---------------------------------------|-------|-------|--------|-------|------|-------------------------------|
| | Hg | As | Cu | Zn | Pb | Cd | |
| 工业最高背景值 | 0.25 | 15.00 | 30.00 | 80.00 | 25.00 | 0.50 | [29] |
| 宁夏背景值 | 0.02 | 11.50 | 20.90 | 56.40 | 20.10 | 0.10 | 《土壤环境质量标准》 (GB 15618-1995) |
| 一级自然背景值 | 0.15 | 15.00 | 35.00 | 100.00 | 35.00 | 0.20 | |
| 二级自然背景值 | 1.0 | 25.0 | 100.0 | 300.0 | 350.0 | 0.6 | |

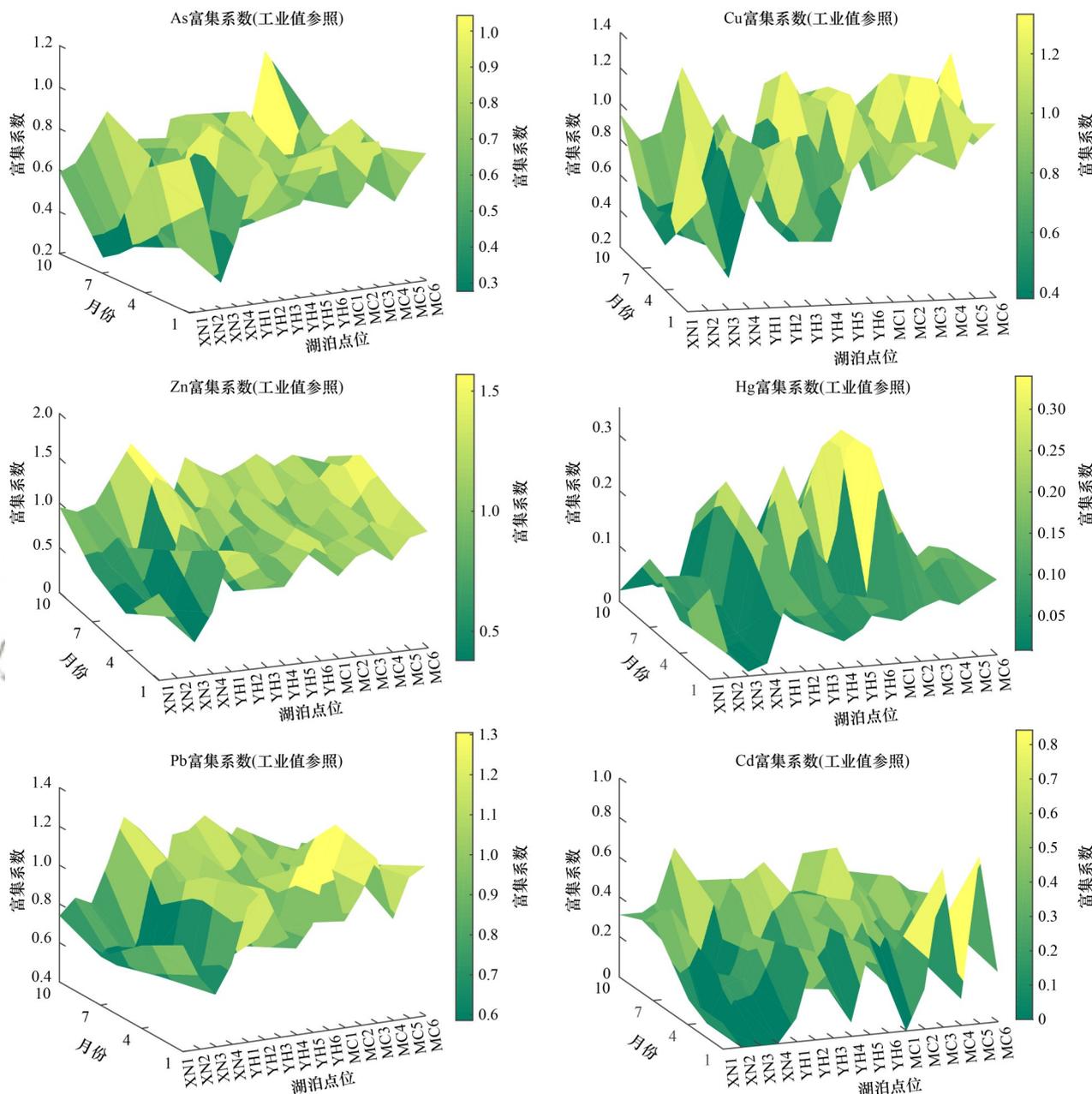


图2 银川市典型湖泊沉积物重金属的富集系数(工业值参照)

Fig. 2 Enrichment coefficients of heavy metals in sediments from typical lakes in Yinchuan

从图2可知,以现代工业化前正常颗粒沉积物中重金属含量的最高背景值为参照,阅海湖、鸣翠湖和犀牛湖沉积物中,Cu、Zn、Hg、Cd和Pb在鸣翠湖中均最为富集,平均富集系数分别为0.99、1.14、0.12、0.39和1.02,远高于阅海湖和犀牛湖.As含量在阅海湖较为富集,平均富集系数为0.71,

高于犀牛湖和鸣翠湖的0.54和0.68.Cu的最高富集系数出现在4月鸣翠湖的4号点位,为1.32.Zn的最高富集系数出现在10月阅海湖的1号点位.As的最高富集系数出现在10月鸣翠湖的4号点位.Hg的最高富集系数出现在4月鸣翠湖的1号点位.Cd的最高富集系数出现在1月鸣翠湖的5号点位.Pb的最高富

集系数出现在1月阅海湖的6号点位.分析结果表明重金属在鸣翠湖的富集程度要高于阅海湖及犀牛湖.

2.2 重金属潜在生态风险评价

阅海湖、鸣翠湖和犀牛湖沉积物重金属潜在生态风险评价结果见图3和表2.图3为单项重金属生态危害系数,表2为多种重金属潜在生态危害指数.

沉积物中多种重金属的潜在生态危害指数RI显示,3个湖泊沉积物重金属生态危害系数远小于40,

生态危害指数远小于150,危害程度都为生态轻微危害.其中,3个湖泊单项生态危害系数较高的是Cd,均值分别为6.14、10.35和11.59.按生态危害系数排序,阅海湖和鸣翠湖沉积物重金属生态危害程度为: Cd>As>Pb>Hg>Cu>Zn,而犀牛湖为: Cd>As>Pb>Cu>Hg>Zn.其中,鸣翠湖1号点位在7月时沉积物重金属潜在生态危害程度相对最高,RI为50.80,最低为犀牛湖3号点位在1月时,只有9.19.

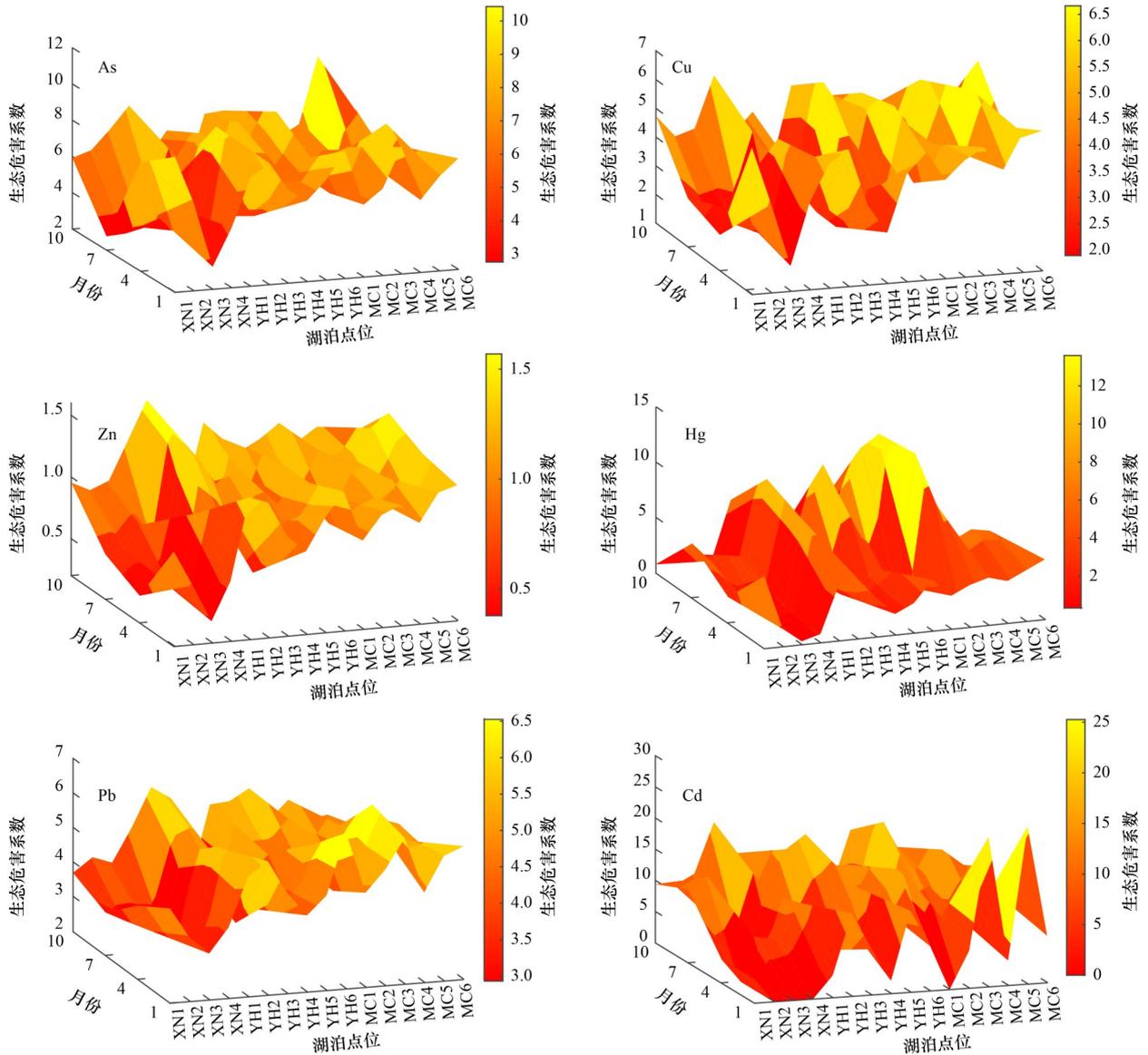


图3 银川市典型湖泊沉积物重金属的潜在生态危害系数(工业值参照)
Fig. 3 Potential ecological hazard factor for heavy metals in sediments from typical lakes in Yinchuan

2.3 细菌多样性分析

银川市典型湖泊沉积物细菌 Chao1 指数和 Shannon 指数见图4.3个湖泊Chao1指数变化范围为3 007.36~5 575.76,均值4 584.53.阅海湖Chao1指数变化范围3 007.363~5 575.76,均值4 527.89,鸣翠湖Chao1指数变化范围3 343.569~5 403.22,均值4 605.43.犀牛湖Chao1指数变化范围3 630.338~

5 561.984,均值4 638.15.由Chao1指数判断,犀牛湖的物种丰富程度较高,鸣翠湖次之,阅海湖最低.3个湖泊Shannon指数均值为9.24,阅海湖Shannon指数变化范围7.554~10.517,均值9.12,鸣翠湖Shannon指数变化范围8.176~10.402,均值9.15,犀牛湖的Shannon指数变化范围8.679~10.705,均值9.57.综上,犀牛湖物种多样性与丰

表 2 银川市典型湖泊重金属的潜在生态危害指数
Table 2 Potential ecological hazard factors for multiple heavy metals of typical lakes in Yinchuan

| 采样点 | 1月 | 4月 | 7月 | 10月 |
|-----|-------|-------|-------|-------|
| XN1 | 31.78 | 21.07 | 26.05 | 25.54 |
| XN2 | 17.06 | 13.34 | 25.23 | 25.82 |
| XN3 | 9.19 | 17.65 | 17.00 | 27.86 |
| XN4 | 14.93 | 21.01 | 13.27 | 40.19 |
| YH1 | 28.84 | 41.48 | 37.65 | 36.47 |
| YH2 | 40.43 | 18.51 | 42.74 | 31.00 |
| YH3 | 27.75 | 23.01 | 38.79 | 17.04 |
| YH4 | 18.38 | 30.60 | 45.86 | 31.32 |
| YH5 | 33.96 | 29.46 | 39.04 | 26.20 |
| YH6 | 34.18 | 38.72 | 41.49 | 29.12 |
| MC1 | 19.16 | 40.81 | 50.80 | 33.75 |
| MC2 | 28.19 | 35.13 | 35.35 | 32.13 |
| MC3 | 50.22 | 32.71 | 30.02 | 37.75 |
| MC4 | 24.15 | 36.15 | 34.45 | 36.55 |
| MC5 | 49.85 | 37.67 | 30.55 | 26.86 |
| MC6 | 34.18 | 31.34 | 32.75 | 28.32 |

富程度较高, 鸣翠湖次之, 阅海湖最低. 群落多样性 3 个湖泊之间差异并不显著, Chao1 指数及 Shannon 指数 3 个湖泊之间差异不显著, Shannon 指数在各个湖泊季节之间差异也不显著. 阅海湖 Chao1 指数在 1 月、4 月和 7 月之间差异显著, 鸣翠湖 Chao1 指数 1 月与 4 月、7 月和 10 月差异显著, 犀

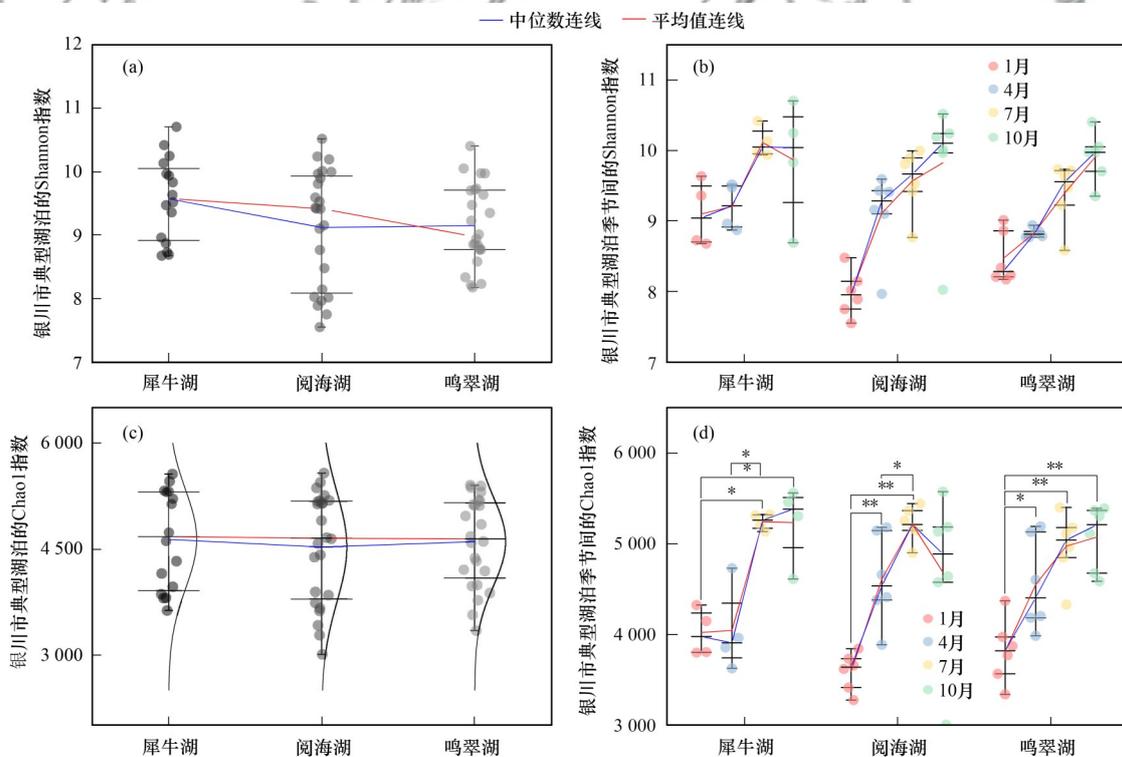
牛湖 Chao1 指数 1 月与 7 月和 10 月及 4 月与 7 月之间差异显著.

2.4 细菌群落结构组成

在门水平上, 3 个湖泊的沉积物细菌群落组成差别不大, 主要由变形菌门(Proteobacteria, 17.47%~66.96%, 相对丰度, 下同)、拟杆菌门(Bacteroidetes, 4.82%~27.56%)、蓝细菌门(Cyanobacteria, 0.26%~15.43%)、绿弯菌门(Chloroflexi, 1.23%~10.84%)、放线菌门(Actinobacteria, 0.08%~7.95%)、广古菌门(Euryarchaeota, 0.45%~8.27%)、厚壁菌门(Firmicutes, 0.66%~4.62%)、疣微菌门(Verrucomicrobia, 0.74%~11.34%)和酸杆菌门(Acidobacteria, 1.15%~5.71%)构成[图 5(a)~5(c)].

在纲的分类阶元上, 沉积物细菌群落主要由 γ -变形菌纲(Gammaproteobacteria, 14.36%~50.66%, 相对丰度, 下同)、 α -变形菌纲(Alphaproteobacteria, 0.89%~7.81%)、 δ -变形菌纲(Deltaproteobacteria, 3.51%~24.54%)、拟杆菌纲(Bacteroidia, 4.22%~23.82%)、热原体纲(Thermoplasmata, 0.04%~7.29%)和厌氧绳菌纲(Anaerolineae, 1.56%~10.13%)等纲构成[图 5(d)~图 5(f)].

阅海湖、鸣翠湖和犀牛湖的优势种菌门(相对丰度排名前 3)均为变形菌门(Proteobacteria)、拟杆



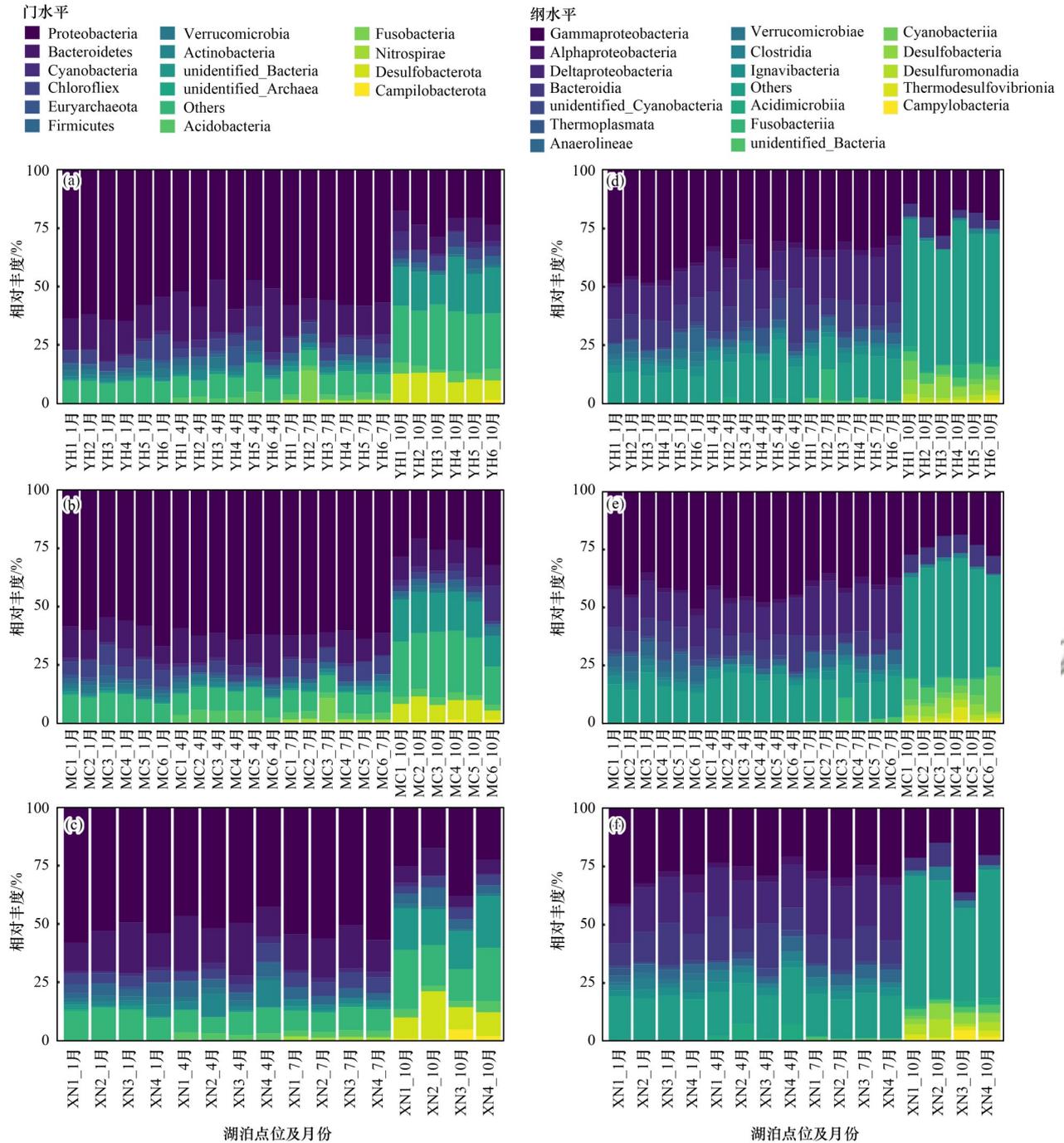
(a)银川市典型湖泊的 Shannon 指数, (b)银川市典型湖泊季节间的 Shannon 指数, (c)银川市典型湖泊的 Chao1 指数, (d)银川市典型湖泊各季节的 Chao1 指数; *表示具有显著关联的“月份-月份”, *表示 $P < 0.05$, **表示 $P < 0.01$, ***表示 $P < 0.001$; 曲线表示符合多样性指数发展的正态分布; 横线自上往下分别表示最大值、75%值、中位数、25%值和最小值

图 4 银川市典型湖泊沉积物细菌群落多样性指数箱型图

Fig. 4 Box plots of bacterial community diversity indices for typical lake sediments in Yinchuan

菌门(Bacteroidetes)和绿弯菌门(Chloroflexi). 在下级分类阶元上, γ -变形菌纲(Gammaproteobacteria)、 α -变形菌纲(Alphaproteobacteria)和 δ -变形菌纲

(Deltaproteobacteria)为优势类群(相对丰度排名前3). 不同季节之间沉积物细菌群落结构差异较大, 具有明显的季节变化(图5).



(a) 阅海湖门水平, (b) 鸣翠湖门水平, (c) 犀牛湖门水平, (d) 阅海湖纲水平, (e) 鸣翠湖纲水平, (f) 犀牛湖纲水平

图5 银川市典型湖泊细菌群落结构与分布

Fig. 5 Structure and distribution of bacterial communities in typical lakes in Yinchuan

2.5 细菌群落结构比较

利用基于 Bray-Curtis 距离的 NMDS 方法评估不同季节湖泊沉积物细菌群落的相似性, 结果见图 6. Stress < 0.2 表明图形具有较好的表现意义, Global R > 0 表示分组有效, P < 0.05 为显著性差异, 椭圆是质心周围的 95% 置信区间. 由图 6 可知, 1 月: Stress =

0.114, Globe R = 0.759 3, P = 0.001; 4 月: Stress = 0.073, Globe R = 0.813 5, P = 0.001; 7 月: Stress = 0.11, Globe R = 0.548 9, P = 0.001; 10 月: Stress = 0.083, Globe R = 0.731 5, P = 0.001; 全年: Stress = 0.097, Globe R = 0.813 5, P = 0.001; 3 个湖泊的沉积物细菌群落组成在不同季节之间均存在显著差异.

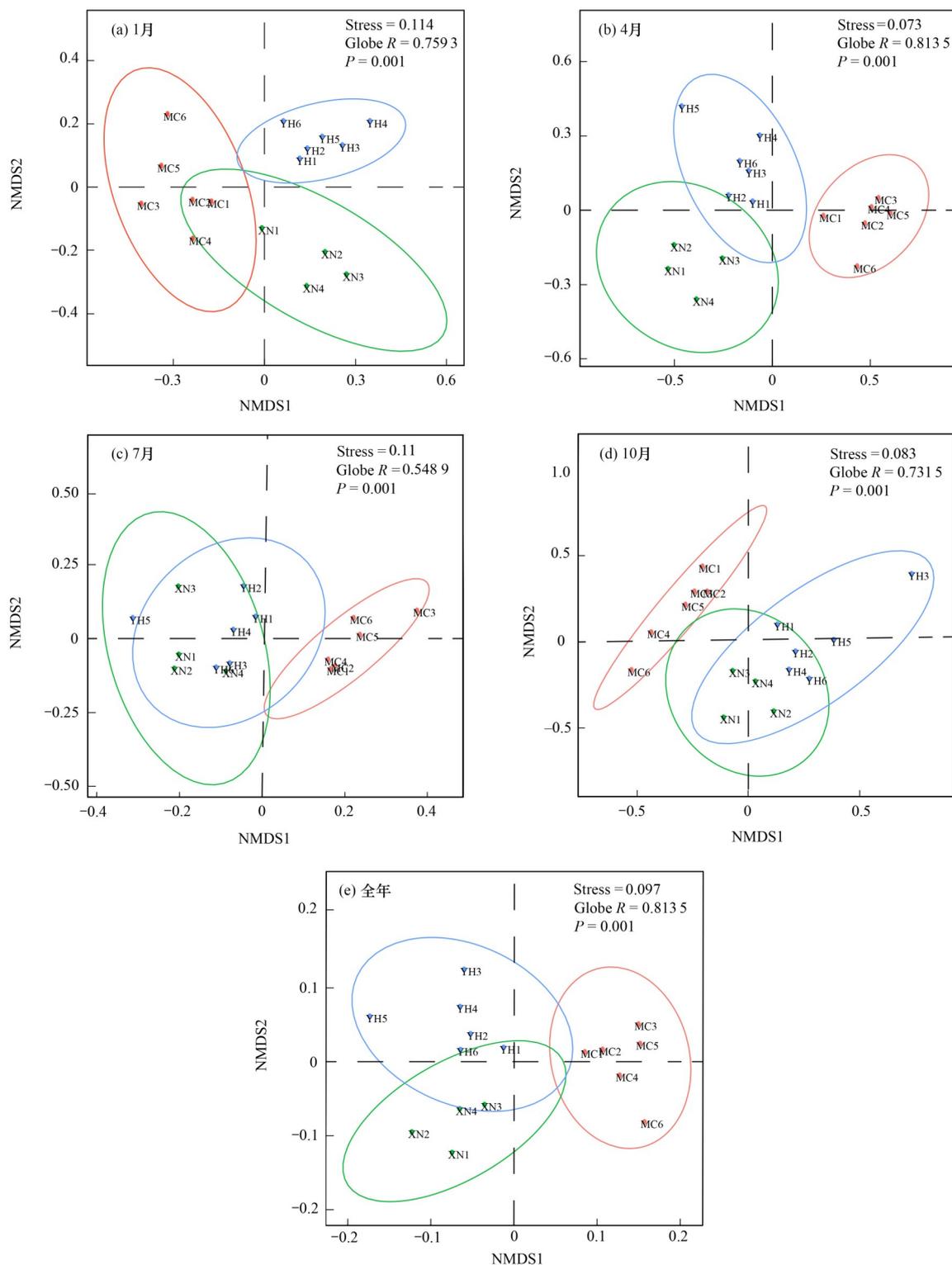


图6 银川市典型湖泊沉积物细菌群落结构的NMDS分析

Fig. 6 NMDS analysis of bacterial community structure in sediments from typical lakes in Yinchuan

2.6 细菌群落结构与重金属的相关性分析

采用 Mantel test 分析湖泊沉积物细菌群落与重金属之间的响应关系, 结果如图 7 所示, 重金属参数的两两比较用 Pearson 相关系数的颜色梯度表示, 边宽表示对应的距离相关性 (Mantel's R), 边颜色表示统计显著性 (Mantel's P). 阅海湖沉积物细菌群落结构

受到 Cu ($P = 0.032$)、Fe ($P = 0.016$)、Mn ($P = 0.011$)、Zn ($P = 0.006$)、As ($P = 0.004$) 和 Pb ($P = 0.007$) 等重金属的显著影响; 鸣翠湖沉积物细菌群落结构则受到 Fe ($P = 0.041$)、Pb ($P = 0.041$) 和 Cr ($P = 0.041$) 等重金属的显著影响; 犀牛湖沉积物细菌群落结构与重金属相关关系不显著.

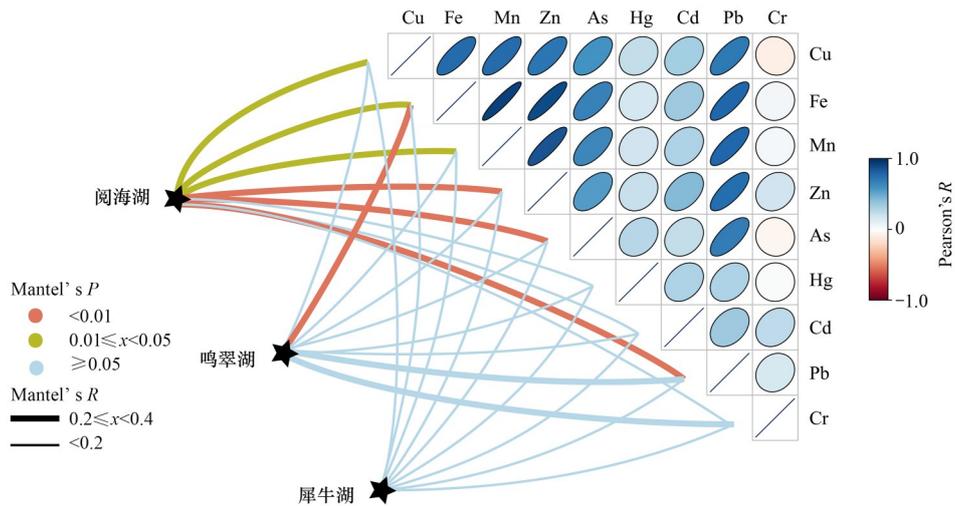


图7 银川市典型湖泊沉积物细菌群落与重金属的 Mantel test 分析

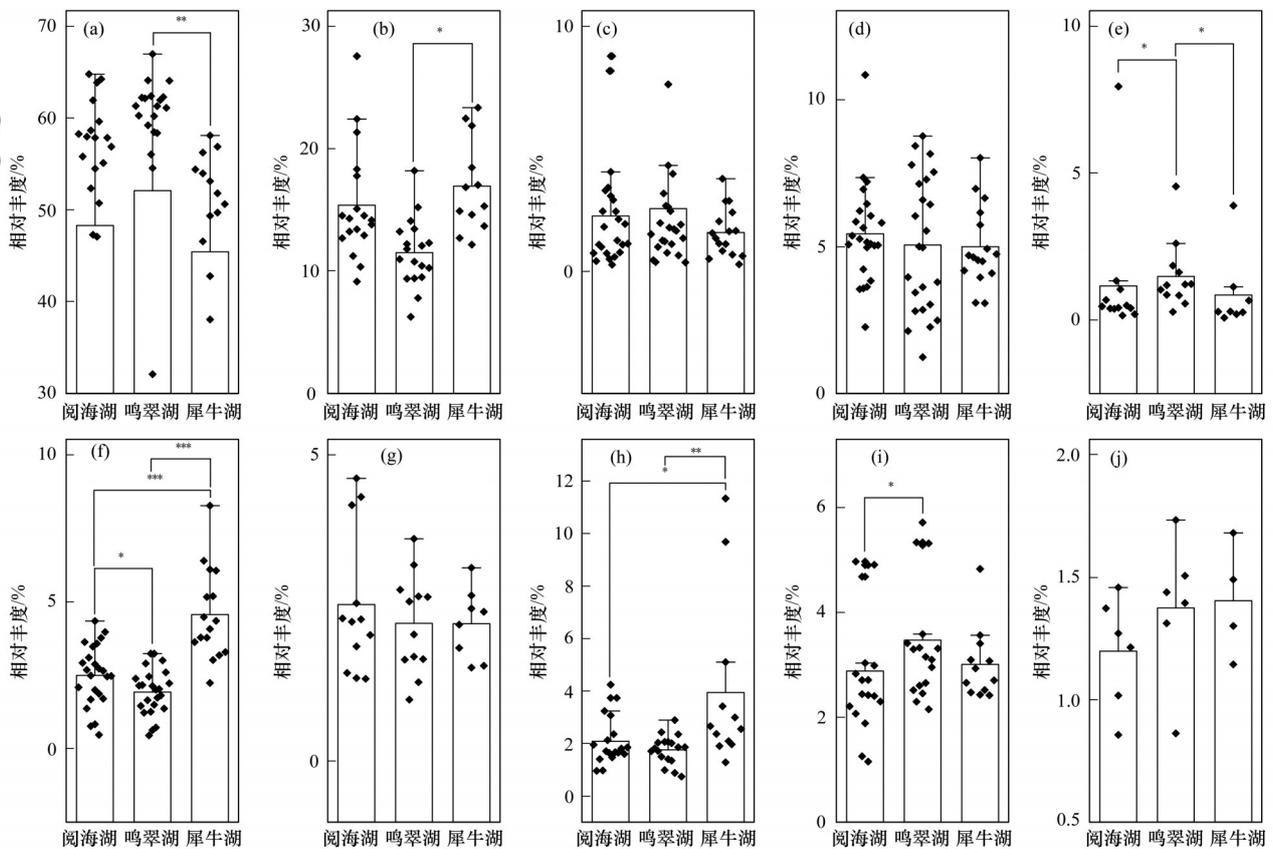
Fig. 7 Mantel test analysis of sediment bacterial communities and heavy metals in typical lakes in Yinchuan

2.7 群落结构的差异与重金属的相关性分析

在门水平上，选取3个湖泊相对丰度排名前10的物种进行差异性检验(图8)，Kruskal-Wallis 检验结果显示，阅海湖与鸣翠湖的广古菌门(Euryarchaeota)、厚壁菌门(Firmicutes)和酸杆菌门(Acidobacteria)差异显著，阅海湖与犀牛湖的厚壁菌门(Firmicutes)及放线菌门(Actinobacteria)差异显著，

鸣翠湖与犀牛湖之间的细菌群落差异最大，变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)、厚壁菌门(Firmicutes)、放线菌门(Actinobacteria)和酸杆菌门(Acidobacteria)均差异显著。

选取阅海湖、鸣翠湖和犀牛湖表现出显著差异性物种与重金属做关联热图(图9)，结果显示，阅海湖放线菌门(Actinobacteria)与Mn($P = 0.048$)和Pb



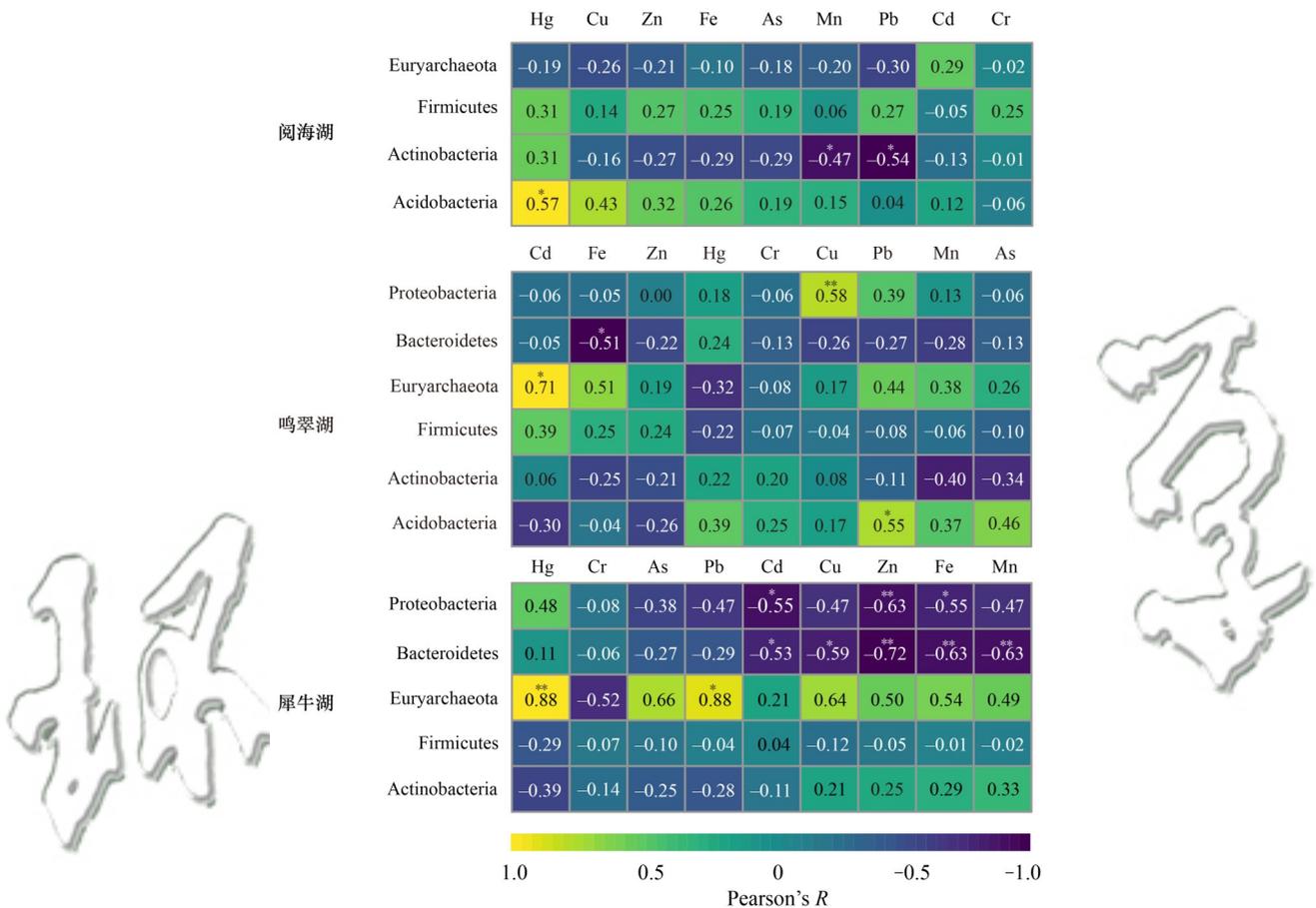
(a)Proteobacteria, (b)Bacteroidetes, (c)Cyanobacteria, (d)Chloroflexi, (e)Euryarchaeota, (f)Firmicutes, (g)Verrucomicrobia, (h) Actinobacteria, (i) Acidobacteria, (j)Nitrospirae; *表示具有显著关联的“湖泊-湖泊”, *表示 $P < 0.05$, **表示 $P < 0.01$, ***表示 $P < 0.001$

图8 银川市典型湖泊之间门分类水平沉积物细菌群落(排名前10)差异性分析

Fig. 8 Analysis of the variability in sediment bacterial communities (top ten) at the phylum level among typical lakes in Yinchuan

($P = 0.021$)呈显著负相关, 酸杆菌门(Acidobacteria)与 Hg ($P = 0.013$)呈显著正相关, 厚壁菌门(Firmicutes)及广古菌门(Euryarchaeota)与重金属相关关系不显著. 鸣翠湖变形菌门(Proteobacteria)与 Cu ($P = 0.002$)呈显著正相关, 拟杆菌门(Bacteroidetes)与 Fe ($P = 0.024$)呈显著负相关, 广古菌门(Euryarchaeota)与 Cd ($P = 0.01$)呈显著正相关, 酸杆菌门(Acidobacteria)与 Pb ($P = 0.017$)呈显著正相关.

犀牛湖变形菌门(Proteobacteria)与 Cd ($P = 0.027$)、Zn ($P = 0.008$)和 Fe ($P = 0.025$)呈显著负相关, 拟杆菌门(Bacteroidetes)与 Cd ($P = 0.034$)、Cu ($P = 0.016$)、Zn ($P = 0.0015$)、Fe ($P = 0.008$)和 Mn ($P = 0.009$)呈显著负相关, 广古菌门(Euryarchaeota)与 Hg ($P = 0.004$)和 Pb ($P = 0.017$)呈显著正相关, 厚壁菌门(Firmicutes)和放线菌门(Actinobacteria)与重金属的相关关系不显著.



*表示具有显著关联的“细菌-重金属”, *表示 $P < 0.05$, **表示 $P < 0.01$, ***表示 $P < 0.001$; 数值表示“细菌-重金属”所对应的 Pearson's R 数值

图9 银川市典型湖泊差异性物种与重金属的关联热图

Fig. 9 Heat map of the association between differential species and heavy metals in typical lakes in Yinchuan

3 讨论

3.1 银川市典型湖泊重金属特征及风险评价

阅海湖、鸣翠湖和犀牛湖重金属污染水平评估及潜在生态风险评价显示, 3个湖泊各采样点沉积物重金属生态危害系数远小于40, 生态危害指数远小于150, 危害程度均为生态轻微危害. 3个湖泊重金属含量特征较为相似, 造成这种结果的原因与相同的补水条件及地理环境有关. 有研究表明, 湖泊中重金属多通过各种生物和物理化学作用富集于底泥中^[30], 阅海湖、鸣翠湖和犀牛湖均通过引黄及农田退水补给水体, 且3个湖泊周围无重工业, 水环

境较为相似, 底质也较为相似, 因此沉积物中重金属特征与风险相似.

3.2 银川市典型湖泊细菌群落结构及多样性

沉积物细菌群落多样性受季节变化影响^[31], 也受地理位置的影响^[32-34], 温度、湿度、总有机碳和总氮等因素均能够显著地影响细菌的群落结构^[35]. 3个湖泊之间群落多样性及丰富程度差异并不显著, 但每个湖泊不同季节沉积物细菌的多样性有显著变化, 群落组成也存在显著差异. 阅海湖、鸣翠湖和犀牛湖的地理环境、水环境和底质等条件均较为相似, 地理尺度差异小, 不同湖泊沉积物细菌群落的分离程度低于不同季节的沉积物细菌群落, 因此,

细菌群落结构受季节变化影响远高于区域影响, 而季节之间出现显著差异的原因主要是由于水温变化导致。

阅海湖、鸣翠湖和犀牛湖细菌群落最优势菌门均为: 变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)和绿弯菌门(Chloroflexi)和变形菌门(Proteobacteria)。在纲级水平上显示主要由 γ -变形菌纲(Gammaproteobacteria)和 α -变形菌纲(Alphaproteobacteria)组成, γ -变形菌纲(Gammaproteobacteria)是纲级阶元上最占优势的物种, 其中大多数细菌是化学自养的, 主要通过氧化氢、硫和铁实现代谢^[36]。 γ -变形菌纲(Gammaproteobacteria)主要由硫杆菌属(*Thiobacillus*)、脱氯单胞菌属(*Dechloromonas*)、念珠菌属(*Candidatus_Cometibacter*)和*Deftuicoccus*组成, 硫杆菌属(*Thiobacillus*)可以将金属硫化物氧化成硫酸, 脱氯单胞菌(*Dechloromonas*)参与某些金属的氧化还原过程^[37], 而念珠菌属(*Candidatus_Cometibacter*)可以通过改变厌氧/厌氧循环来积累磷酸盐。

拟杆菌门(Bacteroidetes)为第二大门类, 包括黄杆菌纲(Flavobacteria)和鞘脂杆菌纲(Sphingobacteria)。黄杆菌纲主要存在于水生环境中, 多数黄杆菌纲细菌对人无害, 而鞘脂杆菌纲在海洋细菌中占有较大比例, 可以降解纤维素^[38]。绿弯菌门(Chloroflexi)为第三大门类, 与前两个门类相比, 绿弯菌门在3个湖泊沉积物中的分布更为均匀, 这可能是由于其更大的环境适应性。

沉积物中优势菌门也呈现显著的季节变化, 10月阅海湖、鸣翠湖和犀牛湖的优势菌种变形菌门(Proteobacteria)比例下降, 蓝细菌门(Cyanobacteria)和广古菌门(Euryarchaeota)等种类出现显著增长。广古菌门含有数量最大, 种类最多的已培养古菌类群, 不仅参与甲烷的生产、厌氧甲烷和其它短链碳氢化合物的氧化, 还参与碳氢化合物的转化以及硫、氮和铁的循环, 比如具有亚硝酸盐和硫还原作用的*Hadesarchaea*和*Theionarchaea*等新类群^[39]。蓝细菌门分布极广, 普遍生长于淡水、海水和土壤中, 在极端环境(如温泉、盐湖、贫瘠的土壤、岩石表面或风化壳中和植物树干等)中也能生长, 许多蓝细菌门类群具有固氮能力, 可以通过氮的固定来提高稻田和其他土壤的肥力^[40]。蓝细菌门类群在氮和磷丰富的水体中生长旺盛, 可作为水体富营养化的指示生物, 在污水处理和水体自净中起积极作用, 但生长过盛易导致水华和赤潮等现象发生^[41]。

3.3 银川市典型湖泊细菌群落结构与重金属的相关性

有研究表明, 沉积物细菌群落结构受到pH、总磷、氨氮和有机质等环境因子的影响^[42,43], 沉积物重金属也是影响沉积物细菌群落组成的重要因素^[44], 谢学辉等^[45]的研究表明重金属含量对土壤中细菌多样性有重要影响。Cu、Zn和Cd等重金属可使水体中部分微生物生长受到抑制, 降低微生物群落的多样性^[46]; Cd、Cu和As等重金属会导致土壤微生物群落的整体丰度下降, 重金属耐受菌的丰度增加, 并且过量重金属会抑制微生物的基质代谢和呼吸活动^[47]; Cr、Pb和Zn与硝化菌、拟杆菌和疣微菌的丰度呈现出显著的负相关关系, 但可以促进绿弯菌的生长^[48]。

银川市3个典型湖泊沉积物细菌群落结构对于重金属的响应差异较大, 阅海湖细菌群落结构与Cu、Fe、Mn、Zn、As和Pb显著相关, 鸣翠湖细菌群落结构与Fe、Pb和Cr显著相关, 犀牛湖细菌群落结构与重金属相关关系不显著。银川市典型湖泊门水平分类上出现的主要差异物种为变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)、广古菌门(Euryarchaeota)、厚壁菌门(Firmicutes)、放线菌门(Actinobacteria)和酸杆菌门(Acidobacteria), 3个湖泊差异性物种对于重金属的响应也各不相同。关联热图表明群落结构相似的物种对于重金属表现出了相似的响应, 而群落结构出现差异的物种则对于重金属表现出了截然不同的响应, 造成这种现象的原因可能是细菌群落内与重金属相关的基因数量的差异所导致。Cu与细菌 α -多样性的降低有关^[49], Cu对犀牛湖中拟杆菌门(Bacteroidetes)表现出了显著负向影响。而Zn则一方面促进了群落结构多样性的升高, 另一方面又抑制了种群的分布^[50], Zn对犀牛湖中变形菌门(Proteobacteria)及拟杆菌门(Bacteroidetes)均表现出显著负向影响。Cr和Mn与细菌群落 α -多样性显著负相关, Mn对阅海湖的放线菌门(Actinobacteria)及犀牛湖的拟杆菌门(Bacteroidetes)均表现出显著的负向影响。此外, 重金属可影响一些细菌的代谢功能和遗传信息流程, 以及一些与C和N循环相关的生态功能^[51]。As和Pb的浓度对细菌群落有明显的抑制作用, 会使微生物碳、氮和硫代谢能力降低甚至丧失^[52,53]。As对于3个湖泊的差异性物种没有表现出显著影响, Pb对阅海湖中放线菌门(Actinobacteria)表现出显著负向影响, 对鸣翠湖中酸杆菌门(Acidobacteria)和犀牛湖中广古菌门(Euryarchaeota)却表现出了显著的正向影响, 表明生态系统中细菌会和重金属之间发生互作^[54]。

沉积物重金属的种类和含量对银川市阅海湖和鸣翠湖沉积物细菌群落结构有显著影响, 沉积物细菌群落结构对于重金属的响应差异较大, 重金属是引起湖泊沉积物细菌群落结构变化的重要环境因子。

4 结论

(1)银川市3个典型湖泊沉积物重金属生态危害程度都为生态轻微危害, 重金属在鸣翠湖的富集程度要高于阅海湖和犀牛湖。

(2)银川市3个典型湖泊沉积物细菌的主要优势菌门为变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)和绿弯菌门(Chloroflexi), 下级优势阶元为 γ -变形菌纲(Gammaproteobacteria)、 α -变形菌纲(Alphaproteobacteria)和 δ -变形菌纲(Deltaproteobacteria)。银川市3个典型湖泊门水平分类上出现的主要差异物种为变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)、广古菌门(Euryarchaeota)、厚壁菌门(Firmicutes)、放线菌门(Actinobacteria)和酸杆菌门(Acidobacteria)。3个湖泊之间细菌群落多样性及丰富程度差异并不显著, 各湖泊不同季节沉积物细菌多样性与群落结构有显著变化。

(3)阅海湖沉积物细菌群落与Cu、Fe、Mn、Zn、As和Pb显著相关, 鸣翠湖沉积物细菌群落与Fe、Pb和Cr显著相关, 犀牛湖沉积物细菌群落与重金属离子无显著相关关系。沉积物重金属的种类和含量对银川市阅海湖和鸣翠湖沉积物细菌群落结构有显著影响, 是引起湖泊沉积物细菌群落结构变化的重要环境因子。

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