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关帝山森林土壤真菌群落结构与遗传多样性特征

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摘要: 土壤微生物群落驱动土壤碳、氮、磷、硫生物地球化学循环, 在维持土壤碳汇和生态系统功能等方面发挥重要的作用. 分析环境与空间因素在寒温带针叶林土壤微生物群落构建中的作用, 可以为区域森林生态系统管理措施的制定提供理论依据. 本文利用 Illumina 高通量测序技术分析了关帝山庞泉沟自然保护区华北落叶松 (*Larix principis-rupprechtii*) 林、青杆 (*Picea wilsonii*) 林、油松 (*Pinus tabulaeformis*) 林以及桦树 (*Betula* spp.) 林这 4 种林型的 5 个土壤真菌群落 (LpMC1、LpMC2、PwMC、PtMC 和 BMC) 的结构. 同时测定林下土壤环境因子及林下植被多样性, 分析真菌群落的结构与植被和土壤环境因子的相关性. 结果表明: ① 5 个样地中共有 7 个真菌门和 33 个优势真菌属; ② 冗余分析结果表明: 土壤 pH、温度、含水率、全氮含量、 NH_4^+ 含量、全碳含量、蔗糖酶活性、脲酶活性、林下植被优势度和均匀度与土壤真菌群落结构显著相关; ③ 聚类分析和 PCA 分析结果表明, 森林植被类型、土壤环境因子和林下植被对土壤真菌群落结构影响显著. ④ 空间变量 (PCNM) 分析结果表明, 在局域尺度 (local scale) 上扩散限制对研究区域真菌群落构建的影响不显著. 本研究区森林土壤真菌群落结构主要受到环境选择 (土壤 pH、温度、含水率、全氮含量、 NH_4^+ 含量、全碳含量、蔗糖酶活性、脲酶活性、林下植被优势度和均匀度、森林类型) 的显著影响.

关键词: 关帝山; 高通量测序; 真菌群落结构; 针叶林土壤

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Characteristics of Fungi Community Structure and Genetic Diversity of Forests in Guandi Mountains

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Abstract: Soil microorganisms drive the biogeochemical process of carbon, nitrogen, phosphorus and sulfur, and play a key role in maintaining soil carbon sink and ecosystem function. The study on effects of environmental and spatial factors on the structure of microbial community in boreal coniferous forest soil will provide theoretical basis for making management measures in local forest ecosystem. Our research analyzed five soil fungi communities (LpMC1, LpMC2, PwMC, PtMC, and BMC) in four forest types, including *Larix principis-rupprechtii* forest, *Picea wilsonii* forest, *Pinus tabulaeformis* forest and *Betula* spp. forest, respectively, in Pangquangou Nature Reserve in Guandi Mountains with Illumina high-throughput sequencing technology. Meanwhile, soil environmental factors and diversity of undergrowth plants were determined to analyze the relationship between fungi community structure and vegetation as well as soil environmental factors. The results showed that: ① There were seven eumycota and thirty-three advantageous fungal genera in the five sample sites; ② Redundancy analysis results showed that soil pH, temperature, moisture, total nitrogen, the content of NH_4^+ , total carbon, invertase activity, urease activity, undergrowth dominance and evenness were significantly associated with soil fungi community structure; ③ Cluster analysis and principal component analysis showed that forest vegetation type, soil environmental factors and undergrowth had significant effects on soil fungi community structure; ④ The results of PCNM analysis showed that at a local scale, dispersal limitation had no significant influence on fungi community structure in the study area. The forest soil fungi community structure in the study area was significantly affected by environmental selection (soil pH, temperature, moisture, total nitrogen, the content of NH_4^+ , total carbon, invertase activity, urease activity, undergrowth dominance and evenness, forest type).

Key words: Guandi Mountains; high-throughput sequencing; fungi community structure; coniferous forest soil

微生物在生态系统物质循环、能量转换等过程中发挥重要作用. 关于微生物群落构建机制的争论始于 1934 年 Bass-Becking 提出的 “Everything is everywhere, but environment selects” 的观点, 认为微生物具有极强的扩散能力, 不存在扩散限制, 环境选择对于微生物群落的构建起主导性作用, 即不同的

非生物环境因子决定了微生物群落的结构和多样

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性. 近年来的研究结果不断对这一观点提出挑战^[1], 认为环境选择(生物因子和非生物因子)和扩散限制(dispersal limitation)是生态系统中生物群落结构形成的两个主要过程^[2], 而这一结果对微生物群落同样具有适用性. 环境选择是一个确定性或生态位过程(deterministic or niche processes), 扩散限制是一个随机或中性过程(stochastic or neutral processes), 这两个过程在微生物群落构建过程中的相对重要性及其调控机制是生态学研究的一个热点问题^[3]. 温带森林中的多项研究结果显示, 环境生物因子对土壤根际微生物群落的影响主要表现在植物群落的组成^[4]、生产力^[5]、根系密度^[6]等方面. 森林生态系统中真菌群落的分布与某些非生物因子, 如土壤 pH^[7]、土壤营养^[8]和海拔高度^[9]等密切相关, 这一结果支持了微生物群落形成过程中环境选择发挥重要作用. 群落 β 多样性随地理距离的增加而降低(distance-decay relationship)是生物地理学的主要模型, 适合于不同的动植物类型、地理梯度和环境, 甚至在生态位过程和中性过程(扩散限制)中也存在这样的模式. 最近对微生物群落的研究显示, 群落的相似度也表现出随地理距离增加而衰减的模式. 土壤真菌群落呈现出高度的局域(local scale)的生物多样性, 如丛枝菌根(arbuscular mycorrhizal fungi, AM)、子囊真菌(ascomyceteous fungi)^[10]. 对全球尺度^[7]和区域尺度(regional scale)的4个热带森林和3个温带森林的外生菌根菌(ectomycorrhizal fungal)的研究表明, 扩散过程影响了真菌群落的构建^[11]. 但也有研究显示, 外生菌根菌群落不受扩散限制的影响^[9]. 本研究针对寒温带性针叶林和阔叶林土壤真菌群落的结构和多样性开展研究, 对进一步澄清微生物群落的构建机制提供数据支持.

庞泉沟自然保护区位于吕梁山脉的关帝山腹地, 是以保护世界珍禽褐马鸡(*Crossoptilon mantchuricum*)及其栖息地华北落叶松(*Larix principis-rupprechtii*)、白杆(*Picea meyeri*)、青杆(*Picea wilsonii*)天然次生林为主的森林和野生动物类型的自然保护区. 森林群落类型多样、结构差异明显, 可以在小尺度范围忽略气候因子的差异, 研究森林植被类型和土壤因子对微生物群落结构和功能的影响, 又可以利用不同的海拔高度研究气候因子的影响, 是研究微生物群落结构和功能的理想实验室. 本文基于核糖体 ITS I 的高通量测序技术研究了该区落叶阔叶林[白桦(*Betula platyphylla*)、红桦

(*Betula albosinensis*)混交林)、常绿针叶林[青杆和油松(*Pinus tabulaeformis*)]和落叶针叶林(华北落叶松)土壤真菌群落的结构. 通过揭示微生物群落结构和功能受气候、环境因子和植物群落的调控机制, 以期为生物多样性保护和森林管理措施的制定提供依据.

1 材料与方法

1.1 研究区概况

庞泉沟自然保护区位于山西省交城、文水、方山、娄烦等县的交界处. 地理位置 111°22' ~ 111°33'E, 37°45' ~ 37°55'N, 海拔 1 600 ~ 2 831 m, 主要森林类型是由针叶林华北落叶松、白杆、青杆、油松以及白桦等树种组成的纯林和混交林. 气候为暖温带大陆性山地气候, 年平均气温 4.2℃, 年平均降水量 822.6 mm, 土壤属于山地土壤类型. 实验地设在保护区的神尾沟和八道沟. 5个微生物群落(LpMC1、LpMC2、PwMC、PtMC、BMC)样品分别取自阴坡高海拔华北落叶松林(111°32'22.81"E, 37°53'13.93"N; 2 709 m)、阴坡低海拔华北落叶松林(111°30'33.77"E, 37°53'06.30"N; 1 950 m)、阴坡青杆林(111°27'9.12"E, 37°51'56.22"N; 1 888 m)、阳坡油松林(111°27'39.16"E, 37°50'54.30"N; 1 894 m)和阴坡桦树林(111°25'57.19"E, 37°53'02.62"N; 2 161 m). 记录每个样地内林下植被的种类、株数、盖度和高度.

1.2 样品采集

本研究于2015年7月采样. 运用5点混合取样法采集土壤, 即在每一个采样地点设置 10 m × 10 m 的样方, 利用对角线法选取 5 个点. 首先去除地表约 5 cm 厚的地表植被和覆盖物, 再用土钻钻取 0 ~ 20 cm 深的土壤样品, 放入无菌塑料袋内, 于冰盒内保存, 尽快带回实验室, 并于 -20℃ 下保存. 在 24 h 之内, 将每个样地的 5 个土壤样品混合均匀并过直径为 2 mm 的网筛, 除去根系、石块等杂物, 其中一部分风干用于土壤理化性质的测定, 一部分放入 -80℃ 冰箱保存, 用于高通量测序.

1.3 分析方法

1.3.1 土壤环境因子分析

(1) 土壤理化性质分析

自然风干的土样用于土壤理化性质的测定. 土壤含水量用烘干法测定; 土壤 pH 值(土水比为 1:2.5)用电位法测定; 土壤全氮(TN)和全碳(TC)用 vario MACRO cube 元素分析仪(德国)测定; 土壤硝

态氮和铵态氮用 CleverChem 380 间断元素分析仪测定;土壤有机质和有机碳用低温外热重铬酸钾氧化-比色法测定。

(2) 土壤酶活性分析

脲酶采用苯酚钠-次氯酸钠比色法,其活性以 37℃ 下培养 24 h 后 1 g 土壤产生的 $\text{NH}_3\text{-N}$ 的 mg 数表示;蔗糖酶采用 3,5-二硝基水杨酸比色法,其活性以 37℃ 培养 24 h 后 1 g 土壤产生的葡萄糖的 mg 数表示; H_2O_2 酶采用 KMnO_4 滴定法,其活性以 20 min 内每 g 土壤分解的过氧化氢的 mg 数表示^[12]。

(3) 林下植被多样性分析

记录每个样地内林下植被的种类、株数、盖度和高度。计算公式如下。

群落优势度指数:

$$\text{Simpson}(D) = \sum_{i=1}^S P_i^2$$

群落多样性指数:

$$\text{Shannon}(H) = - \sum_{i=1}^S P_i \ln P_i$$

Pielou 均匀度指数:

$$J = H/\ln S$$

式中, S 为植物群落丰富度指数; P_i (植物重要值) = (相对盖度 + 相对高度)/2。

1.3.2 土壤真菌群落高通量测序分析

5 个样地的土壤样品分别称取 0.5 g,各 3 个重复,用 E. Z. N. A. Soil DNA Kit 试剂盒(Sangon 公司,中国)提取土壤微生物基因组总 DNA,详细步骤参考试剂盒说明书。将每个土样提取出的 3 个 DNA 样品混合起来送往上海生物工程有限公司进行高通量测序。

通过 Illumina HiSeq 测序平台,利用引物 ITS1F (CTTGGTCATTTAGAGGAAGTAA) 和 ITS2-Rev (GCTGCGTTCTTCATCGATGC) 对核糖体 ITS I 高变区进行测序。

1.4 数据处理

1.4.1 微生物群落 OTU 分析

利用 Prinseq 软件剔除长度小于 50bp 的序列以及序列尾部质量值在 20 以下的碱基,再对低复杂度的序列进行过滤,去除预处理后序列中的非扩增区域序列。利用 Mothur 软件中的 pre.cluster 对序列进行测序错误校正,再用 chimeras.uchime 去除序列中的嵌合体,随后用 Uclust 软件对符合要求的序列进行聚类,用 Mothur 软件对所得序列进行分析,最后

以 97% 的相似性作为阈值划分操作分类单元 (OTU)。

1.4.2 微生物群落多样性分析

利用 Mothur 软件计算土壤样品中真菌的 α 多样性值,包括群落多样性的指数 Shannon 指数^[13] 和 Simpson 指数^[14]、群落丰富度的指数 Chao1 指数^[15] 和 ACE 指数^[16] 以及测序深度指数 Coverage 指数^[17]。

1.5 统计分析

利用 Mothur 软件做 rarefaction 分析及分类学分析,利用 R 语言工具制作曲线图。利用 SPSS 19.0 软件对各样地变量之间的显著性差异进行单因素方差分析(one-way analysis)和多重比较分析(LSD),显著性水平设为 $P < 0.05$ 。利用 R 语言对土壤环境因子、林下植被和真菌群落结构做相关矩阵分析,并对 5 个样地的土壤环境因子和林下植被做 UPGMA 聚类分析。使用 Canoco 4.5 软件对土壤环境因子和真菌群落进行冗余分析(redundancy analysis, RDA),为保证数据满足正态分布及减小异常值对分析结果的影响,对数据进行 $\lg(x+1)$ 转换,显著性水平为 $\alpha = 0.05$;同时对 5 个样地的土壤真菌群落做主成分分析(principal component analysis, PCA)。利用邻体矩阵主坐标分析(PCNM)对空间变量对土壤真菌群落的影响进行分析,主要步骤为:①构建样地之间的(欧式)地理距离矩阵;②削减距离矩阵规模;③计算削减距离矩阵的主坐标分析;④保留具有正空间相关[Moran 指数大于 E(1)]的特征向量;⑤使用保留的特征向量作为空间解释变量,与响应变量进行 RDA 分析。

2 结果与分析

2.1 不同森林类型的土壤环境因子

2.1.1 土壤理化性质

表 1 所示,土壤 pH 在 5 个样地间差异显著,阳坡温性油松林样地土壤偏碱性,而阴坡桦树林和寒温性华北落叶松林和青杆林样地均呈弱酸性。土壤有机质和碳氮含量在 5 个样地间差异显著,高海拔华北落叶松样地的有机质、全碳、全氮、有机碳以及 NH_4^+ 含量均为最大,而低海拔华北落叶松样地中全碳含量最小,说明气候条件(温度)对土壤碳氮含量具有一定的影响;油松林样地中全氮含量最小,桦树林样地中有机质、有机碳和 NH_4^+ 含量最小, NO_3^- 含量最大,青杆林样地中 NO_3^- 含量最小,说明温性常绿针叶林和寒温性落叶针叶林以及针叶林和

阔叶林土壤中碳氮代谢过程和效率存在差异性. 高海拔华北落叶松样地中土壤含水率最高, 达到 47.928%, 油松林样地中最低, 仅为 8.551%, 低海拔华北落叶松样地、青杆林样地和桦树林样地之间无显著性差异.

2.1.2 土壤酶活性

土壤酶主要来源于动植物和微生物细胞的分泌及其残体的腐解^[12]. 本研究中, 油松林土壤过氧化氢酶和脲酶活性显著大于其它 4 个样地, 低海拔华北落叶松林中均为最小; 高海拔和低海拔落叶松林

样地以及桦树林样地之间无显著差异. 蔗糖酶活性在 5 个样地间差异显著, 高海拔华北落叶松林的土壤蔗糖酶活性最高 (6.072 ± 0.373); 油松林样地土壤蔗糖酶活性最低 (0.577 ± 0.041 , 表 1).

2.1.3 林下植被群落多样性

林下植被多样性指数在各样地之间具有一定的差异, 其中, 阴坡高海拔华北落叶松样地林下植被多样性最高, 优势度最低, 阴坡青杆林样地中林下植被优势度最高, 均匀度最低, 阳坡油松林样地林下植被多样性最低, 均匀度最高 (表 1).

表 1 土壤环境因子及林下植被多样性¹⁾

Table 1 Soil environment factors and underground vegetation diversity of analyzed soil samples					
样地/真菌群落名称	华北落叶松林 1	华北落叶松林 2	青杆林	油松林	桦树林
pH	5.932 ± 0.059 e	6.669 ± 0.006 c	6.012 ± 0.015 d	8.125 ± 0.038 a	7.058 ± 0.020 b
土壤温度 (Q_{10})/℃	12.223 ± 0.452 c	16.829 ± 1.090 a	14.614 ± 1.373 b	16.406 ± 0.951 ab	15.031 ± 0.763 ab
含水率/%	47.928 ± 7.710 a	22.446 ± 0.859 b	21.642 ± 2.048 b	8.551 ± 0.991 c	24.124 ± 4.822 b
有机质/%	6.013 ± 0.307 a	3.158 ± 0.160 c	5.343 ± 0.286 b	3.032 ± 0.029 c	2.010 ± 0.152 d
全氮 (TN)/%	0.448 ± 0.004 a	0.156 ± 0.008 d	0.289 ± 0.007 b	0.124 ± 0.002 e	0.209 ± 0.004 c
NO ₃ ⁻ -N/mg·kg ⁻¹	8.619 ± 0.272 c	14.464 ± 1.000 b	4.280 ± 0.152 e	5.296 ± 0.259 d	19.580 ± 0.356 a
NH ₄ ⁺ -N/mg·kg ⁻¹	33.675 ± 2.335 a	24.795 ± 0.192 b	19.219 ± 4.133 c	13.155 ± 0.467 d	3.383 ± 0.731 e
全碳 (TC)/%	6.929 ± 0.029 a	1.974 ± 0.087 d	4.416 ± 0.089 b	2.742 ± 0.040 c	2.727 ± 0.032 c
有机碳 (SOC)/%	3.230 ± 0.165 a	1.696 ± 0.086 c	2.870 ± 0.154 b	1.628 ± 0.015 c	1.079 ± 0.082 d
过氧化氢酶活性/mg·(g·20 min) ⁻¹	0.741 ± 0.053 bc	0.683 ± 0.104 c	0.961 ± 0.139 ab	1.053 ± 0.223 a	0.705 ± 0.053 bc
脲酶活性/mg·(g·24 h) ⁻¹	2.251 ± 0.076 bc	1.574 ± 0.003 c	2.760 ± 0.838 b	4.455 ± 0.148 a	1.692 ± 0.079 c
蔗糖酶活性/mg·(g·24 h) ⁻¹	6.072 ± 0.373 a	1.612 ± 0.092 c	1.844 ± 0.161 c	0.577 ± 0.041 d	3.844 ± 0.247 b
林下植被优势度 (D)	0.258 ± 0.042 b	0.294 ± 0.034 ab	0.364 ± 0.029 a	0.342 ± 0.024 ab	0.334 ± 0.060 ab
林下植被多样性 (H)	1.470 ± 0.176 a	1.449 ± 0.036 ab	1.294 ± 0.075 ab	1.134 ± 0.119 b	1.256 ± 0.135 ab
林下植被均匀度 (J)	0.922 ± 0.009 a	0.840 ± 0.072 ab	0.748 ± 0.017 b	0.952 ± 0.031 a	0.860 ± 0.049 ab

1) 表中数据为平均值 ± 标准差, 同一行数据不同小写字母表示差异显著 ($P < 0.05$), 下同

对 5 个样地的土壤环境因子和林下植被多样性进行 UPGMA 聚类分析 (图 1), 结果表明, 桦树林样地和阴坡华北落叶松样地最为接近, 油松林样地与其他 4 个样地之间差异最大.

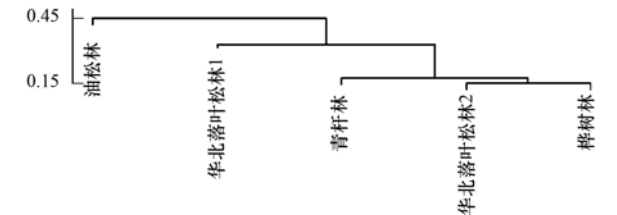


图 1 基于土壤环境因子和林下植被多样性的 UPGMA 聚类
Fig. 1 UPGMA clustering figure based on soil environmental factors and diversity of undergrowth vegetation

2.2 土壤真菌群落结构

5 个样地土壤真菌群落 α 多样性分析结果见表 2. 高海拔华北落叶松样地中的真菌群落 LpMC1 中 Shannon 指数最大, Simpson 指数最小, 因此 LpMC1 中真菌多样性最大, 其后依次为 LpMC2 > PtMC > BMC > PwMC; 5 个样地的土壤真菌丰度大小依次为

PtMC > LpMC2 > PwMC > BMC > LpMC1. 综上所述, LpMC1 中真菌多样性最大, 丰富度最小, PwMC 中多样性最小, PtMC 中丰富度最大. Coverage 指数显示桦树林样地的取样深度最佳.

5 个样地中共有 7 个真菌门和 322 个真菌属 (图 2), 其中, 子囊菌门 (Ascomycota) 和担子菌门 (Basidiomycota) 相对丰度最大, 且 LpMC1 和 LpMC2 中子囊菌门的相对丰度显著大于其它 3 个真菌群落, 而其担子菌门的丰度则小于其它 3 个真菌群落. 5 个真菌群落中相对丰度大于 1% 的优势真菌属共有 33 个, 其中, 丝盖伞属 (*Inocybe*) (51.04%)、高腹菌属 (*Gautieria*) (80.45%)、湿伞属 (*Hygrocybe*) (18.58%) 和红菇属 (*Russula*) (82.81%) 分别在 LpMC2、PwMC、PtMC 和 BMC 群落中占据显著优势, 被孢霉属 (*Mortierella*) (2.71%, 3.23%) 和伞状霉属 (*Umbelopsis*) (1.59%, 1.57%) 在 LpMC1 和 LpMC2 中优势度较大, 涛旋孢属 (*Zalerion*) (4.47%)、*Geminibasidium* (2.67%)、*Hydnotrya*

表 2 土壤真菌群落多样性

Table 2 Diversity of soil fungal communities

微生物群落	序列数	真菌多样性指数					
		OTU	Shannon	Simpson	ACE	Chao1	Coverage
LpMC1	16 027	596	4. 62	0. 03	790. 95	834. 68	0. 988 894
LpMC2	30 353	956	3. 97	0. 11	1 827. 05	1 540. 38	0. 987 645
PwMC	53 168	811	2. 3	0. 37	1 816. 69	1 455. 92	0. 993 003
PtMC	39 166	909	3. 27	0. 1	2 450. 88	1 738. 92	0. 988 357
BMC	33 324	816	2. 52	0. 36	1 341. 07	1 149. 88	0. 991 178

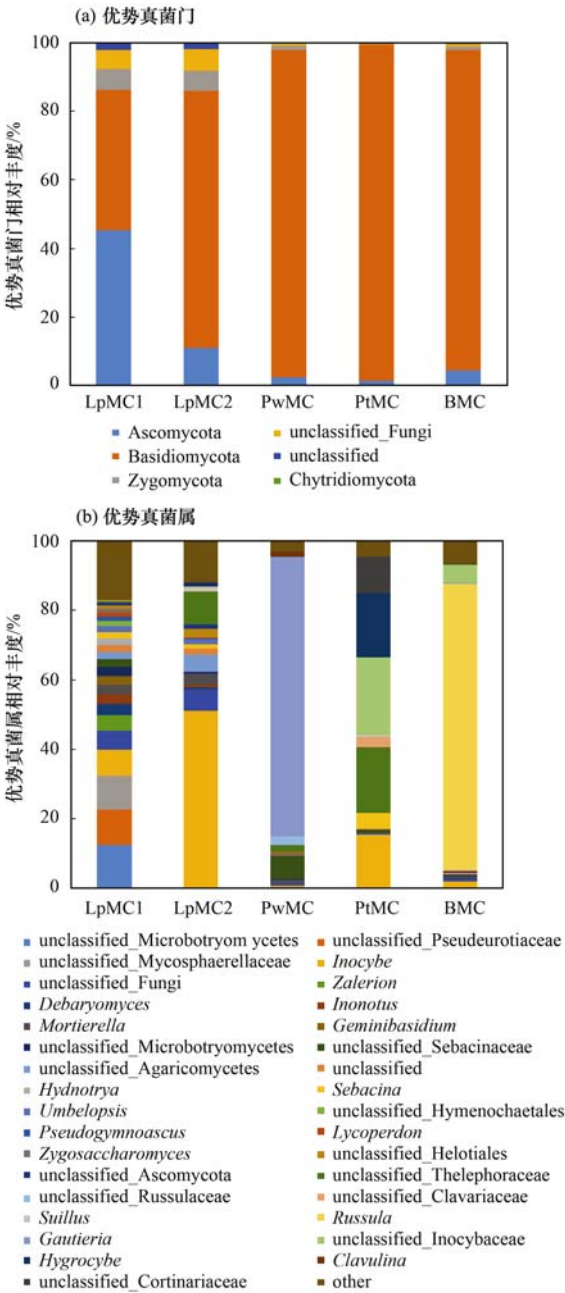


图 2 优势真菌门和优势真菌属相对丰度
Fig. 2 Relative abundance of dominant fungal
phyla and dominant fungal genera

(2.03%) 和接合酵母属 (*Zygosaccharomyces*) (1.05%) 均为 LpMC1 中的特有属。

在属水平上对土壤真菌群落进行 PCA 分析, 结果表明 (图 3), 华北落叶松林土壤真菌群落 (LpMC1、LpMC2) 分布在坐标轴中轴线的右侧, 其它林地土壤真菌群落分布在坐标轴中轴线的左侧, 表明在第 1 主成分中, 不同植被类型中的土壤真菌群落在位置分布上差异显著, 土壤真菌群落组成的差异主要是植被类型的不同引起。在第 2 主成分上, PwMC、BMC 和 LpMC2 可聚为一类, 结果与土壤环境因子和林下植被多样性的聚类结果相似, 表明在第 2 主成分上, 土壤真菌群落组成主要受土壤环境因子和林下植被的影响。

2.3 土壤真菌遗传多样性与土壤环境因子、林下植被的相关性

对 5 个林地土壤中的优势真菌属和土壤环境因子及林下植被多样性指数进行冗余分析 (图 4), 结果显示第 1 轴和第 2 轴累计解释变异量达到 66.3%, 并且土壤含水率、蔗糖酶活性、土壤温度、pH、全氮含量、 NH_4^+ 含量、全碳含量、脲酶活性、林下植被优势度和均匀度对真菌群落结构的影响较大。其中, 含水率作用最大, 它与大部分真菌属呈正相关。由图 4 可知, 涛旋孢属、*Geminibasidium*、*Hydnотrya* 和接合酵母属与含水率、全氮、有机质、有机碳、 NH_4^+ 含量以及蔗糖酶活性均呈极显著正相关, 与土壤温度、pH 和林下植被优势度呈显著负相关; 红菇属与有机质、有机碳及 NH_4^+ 含量呈显著负相关; 丝盖伞属与土壤温度呈显著正相关; 湿伞属与土壤 pH 呈显著正相关, 与含水率、全氮含量和蔗糖酶活性呈显著负相关; 背孢霉属和伞状霉属与含水率和 NH_4^+ 含量呈显著正相关, 与林下植被优势度和土壤 pH 呈显著负相关。

所有变量的相关性矩阵 (图 5) 表明, 土壤真菌群落多样性与土壤环境因子、林下植被具有一定的相关性。土壤真菌群落 Shannon 指数与土壤含水

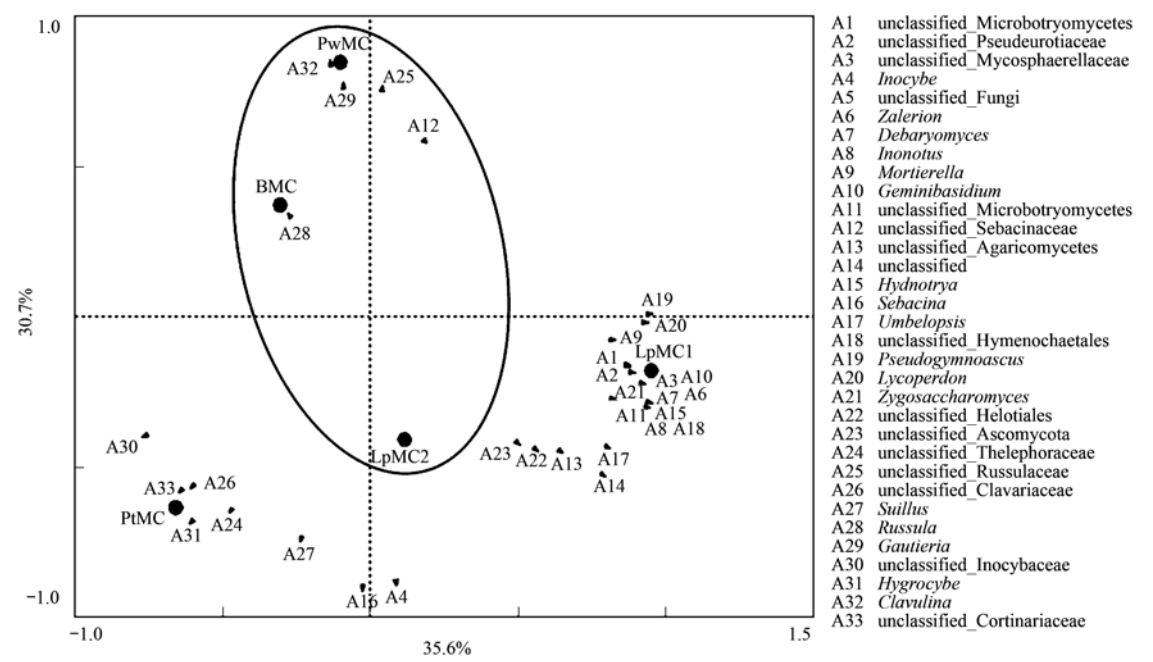


图3 土壤真菌群落 PCA 二维排序

Fig. 3 Two-dimensional PCA of soil fungi community

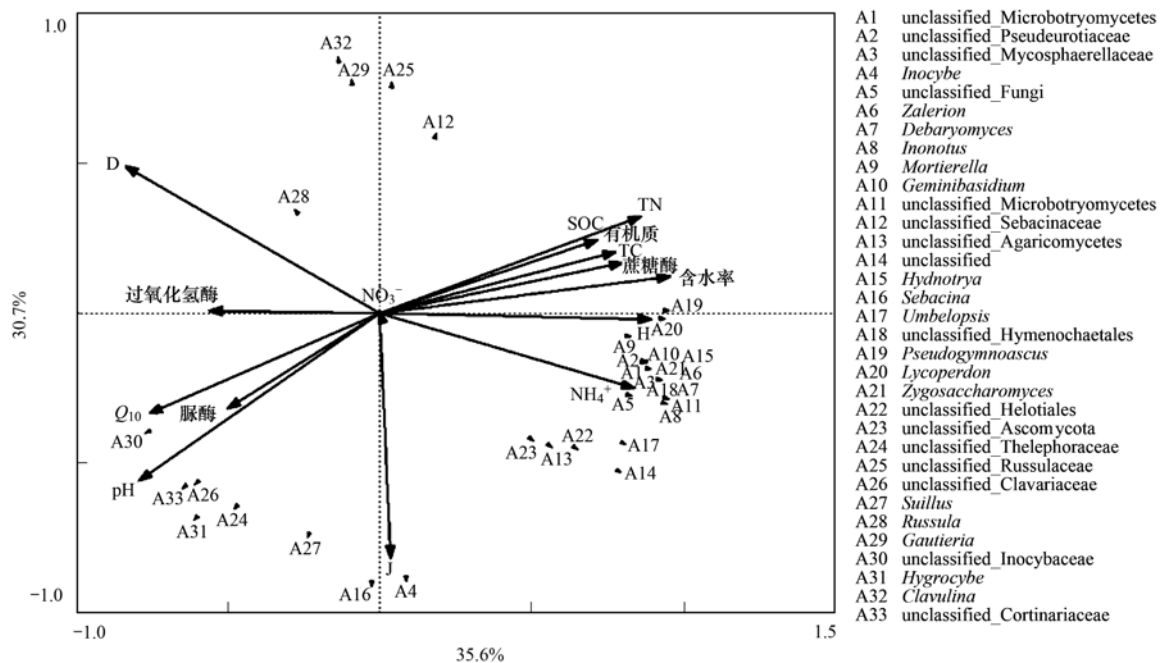


图4 土壤优势真菌群落与环境解释变量的 RDA 排序

Fig. 4 Ordination diagram of RDA with soil dominant fungi communities and environmental explanatory variables

率、林下植被多样性和均匀度以及土壤 NH_4^+ 含量呈显著正相关,与真菌群落 Simpson 指数和林下植被优势度指数呈极显著负相关;真菌群落 Simpson 指数与林下植被优势度指数显著正相关,与林下植被均匀度指数和土壤 NH_4^+ 含量呈极显著负相关;土壤真菌 ACE 指数与 Chao1 指数、pH、过氧化氢酶活性、脲酶活性和土壤温度显著正相关,与土壤含

水率、全氮含量、全碳含量、蔗糖酶活性和林下植被多样性显著负相关;土壤真菌 Chao1 指数与 pH、脲酶活性和土壤温度显著或极显著正相关,与含水率、全碳全氮含量和蔗糖酶活性极显著负相关。

2.4 土壤真菌群落结构与空间变量的相关性

PCNM 特征向量分析结果表明,3 个特征向量中有一个特征向量与土壤真菌群落结构具有

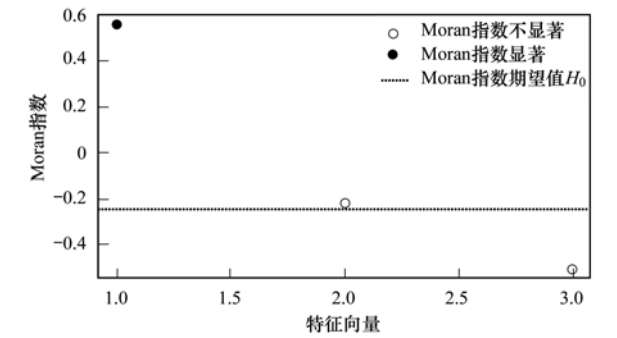


图6 PCNM 特征向量

Fig. 6 Eigenvector in PCNM analysis

表3 研究区真菌群落组成与空间变量的冗余分析(RDA)

Table 3 Redundancy analysis(RDA) for the general fungi composition-spatial relationships				
项目	自由度	方差	F	P (> F)
空间模型	2	0.117	0.530	0.800
残差	2	0.221	—	—

3 讨论

3.1 温带典型森林土壤环境因子及林下植被特征

作为植物和微生物的生存载体,土壤环境因子、林下植被等会直接或间接影响植物和微生物的生长繁殖. 土壤中有机质和碳氮的输入量主要依赖于植物残体的归还量及生物固氮^[18]. 华北落叶松为寒温性落叶针叶林,且样地位于高海拔,温度较低,植被凋落物较多. 凋落物中多含难以分解的木质素、单宁、树脂和蜡质等物质,且凋落的针叶密集覆盖于土壤表面形成空气不流通的环境,更有利于土壤养分的积累^[19];相反,油松为温性常绿针叶林,植被凋落物较少,土壤养分较为贫瘠;与针叶林相比,阔叶树种桦树的凋落物更易被分解,因此土壤中有有机质和有机碳含量较少(表1). 有研究表明,很多针叶树种具有“喜铵性”,从北方针叶林至热带雨林,酸性、弱酸性原始森林土壤中 NH_4^+ 的供应大都远高于 NO_3^- ,硝态氮相对和绝对的过低现象在原始针叶林中尤为明显^[20],这与本研究结果相一致(表1). 这可能是因为:①土壤中的 NO_3^- 不易被胶体吸附(易流失)^[20];②自养硝化菌不耐酸,由于湿润气候和较强淋溶作用而形成的森林土壤固有的低 pH 值抑制了硝化作用^[21];③针叶凋落物中含有较高的木素、单宁或游离酚类物质,不仅会降低有机质的分解速率,还会对土壤产生强烈的硝化抑制,降低土壤中 NO_3^- 的浓度;④北方针叶林下土壤冷湿,不利于氮矿化和硝化作用进行^[22]. 而且,硝化作用对冷湿条件的反应可能比氨化作用更敏感^[23],因而

会导致 NH_4^+ 相对“积累”. 土壤酶在土壤生态系统物质循环和能量流动方面扮演重要的角色^[24]. 本研究显示(图5),过氧化氢酶和脲酶活性与土壤真菌群落和林下植被具有显著相关性,蔗糖酶活性与土壤理化性质相关性较大,说明过氧化氢酶和脲酶可能主要来源于土壤真菌以及某些林下植被的分泌,蔗糖酶受土壤理化性质影响较大.

3.2 土壤真菌群落结构特征

本研究中5个真菌群落中子囊菌门和担子菌门居多[图2(a)]. 子囊菌和担子菌是土壤中主要的分解者^[25],子囊菌门大多数为腐生菌,可以分解很多难降解性有机质,如木质素和角质素,在养分循环中起着重要作用^[26]. 寒温性华北落叶松林凋落物较多,凋落物中多含难以分解的木质素、单宁、树脂和蜡质等物质,因此土壤真菌群落 LpMC1 和 LpMC2 中子囊菌门相对丰度大于其它3个真菌群落. 此外,一些真菌对植被类型的敏感程度高于细菌,如与植物共生的菌根真菌^[27],降解植物残体木质素的担子菌^[28]. 担子菌可能对华北落叶松林土壤环境适应性较差,因此其中的担子菌门相对丰度小于其它3个样地.

丝盖伞属和红菇属是本研究区中较为重要的两种菌根真菌[图2(b)]. 菌根是植物与真菌的互惠共生体,对促进生态系统中植物与真菌之间的物质交换、能量流动、信息传递等具有重要作用^[29]. 红菇属能与壳斗科、松科、桦木科、樟科、山茶科等树种共生^[30],本研究结果显示,红菇属与桦木科植物的共生能力更强. 被孢霉属是一种可培养的纤维素分解真菌,其分解纤维素能力很强. 土壤真菌群落组成与根腐病的发生存在一定的联系,健康植株根际土壤中被孢霉属的相对丰度显著高于发病植株根际土壤^[31],因此推测华北落叶松林根际抵抗根腐病的能力更强.

3.3 土壤真菌群落多样性与林下植被及土壤环境因子的关系

土壤微生物群落结构和多样性会受多种因素的影响,外因包括植被类型、气候条件、土壤类型和人类活动等,另一些为内因,主要是与土壤微生物生长密切相关的土壤有机质组成和土壤养分等. 本研究发现土壤真菌群落多样性与林下植被均匀度呈显著正相关(图5). 林下植被凋落物通过被土壤中的腐生微生物分解给土壤提供养分,这些养分又给真菌的生长繁殖提供营养,营养元素在真菌与林下植

被之间形成循环. 许多研究显示,在真菌分解实验中枯枝落叶具有增效作用^[32],因此林下植被与土壤真菌多样性具有相同的变化趋势,植被对土壤真菌群落多样性有显著的影响^[33].

pH 在土壤生物地球化学循环过程中具有重要作用,与植被类型、土壤类型、管理措施等有关^[34]. 本研究小尺度范围的生境中,pH 通过改变土壤环境因子和林下植被结构,进而影响真菌群落结构(图 5). 其中,土壤 pH 对腐生性真菌影响最大^[35],且土壤真菌在偏酸性土壤中占据优势地位^[36]. 也有研究表明,与细菌相比,真菌群落对土壤 pH 适应范围较宽,pH 在 5~9 之间的土壤均不会抑制真菌的生长^[37],因此该研究区中土壤真菌丰富度与土壤 pH 之间具有显著正相关性. 真菌群落对土壤含水率的变化很敏感,土壤含水率主要影响植物病原体以及共生体等与植物相关的真菌^[35]. 本研究中土壤含水率的增加会提高土壤真菌多样性,降低真菌丰富度(图 5).

真菌在土壤营养元素循环中具有重要的作用. 相关研究表明,氮素的添加(NH_4^+)影响了微生物氮循环过程,如硝化作用和固氮,导致云杉林土壤中真菌生物量的增加^[38]以及松树林中真菌群落组成的变化^[39],与本研究结果相符(图 5). 同时,本研究发现,土壤中 NH_4^+ 含量的变化会通过影响地上植被的多样性和优势度进而对土壤微生物群落结构产生影响(图 5).

有研究表明,真菌群落受到植被类型的影响很大,植被类型不同,凋落物不同,从而导致土壤理化性质产生显著差异,例如土壤 pH、含水率、凋落物的生物量和化学性质以及地下碳的分配等^[40]. 目前关于植被类型对土壤真菌群落影响的原因并没有统一的结论. 已有的研究认为,植物可能是通过影响土壤环境,进而影响土壤微生物群落结构和多样性,土壤微生物多样性与覆盖于土壤上的植物群落多样性呈正相关^[41];也有研究认为,植被类型对真菌群落产生影响一方面是通过植物分泌的根际分泌物,由于不同的植物会产生不同的分泌物,从而影响到土壤微生物群落的组成和分布^[42];另一方面则是植物能够与某些土壤真菌共生或形成菌根菌,这种种间合作的方式提高了合作土壤真菌的竞争能力,从而在有限的资源里就相对地抑制了其它真菌种类的生命活动,因此影响了土壤真菌的多样性^[43].

3.4 土壤真菌群落结构与扩散限制

Green 等^[44]在不同的空间和环境梯度上研究了

土壤真菌群落,结果表明,微生物群落呈现出高度的局域生物多样性,但区域生物多样性仅为中度水平,而在更大的距离尺度上,群落组成的变化率相对较小且不受植被的影响. 本研究中扩散限制对真菌群落多样性并没有显著影响(图 6),可能是由于本研究区域范围较小,且土壤表层分布有大量的菌根真菌孢子^[45],其主要依靠风、空气、水流及其他生物作为载体而进行被动扩散^[46].

4 结论

(1)5 个样地中共有 7 个真菌门和 33 个优势真菌属,其中,子囊菌门和担子菌门丰度最大,丝盖伞属、高腹菌属、湿伞属和红菇属分别是阴坡华北落叶松林、青杆林、油松林和桦树林中的优势菌属,背孢霉属和伞状霉属在高海拔华北落叶松和阴坡华北落叶松中优势度较大,涛旋孢属、*Geminibasidium*、*Hydnотrya* 和接合酵母属为样地高海拔华北落叶松中所特有.

(2)空间变量(PCNM)分析结果表明,扩散限制不是影响该研究区域真菌群落结构的关键因素.

(3)在属水平上对土壤真菌群落进行 PCA 和 RDA 分析,结果表明,该研究区土壤真菌群落组成受到环境选择(植被类型、土壤温度、pH、含水率、全氮含量、 NH_4^+ 含量、全碳含量、脲酶活性、蔗糖酶活性、林下植被优势度和均匀度)的显著影响.

参考文献:

- [1] Guo G X, Kong W D, Liu J B, et al. Diversity and distribution of autotrophic microbial community along environmental gradients in grassland soils on the Tibetan Plateau [J]. Applied Microbiology and Biotechnology, 2015, **99**(20): 8765-8776.
- [2] Cottenie K. Integrating environmental and spatial processes in ecological community dynamics [J]. Ecology Letters, 2005, **8**(11): 1175-1182.
- [3] Ferrenberg S, O'Neill S P, Knelman J E, et al. Changes in assembly processes in soil bacterial communities following a wildfire disturbance [J]. The ISME Journal, 2013, **7**(6): 1102-1111.
- [4] Roy M, Rochet J, Manzi S, et al. What determines *Alnus*-associated ectomycorrhizal community diversity and specificity? A comparison of host and habitat effects at a regional scale [J]. New Phytologist, 2013, **198**(4): 1228-1238.
- [5] Kranabetter J M, Durall D M, Mackenzie W H. Diversity and species distribution of ectomycorrhizal fungi along productivity gradients of a southern boreal forest [J]. Mycorrhiza, 2009, **19**(2): 99-111.
- [6] Peay K G, Kennedy P G, Bruns T D. Rethinking ectomycorrhizal succession: are root density and hyphal exploration types drivers of spatial and temporal zonation? [J]. Fungal Ecology, 2011, **4**(3): 233-240.

- [7] Pölme S, Bahram M, Yamanaka T, *et al.* Biogeography of ectomycorrhizal fungi associated with alders (*Alnus* spp.) in relation to biotic and abiotic variables at the global scale [J]. *New Phytologist*, 2013, **198**(4): 1239-1249.
- [8] Cox F, Barsoum N, Lilleskov E A, *et al.* Nitrogen availability is a primary determinant of conifer mycorrhizas across complex environmental gradients [J]. *Ecology Letters*, 2010, **13**(9): 1103-1113.
- [9] Bahram M, Pölme S, Kõljalg U, *et al.* Regional and local patterns of ectomycorrhizal fungal diversity and community structure along an altitudinal gradient in the Hyrcanian forests of northern Iran [J]. *New Phytologist*, 2012, **193**(2): 465-473.
- [10] Bahram M, Kõljalg U, Courty P E, *et al.* The distance decay of similarity in communities of ectomycorrhizal fungi in different ecosystems and scales [J]. *Journal of Ecology*, 2013, **101**(5): 1335-1344.
- [11] Tedersoo L, Bahram M, Jairus T, *et al.* Spatial structure and the effects of host and soil environments on communities of ectomycorrhizal fungi in wooded savannas and rain forests of Continental Africa and Madagascar [J]. *Molecular Ecology*, 2011, **20**(14): 3071-3080.
- [12] 关松荫. 土壤酶及其研究法 [M]. 北京: 农业出版社, 1986. Guan S Y. Soil enzymes and research method [M]. Beijing: China Agriculture Press, 1986.
- [13] Hill M O. Diversity and evenness; a unifying notation and its consequences [J]. *Ecology*, 1973, **54**(2): 427-432.
- [14] Simpson E H. Measurement of diversity [J]. *Nature*, 1949, **163**(4148): 688.
- [15] Chao A N. Nonparametric estimation of the number of classes in a population [J]. *Scandinavian Journal of Statistics*, 1984, **11**(4): 265-270.
- [16] Chao A N, Lee S M. Estimating the number of classes via sample coverage [J]. *Journal of the American Statistical Association*, 1992, **87**(417): 210-217.
- [17] Esty W W. The efficiency of good's nonparametric coverage estimator [J]. *The Annals of Statistics*, 1986, **14**(3): 1257-1260.
- [18] 熊汉锋, 王运华. 梁子湖湿地土壤养分的空间异质性 [J]. *植物营养与肥料学报*, 2005, **11**(5): 584-589. Xiong H F, Wang Y H. Spatial variability of soil nutrients in wetland of Liangzi Lake [J]. *Plant Nutrition and Fertilizer Science*, 2005, **11**(5): 584-589.
- [19] 杨秀清, 韩有志. 关帝山森林土壤有机碳和氮素的空间变异特征 [J]. *林业科学研究*, 2011, **24**(2): 223-229. Yang X Q, Han Y Z. Spatial variations of soil organic carbon and nitrogen of forestland in Guandi mountain [J]. *Forest Research*, 2011, **24**(2): 223-229.
- [20] 周礼恺. 土壤酶学 [M]. 北京: 科学出版社, 1987. Zhou L K. Soil enzymology [M]. Beijing: Science Press, 1987.
- [21] 崔晓阳, 宋金凤. 原始森林土壤 $\text{NH}_4^+/\text{NO}_3^-$ 生境特征与某些针叶树种的适应性 [J]. *生态学报*, 2005, **25**(11): 3082-3092. Cui X Y, Song J F. Soil $\text{NH}_4^+/\text{NO}_3^-$ nitrogen characteristics in primary forests and the adaptability of some coniferous species [J]. *Acta Ecologica Sinica*, 2005, **25**(11): 3082-3092.
- [22] 沙丽清, 孟盈, 冯志立, 等. 西双版纳不同热带森林土壤氮矿化和硝化作用研究 [J]. *植物生态学报*, 2000, **24**(2): 152-156. Sha L Q, Meng Y, Feng Z L, *et al.* Nitrification and net N mineralization rate of soils under different tropical forests in Xishuangbanna, Southwest China [J]. *Acta Phytocologica Sinica*, 2000, **24**(2): 152-156.
- [23] Pastor J, Post W M. Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles [J]. *Biogeochemistry*, 1986, **2**(1): 3-27.
- [24] Ineson P, Taylor K, Harrison A F, *et al.* Effects of climate change on nitrogen dynamics in upland soils. 1. A transplant approach [J]. *Global Change Biology*, 1998, **4**(2): 143-152.
- [25] Yelle D J, Ralph J, Lu F C, *et al.* Evidence for cleavage of lignin by a brown rot basidiomycete [J]. *Environmental Microbiology*, 2008, **10**(7): 1844-1849.
- [26] Beimforde C, Feldberg K, Nylinder S, *et al.* Estimating the phanerozoic history of the ascomycota lineages: combining fossil and molecular data [J]. *Molecular Phylogenetics and Evolution*, 2014, **78**: 386-398.
- [27] Bardgett R D, McAlister E. The measurement of soil fungal: bacterial biomass ratios as an indicator of ecosystem self-regulation in temperate meadow grasslands [J]. *Biology and Fertility of Soils*, 1999, **29**(3): 282-290.
- [28] Bossuyt H, Denef K, Six J, *et al.* Influence of microbial populations and residue quality on aggregate stability [J]. *Applied Soil Ecology*, 2001, **16**(3): 195-208.
- [29] 刘润进, 陈应龙. 菌根学 [M]. 北京: 科学出版社, 2007. Liu R J, Chen Y L. Mycorrhizology [M]. Beijing: Science Press, 2007.
- [30] 许旭萍, 李惠珍, 黄德鑫. 红菇生态的研究 [J]. *中国食用菌*, 2001, **20**(2): 25-27. Xu X P, Li H Z, Huang D X. Study on ecology of *Russula* [J]. *Edible Fungi of China*, 2001, **20**(2): 25-27.
- [31] 吴照祥, 郝志鹏, 陈永亮, 等. 三七根腐病株根际土壤真菌群落组成与碳源利用特征研究 [J]. *菌物学报*, 2015, **34**(1): 65-74. Wu Z X, Hao Z P, Chen Y L, *et al.* Characterization of fungal community composition and carbon source utilization in the rhizosphere soil of *Panax notoginseng* suffering from root-rot disease [J]. *Mycosystema*, 2015, **34**(1): 65-74.
- [32] Gartner T B, Cardon Z G. Decomposition dynamics in mixed-species leaf litter [J]. *Oikos*, 2004, **104**(2): 230-246.
- [33] Rousk J, Brookes P C, Bååth E. Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization [J]. *Applied and Environmental Microbiology*, 2009, **75**(6): 1589-1596.
- [34] Lauber C L, Strickland M S, Bradford M A, *et al.* The influence of soil properties on the structure of bacterial and fungal communities across land-use types [J]. *Soil Biology and Biochemistry*, 2008, **40**(9): 2407-2415.
- [35] Kivlin S N, Hawkes C V. Tree species, spatial heterogeneity, and seasonality drive soil fungal abundance, richness, and composition in Neotropical rainforests [J]. *Environmental Microbiology*, 2016, **18**: 4662-4673.
- [36] Ogilvie L A, Hirsch P R, Johnston A W B. Bacterial diversity of the broadbalk 'classical' winter wheat experiment in relation to long-term fertilizer inputs [J]. *Microbial Ecology*, 2008, **56**(3): 525-537.

- [37] Nevarez L, Vasseur V, Le Madec A, *et al.* Physiological traits of *Penicillium glabrum* strain LCP 08.5568, a filamentous fungus isolated from bottled aromatised mineral water[J]. International Journal of Food Microbiology, 2009, **130**(3): 166-171.
- [38] Arnebrant K, Bååth E, Söderström B. Changes in microfungal community structure after fertilization of scots pine forest soil with ammonium nitrate or urea[J]. Soil Biology and Biochemistry, 1990, **22**(3): 309-312.
- [39] Donnison L M, Griffith G S, Bardgett R D. Determinants of fungal growth and activity in botanically diverse haymeadows: effects of litter type and fertilizer additions[J]. Soil Biology and Biochemistry, 2000, **32**(2): 289-294.
- [40] Raich J W, Clark D A, Schwendenmann L, *et al.* Aboveground tree growth varies with belowground carbon allocation in a tropical rainforest environment[J]. PLoS One, 2014, **9**(6): e100275.
- [41] 张俊忠, 陈秀蓉, 杨成德, 等. 东祁连山高寒草地土壤可培养真菌多样性分析[J]. 草业学报, 2010, **19**(2): 124-132. Zhang J Z, Chen X R, Yang C D, *et al.* A study on the diversity of soil cultured fungi in the alpine grassland of Eastern Qilian Mountains[J]. Acta Prataculturae Sinica, 2010, **19**(2): 124-132.
- [42] Nayyar A, Hamel C, Lafond G, *et al.* Soil microbial quality associated with yield reduction in continuous-pea[J]. Applied Soil Ecology, 2009, **43**(1): 115-121.
- [43] 王芳, 图力古尔. 土壤真菌多样性研究进展[J]. 菌物研究, 2014, **12**(3): 178-186. Wang F, Bau T. Research advances in the diversity of soil fungi [J]. Journal of Fungal Research, 2014, **12**(3): 178-186.
- [44] Green J L, Holmes A J, Westoby M, *et al.* Spatial scaling of microbial eukaryote diversity[J]. Nature, 2004, **432**(7018): 747-750.
- [45] Berch S M, Fortin J A. Lectotypification of *Glomus macrocarpum* and proposal of new combination: *Glomus australe*, *Glomus versiforme*, and *Glomus tenebrosus* (Endogonaceae) [J]. Canadian Journal of Botany, 1983, **61**(10): 2608-2617.
- [46] Martiny J B H, Bohannan B J M, Brown J H, *et al.* Microbial biogeography: putting microorganisms on the map[J]. Nature Reviews Microbiology, 2006, **4**(2): 102-112.

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