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# 荒漠草原不同植被微斑块土壤粒径分布分形特征与养分的关系

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**摘 要** 采集宁夏中部干旱带荒漠草原4种植被(猪毛蒿、甘草、苦豆子、草木樨状黄芪)微斑块土壤剖面3个层次土壤,测定了各微斑块土壤颗粒粒级分布、有机质、pH值、土壤电导率(EC)、全氮、全磷和全钾等理化性质,探讨了不同植被微斑块土壤粒径分布的分形维数($D$)特征及其与土壤理化性质的关系.结果表明:斑块化植被分布可影响土壤粒径分布,其影响作用以草木樨状黄芪微斑块最大($D$=2.51),甘草微斑块最低($D$=2.46);分形维数与黏粒、粉粒含量呈显著正相关,而与砂粒含量呈显著负相关;土壤粒径分布分形维数与pH和EC呈显著正相关,与有机质和全氮含量呈显著负相关,与全磷和全钾含量无显著相关关系.斑块化植被分布有潜在土地盐碱化和土地退化的趋势.

**关键词** 荒漠草原; 植被微斑块; 土壤粒径分布; 分形维数特征

**Fractal dimension characteristics of soil particle size distribution under different vegetation patches in desert steppe and its relationship with soil nutrients.** DU Ya-xian[1], FAN Jin[1], LI Shi-yao[1], NIU Yu-bin[1], YU Hai-long[1*], HUANG Ju-ying[2] ([1]*College of Recourses and Environment*, *Ningxia University*, *Yinchuan* 750021, *China*; [2]*Institute of Environmental Engineering*, *Ningxia University*, *Yinchuan* 750021, *China*).

**Abstract**: Soil samples from four vegetation mini-patches (*Artemisia scoparia*, *Glycyrrhiza uralensis*, *Sophora alopecuroides*, *Astragalus melilotoides*) in a desert steppe in central Ningxia were collected. Soil physico-chemical properties including soil particle-size distribution, organic matter, pH, EC, total N, total K, total P of three depths were measured. The fractal dimension of particle size distribution characteristics of soils derived from four different vegetation mini-patches and their correlations with soil physico-chemical properties were examined. The results showed that patch vegetation distribution affected the distribution of soil particle size, with the *A. melilotoides* mini-patch being the highest ($D$=2.51) and *G. uralensis* mini-patch being the lowest ($D$=2.46). There were significant positive correlation between fractal dimensions and the contents of clay and silt, and negative correlation between fractal dimensions and sand content. Fractal dimensions were positively correlated with pH value and EC, negatively correlated with the contents of soil organic matter and total N, and had no correlation with the contents of soil total K and total P. The patchy vegetation distribution had potential trends of salinization and degradation.

**Key words**: desert steppe; vegetation mini-patch; soil particle-size distribution; fractal dimension characteristics.

土壤是由大小不同、形状各异的固体组分和孔隙以一定形式联结所形成的多孔介质,具有一定的分形特性[1-3].土壤粒径分布(particle-size distribution, PSD)是表征土壤结构和生产力的重要指标,它决定着土壤的质地与结构,进而影响土壤的持水性和保肥供肥性能[4-6].自Turcotte[7]提出多孔介质材料粒径分布的分形维数概念后,对分形理论应用于定量描述土壤结构及肥力特征的研究随之增多.

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如 Tyler 等[8]、杨培岭等[9]通过土壤粒径分布与质量分布的关联研究，提出了运用分形模型计算土壤粒径、团聚体的分形维数来表征土壤质地和结构的组成及其均匀程度.有研究表明，土壤粒径分布分形维数与土壤类型、土壤母质、地貌类型、植被类型密切相关[10-14]，并且可以用来表征土壤沙化和退化程度、分析成土强度及其发育环境[15-20].目前，关于土壤粒径分布特征对土壤物理性质的影响研究较少，而关于异质化群落分布下土壤粒径分布与土壤属性之间的关系研究则更少.

相对稳定的斑块状植被空间格局是植物适应环境的结果，是干旱区植被存在的主要形式[21].斑块状植被是植物群落的外在形态学表现，要寻找植物斑块格局演化的内在机制，必须分析植物群落演替的驱动力及其作用过程.在荒漠草原生态系统中，土壤要素的空间异质性使植物群落斑块镶嵌结构成为天然草地的基本景观[22-23].植被微生境因子空间异质性显著影响着群落空间异质性分布格局的形成[24].研究草地群落斑块的形成机制及其性状、格局的变化，对于深刻认识草地演替的本质，指导草地管理实践、维护草地生产力和生态功能的可持续性具有重要的意义.植被的空间格局以及土壤资源的异质性相互影响和相互制约形成了地表植被分布的空间异质性.植物群落的组成和植物种群分布格局的改变制约着土壤组成的异质化过程，土壤异质性变化常与生态系统中种群的分布有关[25].而土壤分形维数的变化是否影响到草原植物的生长及其异质化，以及植被斑块形成过程中土壤资源空间分异机理及其与植被相互响应机制研究则相对不足.因此，为探讨异质化群落分布下土壤粒径分布对土壤属性空间分布的影响，本研究以宁夏中部干旱带典型荒漠草原不同植被微斑块下发育的土壤为对象，研究土壤粒径分布的分形特征及其与土壤主要肥力因子的关系，确立不同植被微斑块下发育土壤和不同深度土壤粒径分布分形维数变化规律，以期为荒漠草原管理和土地沙化潜在威胁评价提供参考.

## 1　研究地区与研究方法

### 1.1　研究区概况

研究区位于宁夏盐池县柳杨堡乡杨寨子村的自然草地内(37°48′N，107°27′E)，海拔 1369～1390 m，位于宁夏中部干旱带，地处内陆半干旱向干旱区的过渡带，属于典型的温带大陆性气候，年均气温7.7 ℃，无霜期 165 d，年均蒸发量 2131.8 mm，年降水量 289.4 mm，降水在年内分配不均，多集中于7—9 月.样地地带性土壤类型为灰钙土[26]，土壤质地主要为砂壤土和砂土，土壤 pH、有机 C、全 N、有效 P 含量分别为 8.1～9.2、1.60～12.20 g·kg$^{-1}$、0.22～1.19 g·kg$^{-1}$、0.06～7.05 mg·kg$^{-1}$[27].土壤侵蚀模数为 3000～7000 t·km$^{-2}$·a$^{-1}$.植物群落结构较为简单，植被组成以草本为主，有猪毛蒿(*Artemisia scoparia*)、牛枝子(*Lespedeza potaninii*)、甘草(*Glycyrrhiza uralensis*)、苦豆子(*Sophora alopecuroides*)、草木樨状黄芪(*Astragalus melilotoides*)、猪毛菜(*Salsola collina*)、蒙古冰草(*Agropyron mongolicum*)和糙隐子草(*Cleistogenes squarrosa*)等.

### 1.2　样地设置

样地设置于宁夏盐池县柳杨堡乡杨寨子草原资源生态监测站地势均一且管理模式(放牧强度为4.4 只羊·hm$^{-2}$)一致的一片荒漠草地，地形平坦，无起伏，且面积超过 300 hm$^2$.研究区内有大小不等(10～50 m$^2$)的各类优势种不同的植物群落微斑块.2017 年 7 月下旬调查各优势种群群落斑块的优势种、斑块面积、盖度和高度，参照文献[23]研究方法，若斑块内植物与周边植物群落组成显著不同，且某一种植物在斑块内高度聚集，就以这种高度聚集的植物种对斑块进行命名.确定了猪毛蒿微斑块、甘草微斑块、苦豆子微斑块和草木樨状黄芪微斑块 4 个斑块类型.各样地的主要统计特征见表 1.

### 1.3　样品采集

试验于 2017 年 8 月上旬进行.每一个微斑块类型样点设 5 个平行样地，每个平行样地间隔距离在 30～50 m.采用样方法(样方面积 1 m×1 m)，统计每个样地内的植物种类、每种植物的植株数、盖度，用剪刀齐地面剪下地上部分植物，按物种装入牛皮纸袋带回实验室烘干(65 ℃，48 h)并称重.在各个样地内采用 5 点采样法，每个采样点间距 3～5 m.采样深度为 0～30 cm，每 10 cm 采集一个样品，将每层采集的样品分别混合装袋，土壤样品在室内阴干，去根和砾石，过 2 mm 筛.

### 1.4　测定项目与方法

土壤 pH 采用酸度计法测定；土壤电导率采用电导率分析仪测定；土壤有机质采用重铬酸钾容量法-外加热法测定；土壤全 N 采用凯氏定氮法测定；土壤全 P 采用 $HClO_4$-$H_2SO_4$消煮-钼锑抗比色法测定；土壤全 K 采用火焰光度法测定[28].

使用 Mastersizer 3000(英国，马尔文公司)激光粒度仪测定土壤粒径(以体积分数计)，该粒度仪的

表 1 不同植被微斑块统计数据
**Table 1 Statistics data of different vegetation mini-patches**

| 植被微斑块 Vegetation patch | 斑块形成时间 Patch formation time (a) | 斑块直径 Patch diameter (m) | 斑块高度 Patch height (cm) | 斑块盖度 Patch coverage (%) | 斑块密度 Patch density (plant · $m^{-2}$) | 斑块优势种 Patch dominant species | 斑块内物种数 Species number in each patch | 生物量 Biomass (g · $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| 背景值 Background | ≥20 | 500 | 32.7±1.4 | 53.2±2.1 | 31.2±2.4 | 牛枝子 *Lespedeza potaninii*,猪毛菜 *Salsola collina*,蒙古冰草 *Agropyron mongolicum* | 15 | 109.1±9.9 |
| AS | 2~3 | 5 | 34.1±0.8 | 63.8±0.8 | 43.5±0.4 | 猪毛蒿 *Artemisia scoparia* | 3 | 47.8±6.4 |
| GU | 2~3 | 4 | 47.1±0.7 | 61.5±1.5 | 19.5±0.4 | 甘草 *Glycyrrhiza uralensis* | 2 | 101.5±5.2 |
| SA | 3~5 | 4 | 35.4±0.9 | 76.7±0.9 | 22.3±0.5 | 苦豆子 *Sophora alopecuroides* | 3 | 82.8±9.0 |
| AM | 3~5 | 8 | 55.6±1.3 | 73.6±1.2 | 34.6±0.7 | 草木樨状黄芪 *Astragalus melilotoides* | 3 | 128.9±21.5 |

AS: 猪毛蒿微斑块 *Artemisia scoparia* mini-patch; GU: 甘草微斑块 *Glycyrrhiza uralensis* mini-patch; SA: 苦豆子微斑块 *Sophora alopecuroides* mini-patch; AM: 黄芪微斑块 *Astragalus melilotoides* mini-patch. 下同 The same below.

测量范围为 0.02~2000 μm.根据美国农业部(USDA)土壤质地分级标准[29]对土壤粒径进行分级:黏粒(<2 μm)、粉粒(2~50 μm)、极细砂粒(50~100 μm)、细砂粒(100~250 μm)、中砂粒(250~500 μm)、粗砂粒(500~1000 μm)、极粗砂粒(1000~2000 μm).

**1.5** 分形维数的计算方法

采用 Tyler 等[8]基于土壤粒径体积分数数据导出的分形模型计算分形维数($D$),公式为:

$$\frac{V(r<R_i)}{VT}=\left(\frac{R_i}{RL}\right)^{3-D}$$

式中:$r$ 为粒径;$R_i$为粒径划分中的第 $i$ 级粒径;$V$ 为小于粒径 $R_i$的土壤总体积;$VT$ 为土壤总体积;$RL$ 为土壤粒径分级中的最大粒径,本研究中 $RL$ 为 1000 μm.

上式中两边同时取对数,通过对数曲线的线性回归拟合方程,求出斜率值,3 与斜率值的差值即为分形维数($D$).

**1.6** 数据处理

采用 Excel 2003、SPSS 20.0 对数据进行统计分析,运用最小差异显著法(LSD)进行差异显著性检验,运用 Pearson 相关系数进行相关分析($\alpha=0.05$).用 Origin 9.0 作图.图表中数据为平均值±标准差.

## 2 结果与分析

**2.1** 不同微斑块土壤粒径分布(PSD)特征

土壤粒径分布频率曲线可以反映出土壤粒径的分布状况[30].如图 1 所示,不同微斑块 PSD 高峰范围非常相近:各微斑块内土样粒径分布曲线主要呈单峰型,且变化幅度较大,说明土壤粒径分布的非均匀程度较高.3 个土层间土壤粒径分形维数差异不显著,可能与发育自相同母质及研究区沉积特征有关.粒径峰值集中分布在 50~500 μm.

根据美国农业部(USDA)土壤质地分级标准,0~30 cm深度范围内土壤样本均为砂壤土.从表 2 可以看出,各微斑块的土壤粒径分布分形维数变化

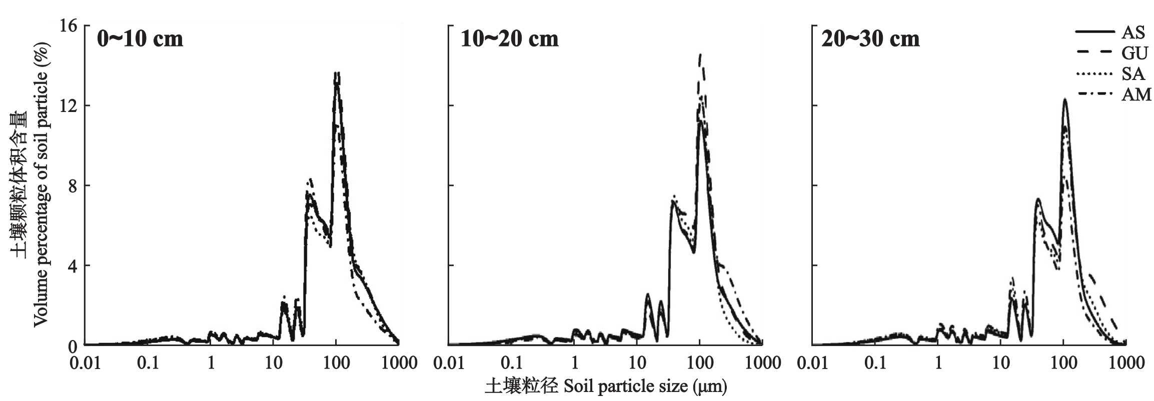


图 1 不同植被微斑块土壤粒径分布(PSD)特征
**Fig.1** Soil particle-size distribution (PSD) characteristics in different vegetation mini-patches.
AS: 猪毛蒿微斑块 *Artemisia scoparia* mini-patch; GU: 甘草微斑块 *Glycyrrhiza uralensis* mini-patch; SA: 苦豆子微斑块 *Sophora alopecuroides* mini-patch; AM: 黄芪微斑块 *Astragalus melilotoides* mini-patch. 下同 The same below.

表 2　不同植被微斑块土壤粒径分布与分形维数特征

**Table 2　Soil particle-size distribution and fractual features in different vegetation mini-patches**

| 微斑块类型 Mini-patch type | 土层 Soil layer (cm) | 土壤粒径体积百分含量 Volume percentage of soil particle size 黏粒 Clay | 粉粒 Silt | 极细砂粒 Very fine sand | 细砂粒 Fine sand | 中砂粒 Middle sand | 粗砂粒 Coarse sand | 分形维数 *D* | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| 背景值 Background | 0~10 | 7.29±0.30ABa | 38.84±2.49Aa | 35.37±1.92Ac | 17.09±0.65Aab | 1.61±0.49Aa | 0.03±0.03Aa | 2.48Aa | 0.95Aa |
| | 10~20 | 6.00±0.10Ba | 42.56±0.74Aab | 34.91±0.80Ac | 14.96±1.06Aa | 1.01±1.26Aa | 0.06±0.07Aa | 2.46Aa | 0.95Aa |
| | 20~30 | 8.40±0.66Aab | 44.00±8.16Aab | 35.46±0.78Aab | 16.80±3.05Aa | 0.75±1.30Ab | 0.03±0.05Aab | 2.50Aa | 0.95Aa |
| AS | 0~10 | 5.11±0.05Ab | 37.87±0.44Aa | 39.96±0.81Ab | 15.26±0.13Ab | 1.63±0.08Aa | 0.17±0.06Aa | 2.43Aa | 0.95Aa |
| | 10~20 | 6.72±1.96Aa | 41.39±6.31Aab | 36.39±2.74Abc | 14.44±4.34Aa | 1.06±1.15Aa | 0.03±0.03Ba | 2.51Aa | 0.94Aa |
| | 20~30 | 8.75±0.94Aab | 37.82±2.94Ab | 40.37±0.08Aa | 12.79±1.48Aa | 0.20±0.35Ab | 0.01±0.02Bb | 2.50Aa | 0.94Aa |
| GU | 0~10 | 5.55±0.23Bab | 35.67±0.61Ca | 41.63±0.78Aab | 15.55±0.18Ab | 1.31±0.01Ba | 0.30±0.10Aa | 2.43Ba | 0.95Aa |
| | 10~20 | 6.30±0.11Ba | 37.34±0.21Bb | 41.94±1.16Aa | 13.80±0.23Ba | 0.63±0.28Ca | 0.02±0.01Ba | 2.44Ba | 0.95Aa |
| | 20~30 | 7.58±0.51Ab | 42.07±0.52Aab | 31.84±0.33Bbc | 16.07±0.79Aa | 2.38±0.06Aa | 0.09±0.05Ba | 2.51Aa | 0.95Aa |
| SA | 0~10 | 4.10±1.55Bb | 26.77±5.37Bb | 45.08±1.65Aa | 22.36±4.84Aa | 1.58±0.44Aa | 0.13±0.01Aa | 2.45Aa | 0.94Aa |
| | 10~20 | 6.53±0.54ABa | 45.28±1.70Aa | 36.01±1.53Bbc | 12.02±0.35Aa | 0.11±0.18Ba | 0Ba | 2.49Aa | 0.94Aa |
| | 20~30 | 8.92±0.66Aab | 49.30±0.74Aab | 26.43±4.16Cc | 15.31±4.61Aa | 0.37±0.36Bb | 0Bb | 2.53Aa | 0.94Aa |
| AM | 0~10 | 5.57±0.75Bab | 38.95±0.51Bb | 39.78±1.23Ab | 14.09±1.29Ab | 1.24±0.83Aa | 0.35±0.48Aa | 2.48Aa | 0.94Aa |
| | 10~20 | 5.73±0.62Ba | 36.50±0.13Bb | 39.26±1.09ABab | 16.91±0.97Aa | 1.56±0.23Aa | 0.07±0.10Aa | 2.48Aa | 0.95Aa |
| | 20~30 | 9.74±0.41Aa | 51.53±6.29Aa | 33.49±2.98Bb | 5.09±1.62Bb | 0.11±0.18Ab | 0Ab | 2.56Aa | 0.92Aa |

不同小写字母表示同一土层不同微斑块间差异显著，不同大写字母表示同一微斑块不同土层间差异显著（$P<0.05$）Different lowercase letters meant significant difference among different vegetation patches in the same soil layer, and different capital letters meant significant difference among different soil layers in the same vegetation patch at 0.05 level. 下同 The same below.

范围较窄,且土壤粒径分布规律性和异质性程度较小;各微斑块内土壤粉粒数量变化范围较大,而黏粒和砂粒含量则相差不大.黄芪微斑块的粉粒含量最高;猪毛蒿微斑块的极细砂粒含量最高;苦豆子微斑块的细砂粒含量最高;甘草微斑块的中砂粒含量最高,粉粒含量最低;各微斑块黏粒含量都低于背景值.从土壤粒径分布分形维数(*D*)来看,黄芪微斑块最大(2.56),甘草微斑块最小(2.43).各微斑块内不同土壤深度土壤机械组成均表现为砂粒体积分数最高,在 38.7%~69.2%;黏粒体积分数最低,在 4.1%~9.7%;粉粒体积分数居中,在 26.8%~51.5%.可见,各植被微斑块土壤中的细颗粒物质含量均低于背景值,说明斑块化植被分布可能不利于土壤结构改善,且随着土壤深度的增加,各微斑块土壤粒径分布分形维数都有增大的趋势,说明各斑块表层土壤都有潜在沙化威胁,且威胁程度是上层土壤大于下层土壤.

## 2.2　不同植被微斑块土壤质地与土壤粒径分布分形维数的关系

从表 3 可知,研究区 4 个微斑块土壤粒径分布分形维数介于 2.32~2.63.各微斑块土壤粒径分布平均分形维数大小顺序:草木樨状黄芪微斑块>苦豆子微斑块>猪毛蒿微斑块>甘草微斑块.其中,甘草微斑块土壤粒径分布分形维数均值小于背景值.

表 4 显示,土壤 PSD 分形维数与黏粒、粉粒含量呈显著正相关,与极细砂粒、细砂粒、中砂粒、粗砂粒含量呈显著负相关,这表明土壤粒径分布分形维数对各粒级土粒含量的反映程度存在差异,土壤中黏粒含量越高,砂粒含量越少,分形维数越大,这与赵文智等[4]、文海燕等[31]的研究结论一致,说明砂粒和黏粒的相对含量决定土壤粒径分布分形维数,土壤粒径分布分形维数能较好地表征土壤粒径组成,并反映土壤质地的均一程度.

## 2.3　土壤粒径分布分形维数与土壤化学性质的关系

如表 5 所示,不同微斑块间的土壤化学性质存在差别.随着土层深度的增加,各微斑块土壤 pH 和 EC 均呈升高趋势,这主要与采样的季节有关,研究区 8 月属于雨季,降水较多,将表层盐分淋溶至深层,而有机质、全 N 含量呈降低趋势.对于 0~10 cm 土层,苦豆子微斑块土壤 pH、全 K 含量显著高于黄芪和猪毛蒿微斑块,黄芪微斑块土壤全N含量显著

表 3　土壤质地与土壤粒径分布分形维数的关系

**Table 3　Relationship between soil texture and soil particle size distribution fractal dimensions**

| 微斑块类型 Mini-patch type | 成土母质 Parent material | 分形维数 Fractal dimension 变幅 Amplitude | 均值±标准差 Mean±SD |
|---|---|---|---|
| 背景值 Background | 风积母质 Weathering parent material | 2.45~2.53 | 2.48±0.01 |
| AS | 风积母质 Weathering parent material | 2.42~2.57 | 2.48±0.01 |
| GU | 风积母质 Weathering parent material | 2.41~2.56 | 2.46±0.02 |
| SA | 风积母质 Weathering parent material | 2.32~2.61 | 2.49±0.08 |
| AM | 风积母质 Weathering parent material | 2.42~2.63 | 2.51±0.04 |

表 4 土壤粒径分布与分形维数的相关系数

Table 4 Correlation coefficients between soil particle-size distribution and fractal dimension

| 微斑块类型 Mini-patch type | 指标 Index | 黏粒 Clay | 粉粒 Silt | 极细砂粒 Very fine sand | 细砂粒 Fine sand | 中砂粒 Middle sand | 粗砂粒 Coarse sand |
|---|---|---|---|---|---|---|---|
| 背景值 Background | 分形维数 Fractal dimension | 0.240 | 0.770 | 0.085 | −0.319 | −0.750 | −0.660 |
| AS | 分形维数 Fractal dimension | 0.789 | 0.566 | −0.563 | −0.595 | −0.746 | −0.904* |
| GU | 分形维数 Fractal dimension | 0.806 | 0.894* | −0.985** | 0.781 | 0.944** | −0.146 |
| SA | 分形维数 Fractal dimension | 0.951** | 0.910* | −0.951** | −0.584 | −0.659 | −0.793 |
| AM | 分形维数 Fractal dimension | 0.947** | 0.929** | −0.982** | −0.807 | −0.930** | −0.599 |
| 整体 Total | 分形维数 Fractal dimension | 0.854** | 0.788** | −0.788** | −0.514* | −0.479* | −0.433* |

* $P<0.05$; ** $P<0.01$. 下同 The same below.

表 5 不同植被微斑块土壤化学性质

Table 5 Soil chemical properties among different vegetation mini-patches

| 微斑块类型 Mini-patch type | 土层 Soil layer (cm) | pH | 电导率 EC (μS·cm⁻¹) | 有机质 Organic matter (g·kg⁻¹) | 全 N Total N (g·kg⁻¹) | 全 P Total P (g·kg⁻¹) | 全 K Total K (g·kg⁻¹) |
|---|---|---|---|---|---|---|---|
| 背景值 | 0~10 | 8.81±0.01Aa | 75.00±0.00Cb | 3.54±0.12Ad | 0.38±0.00Ac | 0.32±0.00Cc | 20.04±0.36Bbc |
| Background | 10~20 | 8.73±0.01Ba | 80.00±0.00Bc | 3.53±0.09Ab | 0.37±0.01Ac | 0.34±0.00Bc | 21.08±0.01Aab |
| | 20~30 | 8.68±0.01Cc | 90.00±0.00Ad | 3.00±0.09Bc | 0.30±0.04Aa | 0.38±0.00Aa | 20.70±0.02ABa |
| AS | 0~10 | 8.14±0.02Bd | 75.00±0.00Cb | 6.66±0.14Aab | 0.46±0.02Ab | 0.34±0.00Bb | 19.53±0.16Cc |
| | 10~20 | 8.16±0.01Bc | 192.50±2.50Bb | 6.52±0.36ABa | 0.44±0.02Aab | 0.36±0.00Ab | 20.26±0.16Bc |
| | 20~30 | 8.77±0.06Ac | 280.00±5.00Abc | 5.39±0.21Ba | 0.35±0.01Ba | 0.34±0.00Ba | 20.94±0.08Aa |
| GU | 0~10 | 8.12±0.00Ad | 85.00±0.00Ca | 7.33±0.28Aa | 0.47±0.00Aab | 0.35±0.00Ab | 20.82±0.16Aa |
| | 10~20 | 8.14±0.00Ac | 217.50±7.50Ba | 6.40±0.28Aa | 0.39±0.00Bc | 0.34±0.00Ac | 21.39±0.11Aa |
| | 20~30 | 9.06±0.00Ab | 355.00±15.00Aa | 5.06±0.00Bab | 0.35±0.01Ca | 0.34±0.01Aa | 21.25±0.15Aa |
| SA | 0~10 | 8.27±0.01Bb | 77.50±2.50Cab | 5.75±0.07Bc | 0.45±0.01Ab | 0.34±0.01Ab | 21.04±0.06A |
| | 10~20 | 8.19±0.01Cc | 195.00±0.00Bb | 6.44±0.09Aa | 0.40±0.00Bbc | 0.34±0.00Ac | 20.33±0.35Ac |
| | 20~30 | 9.20±0.02Aa | 265.00±20.00Ac | 4.86±0.04Cb | 0.34±0.01Ca | 0.36±0.03Aa | 20.37±0.46Aa |
| AM | 0~10 | 8.21±0.01Cc | 80.00±5.00Cab | 6.11±0.39Abc | 0.51±0.00Aa | 0.39±0.00Ca | 20.38±0.12Aab |
| | 10~20 | 8.53±0.04Bb | 195.00±0.00Bb | 5.71±0.50Aa | 0.45±0.00Ba | 0.37±0.01Aa | 20.62±0.05Abc |
| | 20~30 | 9.29±0.01Aa | 320.00±5.00Aab | 5.13±0.05Aab | 0.30±0.01Ca | 0.36±0.00Ba | 20.49±0.51Aa |

高于苦豆子和猪毛蒿微斑块,猪毛蒿微斑块土壤全 P 含量显著高于黄芪微斑块;对于 10~20 cm 土层,黄芪微斑块土壤 pH、全 N、全 P 含量显著高于甘草微斑块,甘草微斑块土壤 EC、全 K 含量显著高于苦豆子和猪毛蒿微斑块;对于 20~30 cm 土层,黄芪微斑块土壤 pH 显著高于猪毛蒿和甘草微斑块,猪毛蒿微斑块的土壤有机质含量显著高于苦豆子微斑块,土壤全 N 含量显著高于黄芪微斑块.

由表 6 可知,土壤全 P、全 K 与各粒级土壤颗粒、分形维数无显著相关关系;土壤粒径分布分形维数、黏粒与土壤 pH、EC 呈显著正相关,与土壤有机质、全 N 呈显著负相关;土壤粉粒与土壤 pH、EC 呈显著正相关,与土壤全 N 呈显著负相关;土壤砂粒与土壤 pH、EC 呈显著负相关,与土壤全 N 呈显著正相关.这说明土壤粒径分布分形维数可以反映一定机械组成条件下土壤 pH 和 EC 等土壤化学性质.

## 3 讨 论

### 3.1 不同微斑块间土壤粒径分布分形维数差异

土壤粒径分布分形维数是不同粒径含量的综合反映,可用以描述土壤内部复杂与不规则结构[32].本研究表明,各微斑块内土壤质地有变粗的趋势,而土壤质地越粗,越难形成很好的结构.各微斑块间不同粒级的土壤粒径分布差异较大,而植被的斑块状分布格局是影响土壤颗粒组成空间异质性的重要因素[33].土壤分形维数可以用来比较土壤成土强度及发育环境[34].本研究中,草木樨状黄芪微斑块生物量大,植被覆盖较高,土壤粒径分布分形维数值也相对较大.较大的植被覆盖和生物量能稳定成土环境,使土壤腐殖化和黏化作用增强,风蚀物、凋落物不断地在植物丛内聚积,这与常庆瑞等[35]、安韶山等[36]的结论一致.土壤粒径分布分形维数分布的异质性

表 6　土壤粒径分布、分形维数与土壤养分的相关系数

Table 6　Correlation coefficients between soil particle-size distribution, fractal dimension and soil nutrients

| | pH | 土壤电导率 EC | 有机质 Organic matter | 全 N Total N | 全 P Total P | 全 K Total K |
|---|---|---|---|---|---|---|
| 黏粒 Clay | 0.784** | 0.807** | -0.590** | -0.827** | 0.091 | 0.018 |
| 粉粒 Silt | 0.595** | 0.596** | -0.346 | -0.636** | 0.181 | -0.190 |
| 极细砂粒 Very fine sand | -0.710** | -0.632** | 0.552** | 0.617** | -0.128 | 0.083 |
| 细砂粒 Fine sand | -0.357 | -0.461* | 0.082 | 0.495* | -0.197 | 0.253 |
| 中砂粒 Middle sand | -0.145 | -0.227 | 0.083 | 0.427* | 0.000 | 0.061 |
| 粗砂粒 Coarse sand | -0.342 | -0.534** | 0.469* | 0.543** | 0.221 | -0.136 |
| 砂粒 Sand | -0.631** | -0.577** | 0.235 | 0.630** | -0.137 | 0.133 |
| 分形维数 Fractal dimension | 0.611** | 0.645** | -0.456* | -0.604** | 0.070 | -0.076 |

程度越大,土壤质地越不均匀,土壤粒径分布分形维数值也越大[37].本研究中,各微斑块间土壤粒径分布分形维数存在差异,但变幅较小,且土壤粒径分布规律性和异质性程度较小.分析其原因,本研究区土壤母质主要为风积物,质地相对均一.说明土壤粒径分布虽受到其植被环境变化的影响,但其分形维数更多地继承了成土母质的特征[38].此外,微斑块内植物的异质性与土壤异质性相互影响相互制约,主要表现为:在不同植被微斑块内,土壤理化性质存在差异.这是由于不同植被微斑块内存在各自的微环境,其凋落物的分解和养分循环不同,这在不同程度上改变了土壤理化性质.土壤的空间异质性促使适生生物迁入或者保留,而非适生生物则隐退或消失,形成了与背景植被性状迥异的斑块群落,且草地群落的组成结构逐渐简单化,植物种类减少(表 1).说明微斑块内植物组成和分布格局的改变制约着土壤组成的异质化过程[39].

### 3.2　微斑块土壤粒径分布分形维数与土壤颗粒组成的关系

土壤粒径分布(PSD)是反映土壤结构和土壤发育程度的重要指标之一.分形维数大小反映了土壤组成中黏粒、粉粒和砂粒含量的变化以及土壤结构的变化[40].通常来说,土壤细粒物质含量越高,分形维数越大.本研究中,分形维数数值的大小随着土壤黏粒(<2 μm)、粉粒(2~50 μm)百分含量的增加呈逐渐增大的趋势,随着砂粒含量的增加呈逐渐减小的趋势.这与吕圣桥[41]和赵文智等[4]的研究结果一致.各微斑块土壤颗粒分形维数均随土层深度增加而趋于稳定(表 2 和表 3),但分形维数略高于赵文智等[4]在土地沙质荒漠化发展过程中固定沙地土壤粒径分形维数的变化区间,说明还有潜在沙化威胁.究其原因,主要是研究样地地势平坦但位于荒漠草原低洼处,且土壤母质来源于风积母质,质地均一.说明成土母质与沉积环境是决定深层土壤颗粒分形维数的关键因素.相似的环境因子组合下分布着相似的土壤,并占据相应的空间位置.环境组合越相似,其对应的土壤也应越相似[42].本研究区土壤是长时间尺度下风化、成土作用的结果,且其地势平缓,空间异质性理应相对均质,但在本研究中,土壤颗粒分布表现出一定的空间异质性并与斑块状植被分布形成组合,这可能与动物采食习性差异和斑块内不同植物根系、叶片滞尘差异以及土壤微生物等通过物理、化学及生物过程改变土壤粒径分布有关.

### 3.3　土壤粒径分布、分形维数与土壤养分的关系

理想的粒径分布及养分条件能为植被生长繁衍提供适宜的土壤肥力环境.土壤粒径分布可以用来表征土壤水分和养分持有性能的基本物理参数,并能体现土壤结构、养分状况和养分转化程度及转化速率等[43-44].土壤黏粒和粉粒的吸附作用是土壤有机质稳定的主要因素,黏粒和粉粒的数量可以用来衡量土壤有机质是否可以被稳定吸附于土粒表面.土壤有机质、全 N 含量的降低表征土壤肥力水平降低[45].

在本研究中,随着土壤粒径分布分形维数的增大,土壤有机质、土壤全 N 含量降低,这与红壤丘陵区耕作土壤[45]以及石灰岩区土壤[46]分形特征及其与土壤性质的关系的研究结果一致.可见,土壤粒径分布分形维数值在某种程度上反映了土壤肥力水平的变化.从土壤质量变化与植被演替关系的角度来看,土壤粒径分布分形维数不仅可以反映土壤颗粒组成特征和土壤质量状况,而且在一定程度上反映了荒漠草原的退化程度.

有研究表明,土壤分形维数能够反映土壤结构、属性及肥力[47-48].土壤电导率(EC)能够反映土壤的盐碱状况,EC 提高表明土壤盐碱化加重[29].在本研究中,土壤 pH、EC 与土壤粒径分布分形维数呈显著

正相关,且各植被微斑块土壤 EC 均高于背景草地,这与晋西黄土区不同林地土壤粒径与土壤肥力相关性的研究结论一致[49].这表明斑块化植被分布有潜在土地盐碱化趋势.

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## 封 面 说 明

封面图片由江西农业大学国土资源与环境学院硕士李琪于 2018 年 11 月 26 日拍摄于南昌市瑶湖郊野森林公园.该公园位于江西省南昌市高新区麻丘镇瑶湖东岸,属亚热带季风性气候,年均温大于 13 ℃,年降水量大于 800 mm,主要植被为亚热带常绿阔叶林.该公园在建设过程中以大面积的森林、草地、水系和湿地等景观作为背景框架,以黄金海岸沙滩、水中木栈道、热带风情岛和杜鹃山等园中园作为点缀,打造出一个湿地生态恢复与重建、调节区域气候等与旅游相结合的生态型公园.瑶湖郊野森林公园的建成对优化南昌市大气环境和绿地景观具有重要意义.

杜雅仙, 樊瑾, 李诗瑶, 等. 荒漠草原不同植被微斑块土壤粒径分布分形特征与养分的关系. 应用生态学报, 2019, **30**(11): 3716-3724

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