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# 生态学报

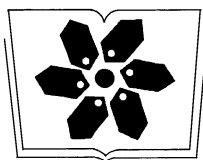
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# 生态学报

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**封面图说:** 红树林粗大的气生根——红树林是热带、亚热带海湾及河口泥滩上特有的常绿灌木或乔木群落。由于海水环境条件特殊,红树林植物具有一系列特殊的生态和生理特征。其中之一就是气根,红树从根部长出许多指状的气生根露出海滩地面,以便在退潮时甚至潮水淹没时用以通气,故称呼吸根。在中国,红树林主要分布在海南、广西、广东和福建省沿海,它一般分布于高潮线与低潮线之间的潮间带,往往潮差越大,红树的呼吸根就长得越高越粗大。

彩图提供: 陈建伟教授 北京林业大学 E-mail: cites.chenjw@163.com

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张伟东, 吕莹, 肖莹, 王雪峰, 尚艳芳. 线虫群落对抚顺煤矸石山周边土壤可溶性盐污染的响应. 生态学报, 2012, 32(8): 2439-2446.

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## 线虫群落对抚顺煤矸石山周边土壤 可溶性盐污染的响应

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**摘要:**于 2006 年 5 月对抚顺西露天矿西舍场煤矸石山周边的次生盐渍化样地进行可溶性盐含量和土壤线虫调查,经淘洗-过筛-离心漂浮法提取土壤线虫,应用线虫多样性指数和功能类群指数研究该区域土壤线虫群落的特征及差异。研究结果表明,抚顺西露天矿西舍场矸石山周围环境受到了煤矸石风化产生的以硫酸钠为主的可溶性盐污染,但污染程度不高,土壤整体健康状况良好;共鉴定出线虫 29 属,其中 *Acrobeloides*、*Cervidellus* 和 *Mesorhabditis* 为优势属,随采样点距矸石山距离的增加线虫优势属也有所变化;研究区域中食细菌线虫和植物寄生线虫的绝对丰度高于食真菌线虫和捕食-杂食线虫的绝对丰度;土壤 pH、矿化度、 $\text{HCO}_3^-$ 、 $\text{Cl}^-$ 、 $\text{SO}_4^{2-}$ 、 $\text{NO}_3^-$  与线虫生态指数间存在显著相关关系。因此,通过开展线虫群落对土壤可溶性盐污染的响应研究,能为促进土壤生态系统健康发展提供科学依据。

**关键词:**土壤线虫群落;可溶性盐污染;土壤生态系统;生态指数

## Responses of soil nematode communities to soluble salt contamination around Gangue hill in Fushun

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**Abstract:** Soluble salt contents and soil nematode communities were investigated to evaluate soil pollution dues to soluble salt contents in the secondary salinization plots around the Gangue hill of Fushun West open-pit mine in May, 2006. Six sampling sites were established along with the vertical direction to the Gangue hill between Tiantun and Qingtaizi, and site 1 was closest to the Gangue hill, while site 6 was the most distant to the hill. Annual herbs were more likely to distribute at sites that closer to Gangue hill, while perennial herbs became more and more common along with the increasing distance from the hill. The values of soil pH showed a increased trend from site 1 to site 6; the highest degree of mineralization, the highest contents of  $\text{HCO}_3^-$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  appeared at site 1. In contrast, the contents of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  were higher at site 6 than those at other sites. Soil nematodes were extracted from soil samples by using elutriate-sieving-flotation and centrifugation methods, and were used as bioindicators for assessing soil quality in the present study. Nematode abundance, diversity indices (Shannon-Wiener diversity index  $H'$ , Pielou evenness index  $J'$ , Simpson dominance index  $\lambda$ , trophic diversity index  $TD$ , specise richness  $SR$ ), functional indices (Wasilewska index  $WI$ , maturity index  $MI$ ), life history strategy (colonizer-persister), community structure and assemblage compositions were used to reveal the differences of soil nematode communities among different sites in this study area. The observed results showed that the environment in the sampling area was polluted by soluble sulfate which was a main production created by weathering of Gangue, but the degree of pollution was not very serious. In general, the soil was healthy in this area. Twenty-nine genera of nematodes were

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identified, *Acrobeloides Cervidellus* and *Mesorhabditis* were the three most dominant genera at all sampling sites, and the dominant genera changed with the increasing distance to the Gangue hill. No significant differences in the values of  $\lambda$ ,  $H'$ ,  $MI$  and  $J'$  were observed among 6 sites.  $MI$  showed a trend which is inversely proportional to the distance from Gangue hill. Both the highest values of  $WI$ ,  $\lambda$  and the lowest values of  $f/b$ ,  $MI$ ,  $J'$  appeared at site 6. The absolute abundances of bacterivores and plant-parasites nematodes were higher than those of fungivores and omnivore-predators, which suggesting bacterivorous and plant-parasitic nematodes were more diffuse than fungivores and omnivore-predators. Soil nematode communities were altered by soil elements only apart from contents of  $\text{CO}_3^{2-}$ ,  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$ . The degree of mineralization and contents of  $\text{HCO}_3^-$  positively correlated with the number of species ( $S$ ) and  $SR$ , and soil pH and content of  $\text{NO}_3^-$  negatively correlated with nematode ecological indices. The content of  $\text{Cl}^-$  positively correlated with  $WI$ , but negatively with  $TD$ . The contents of  $\text{SO}_4^{2-}$  significantly correlated with  $WI$ ,  $\lambda$ ,  $J'$ ,  $f/b$  and  $TD$ . The above results indicate that the responses of nematode communities to soluble salt contamination are effective to monitor the soil environment quality and can provide scientific bases to promote the healthy development of soil ecosystems.

**Key Words:** soil nematode community; soluble salt contamination; soil ecosystem; ecological indices

大量的煤矸石堆积及其自燃对矿区以及周边环境造成严重的污染和危害,煤矸石经雨水淋溶形成的含有盐基离子的酸性水渗透到地下,严重污染矿区和周边环境的地表水、地下水以及土壤。

土壤线虫是土壤生态系统的重要功能组分<sup>[1-2]</sup>,在有机质分解、植物营养矿化及养分循环过程中起重要作用<sup>[2-3]</sup>。由于土壤线虫类群和数量丰富,很多物种可以在极端条件下生存<sup>[4]</sup>,而且世代时间短,对生境变化反应灵敏,对其研究不仅有助于揭示土壤生态系统的结构,还可以提供有关土壤生态过程的独特信息<sup>[5]</sup>,因此被广泛应用于土壤干扰程度的指示生物<sup>[6-8]</sup>。线虫具有监测土壤系统过程及状况的潜力<sup>[5]</sup>,可以作为不同生态系统土壤过程的指示因子<sup>[9-11]</sup>。土壤线虫群落组成及多样性的变化还可以指示土壤生态系统扰动及恢复水平<sup>[12-15]</sup>。20 世纪 80 年代以来国外关于不同环境条件及管理措施下土壤线虫群落变化的研究得到重视<sup>[16-20]</sup>。我国则从 20 世纪 90 年代开始有相关报道<sup>[14, 21-24]</sup>。

本文以抚顺西露天矿西舍场煤矸石山周边为实验样地,着重研究土壤线虫群落在不同盐基离子污染梯度状态下的数量、群落组成、多样性等的变化趋势和特征,反映其生存的土壤环境质量状况,为以线虫作为污染土壤的诊断指标提供理论依据。通过研究土壤线虫物种多样性、营养类群多样性、生活史多样性和功能多样性的分布规律及其各种生态指数,重点开展线虫群落对可溶性盐污染土壤的响应研究,为促进土壤生态系统健康发展提供科学依据,为进一步开展土壤污染修复工作提供参考,为从土壤动物学角度进行可溶性盐污染土壤指示评价提供有效的方法。

## 1 样地概况

抚顺市位于辽宁省东北部,抚顺煤田是辽宁省最大产煤矿区。西露天矿位于抚顺煤田的最西部,即抚顺市西南侧。西露天矿是世界上最大的露天矿之一,也是我国最大的综合露天矿。露天矿于 1914 年始建,西舍场是西露天矿 3 个舍场中最大的,它位于西露天矿坑西 2.5 km,于 1928 年开始起用,至今已有 70 余年的堆积历史,其占地面积约 13.4 km<sup>2</sup>,主要收容露天采矿的剥离物如油母页岩贫矿和废页岩。这些煤矸石的存放占用了大量的土地,严重污染了环境,给当地人民生活带来了极大的危害。

抚顺地区属温带半湿润季风型大陆气候,平均气温 5.5—7.4 ℃,平均降雨量为 826 mm,降雨集中于 7、8 月份。西露天矿坑周围地势较为平坦,大部分已用作耕地,海拔高度为 70—80 m,至西露天矿坑南部边界转为山坡。田屯—青台子地区地形起伏具有从东北向西南倾斜的趋势。西舍场的西南方向 1.5 km 处,由南向北贯穿的是李石河,自南向北流经田屯—青台子地区,东岸接受西舍场矸石山坡下发育的 5 条“V”型冲沟的溪流水补给。李石河还是天然屏障,使得煤矸石山溢流水污染范围局限于田屯、青台子地区的河东岸地段。从总体上看,西舍场南高北低,汇水方向由南向北,径流由南部丘陵流向舍场。

本研究对抚顺西露天矿西舍场矸石山周围主要植物进行鉴定(表1),结果如下:距矸石山较近的样点采集到的植物多为1年生草本植物,且为典型的旱生植物,根系发达,叶肉质,并耐盐碱,能够在贫瘠的土壤上生长繁殖。而随着距矸石山距离的增加,土壤养分条件有所改善,多年生草本植物的数量有所增加。

表1 抚顺西露天矿西舍场矸石山周围主要植物类型

Table 1 The main plant types around Gangue hill of Fushun West Open-pit mine

| 种 Species                                     | 生活型 Life form | 种 Species                          | 生活型 Life form |
|-----------------------------------------------|---------------|------------------------------------|---------------|
| 地锦草 <i>Euphorbia humifusa</i> Willd.          | 1年生草本         | 蒺藜狗子 <i>Tribulus terrestris</i> L. | 1年生草本         |
| 蒺藜 <i>Polygonum aviculae</i> L.               | 1年生草本         | 猪毛菜 <i>Salsola collina</i> pall.   | 1年生草本         |
| 辽宁碱蓬 <i>Suaeda Liaotungensis</i> Kitag.       | 1年生草本         | 月见草 <i>Oenothera biennis</i> L.    | 多年生草本         |
| 狗娃花 <i>Heteiopappus hispidus</i> (Thunb) less | 多年生草本         | 艾蒿 <i>Artemisia argyi</i>          | 多年生草本         |
| 圆叶牵牛 <i>Pharbitis purpurea</i> (L.) voigt.    | 多年生草本         |                                    |               |

## 2 研究方法

土壤样本采集时间为2006年5月10日,土壤样本取自抚顺市西露天矿西舍场矸石山周围田屯—青台子一带,以李石寨一次变电所为参照点沿垂直矸石山方向由近及远分别选取6个采样点,每200 m取一个样点,样点1最靠近矸石山,样点6最远离矸石山,采样网格为40 m×80 m,以三点混合法在每块样地上取样。取样深度为0—20 cm,先去掉表层腐殖质,然后用取样铲挖取大约400 g土壤样本,将采集的土壤样品混匀并装入塑料袋中,贴好标签,带回实验室后放置于4℃冰箱。

### 2.1 土壤线虫的分离及鉴定

用淘洗-过筛-离心漂浮法分离线虫<sup>[25]</sup>,线虫总数通过解剖镜直接确定,按测得的土壤水分,折算成100 g干土中土壤线虫的数量。随机抽取100条线虫在光学显微镜下进行科属鉴定,参照Siddiqi和Bongers的分类图鉴进行。根据线虫的取食习性和食道特征可将其划分为4个营养类群:食细菌线虫(Bacterivores, BF)、食真菌线虫(Fungivores, FF)、植物寄生线虫(Plant-parasites, PP)和捕食-杂食线虫(Omnivore-predators, OP)<sup>[26-28]</sup>。

### 2.2 土壤中可溶性盐含量的测定

土壤可溶性盐总量测定采用电导法;Ca<sup>2+</sup>和Mg<sup>2+</sup>的测定用EDTA滴定法;阴离子分析中除SO<sub>4</sub><sup>2-</sup>外,其他离子采用半微量滴定法;SO<sub>4</sub><sup>2-</sup>采用BaSO<sub>4</sub>重量法。

### 2.3 数据处理

#### 2.3.1 多样性指数计算

$$\text{Shannon-Wiener 多样性指数}(H') \quad H' = - \sum ni/N \times \ln(ni/N)$$

式中, $n_i$ 为第*i*个类群的个体数, $N$ 为群落中所有类群的个体总数。

$$\text{Pielou 均匀度指数}(J') \quad J' = H' / \ln S$$

式中, $S$ 为类群数。

$$\text{Simpson 优势度指数}(\lambda) \quad \lambda = \sum Pi^2$$

式中, $P_i = n_i/N$ 。

$$\text{Margalef 丰富度指数}(SR) \quad SR = (S - 1) / \ln N$$

$$\text{线虫营养多样性指数}(TD) \quad TD = 1 / \sum Pi^2$$

#### 2.3.2 功能类群指数

$$WI = (f+b)/pp$$

式中, $b$ 为食细菌线虫数量; $f$ 为食真菌线虫数量; $pp$ 为植物寄生线虫数量。

$$\text{MI 指数} \quad MI = \sum_{i=1}^n cp_i \times P_i$$

式中,  $cp_i$  为非植物寄生性土壤线虫第  $i$  类群的 colonizer-persister 值,  $cp$  值范围 1—5,  $cp = 1$  表明线虫世代时间短, 产卵量大, 卵个体小, 代谢快, 耐环境压力,  $cp = 5$  表明线虫生命周期长, 代谢活动低, 产卵数量少但个体大, 具有能透过的表皮, 对污染物和其它扰动非常敏感;  $n$  为非植物寄生性土壤线虫类群数;  $P_i$  为土壤线虫群落非植物寄生性线虫第  $i$  类群的个体数占群落总个体数的比例。

线虫数据进行  $\ln(x+1)$  转化后均采用 Microsoft Excel 2003 和 SPSS 17.0 软件进行统计分析。

### 3 结果

#### 3.1 土壤可溶性盐含量

煤矸石经雨水淋溶形成的含有盐基离子的酸性水通过地表水和地下水携带进入土壤, 土壤 pH 值随距矸石山距离的增加而升高; 矿化度、 $\text{HCO}_3^-$ 、 $\text{Ca}^{2+}$  和  $\text{Mg}^{2+}$  的最高值都出现在样点 1, 而且  $\text{Ca}^{2+}$  和  $\text{Mg}^{2+}$  具有相同的变化趋势;  $\text{Cl}^-$ 、 $\text{SO}_4^{2-}$  在样点 6 最高并且变化趋势相似 (表 2)。

表 2 抚顺市西露天矿西舍场矸石山周围土壤盐分要素含量

Table 2 Soil salinity element contents around Gangue hill of Fushun West Open-pit mine

| 样点<br>Site | pH     | 矿化度<br>Degree of<br>mineralization<br>/(g/L) | $\text{CO}_3^{2-}$<br>/(mg/kg) | $\text{HCO}_3^-$<br>/(mg/kg) | $\text{Cl}^-$<br>/(mg/kg) | $\text{SO}_4^{2-}$<br>/(mg/kg) | $\text{NO}_3^-$<br>/(mg/kg) | $\text{Ca}^{2+}$<br>/(mg/kg) | $\text{Mg}^{2+}$<br>/(mg/kg) |
|------------|--------|----------------------------------------------|--------------------------------|------------------------------|---------------------------|--------------------------------|-----------------------------|------------------------------|------------------------------|
| 1          | 7.83b  | 4.8a                                         | 1.81b                          | 25.27a                       | 58.41b                    | 50.41a                         | 25.39c                      | 212.15a                      | 68.33a                       |
| 2          | 7.73b  | 3.37c                                        | 1.85b                          | 18.38a                       | 32.47c                    | 26.97b                         | 56.17b                      | 189.46a                      | 44.26b                       |
| 3          | 7.58c  | 4.15b                                        | 2.34a                          | 20.33a                       | 43.96c                    | 30.17b                         | 49.21b                      | 70.46c                       | 11.51c                       |
| 4          | 8.06ab | 3.52bc                                       | 2.42a                          | 17.59a                       | 32.21c                    | 28.59b                         | 66.59ab                     | 74.78c                       | 19.81c                       |
| 5          | 8.19a  | 2.66c                                        | 2.64a                          | 15.66a                       | 47.23bc                   | 36.28b                         | 85.47a                      | 148.47ab                     | 34.59b                       |
| 6          | 8.25a  | 4.52a                                        | 1.52b                          | 23.78a                       | 71.33a                    | 62.14a                         | 52.67b                      | 112.97bc                     | 17.29c                       |

每一列数字后同一字母表示无显著差别, 不同字母表示有显著差别

#### 3.2 土壤线虫群落特征研究

##### 3.2.1 土壤线虫属的分布特征

6 个采样点中共鉴定出线虫 29 个属 (表 3), 其中 *Acrobeloides* 属线虫为优势属。样点 1 *Hirschmanniella* 属最多, 占线虫总数的 18.1%; 样点 2 *Pratylenchus* 属最多, 占线虫总数的 20.0%; 样点 3 *Aphelenchoides* 属最多, 占线虫总数的 13.6%; 样点 4 和样点 5 *Acrobeloides* 属最多分别占线虫总数的 15.3% 和 21.9%; 样点 6 *Cervidellus* 属最多, 占线虫总数的 25.9%。

##### 3.2.2 线虫营养类群的分布特征

按照食物的来源, 将线虫分为 4 个营养类群, 即食细菌线虫 (BF)、食真菌线虫 (FF)、植物寄生性线虫 (PP) 和捕食-杂食线虫 (OP), 它们反映了土壤食物网营养类群的结构<sup>[31]</sup>。如表 3, 在本研究 6 个采样点中食细菌类群和植物寄生类群绝对丰度较高, 而食真菌类群和捕食-杂食类群绝对丰度较低。其中, 食细菌线虫所占比例为 34.1%—63.5%, 植物寄生性线虫占 23.5%—42.3%, 是主要的营养类群, 食真菌线虫占 5.9%—16.1%, 捕食-杂食线虫所占比例为 7.1%—16.4%。

##### 3.2.3 线虫多样性与功能类群分布特征

指数  $\lambda$ 、 $H'$ 、 $MI$  和  $J'$  在 6 个样地中无明显波动, 其中  $MI$  指数有随距矸石山距离的增加而降低的趋势。 $WI$  和  $\lambda$  的最大值,  $f/b$ 、 $MI$ 、 $J'$  的最小值均出现在样地 6 (表 4)。

##### 3.2.4 土壤线虫群落与土壤可溶性盐的相关关系

本研究发现土壤 pH 值与  $f/b$  成极显著负相关; 矿化度与  $S$ 、 $SR$  均有正相关关系, 显著性水平均为  $P = 0.05$ ;  $\text{HCO}_3^-$  与  $S$ 、 $SR$  均存在显著正相关关系;  $\text{Cl}^-$  与  $TD$  负相关而与  $WI$  正相关, 相关性水平均为  $P = 0.05$ ;  $\text{SO}_4^{2-}$  与  $WI$ 、 $f/b$ 、 $TD$ 、 $\lambda$ 、 $J'$  均有相关关系;  $\text{NO}_3^-$  与  $SR$  负相关; 阳离子  $\text{Ca}^{2+}$  和  $\text{Mg}^{2+}$  与线虫生态指数均无相关关系 (表 5)。

表 3 不同样点土壤线虫相对多度及营养类群/%

Table 3 Relative abundance of nematode and trophic groups in the different sampling site

| 属                         | 样点 Site |      |      |      |      |      |
|---------------------------|---------|------|------|------|------|------|
|                           | 1       | 2    | 3    | 4    | 5    | 6    |
| 食细菌线虫 Bacterivores        | 43.1    | 34.1 | 37.0 | 38.7 | 43.8 | 63.5 |
| <i>Acrobeles</i>          | 2.6     | 0.0  | 0.0  | 0.0  | 0.0  | 1.2  |
| <i>Acroboloides</i>       | 7.8     | 12.9 | 8.6  | 15.3 | 21.9 | 0.0  |
| <i>Cervidellus</i>        | 1.7     | 0.0  | 1.3  | 4.5  | 0.0  | 25.9 |
| <i>Chiloplacus</i>        | 0.0     | 1.1  | 0.0  | 0.0  | 0.0  | 2.4  |
| <i>Eucephalobus</i>       | 3.4     | 0.0  | 0.0  | 0.0  | 6.3  | 4.7  |
| <i>Mesorhabditis</i>      | 13.0    | 11.8 | 11.1 | 12.6 | 0.0  | 12.9 |
| <i>Plectus</i>            | 0.0     | 0.0  | 3.7  | 0.0  | 1.0  | 3.5  |
| <i>Prismatolaimus</i>     | 0.9     | 2.4  | 4.9  | 0.0  | 0.0  | 0.0  |
| <i>Protorhabditis</i>     | 10.3    | 5.9  | 7.4  | 3.6  | 14.6 | 10.6 |
| <i>Wilsonema</i>          | 3.4     | 0.0  | 0.0  | 2.7  | 0.0  | 2.3  |
| 食真菌线虫 Fungivores          | 9.4     | 9.5  | 16.1 | 7.3  | 6.3  | 5.9  |
| <i>Aphelenchoides</i>     | 6.0     | 2.4  | 13.6 | 7.3  | 0.0  | 5.9  |
| <i>Paraphelenchus</i>     | 3.4     | 7.1  | 2.5  | 0.0  | 6.3  | 0.0  |
| 植物寄生线虫 Plant-parasites    | 36.3    | 40.0 | 38.3 | 42.3 | 35.3 | 23.5 |
| <i>Bitylenchus</i>        | 0.0     | 7.0  | 2.5  | 1.8  | 0.0  | 0.0  |
| <i>Coslenchus</i>         | 1.7     | 0.0  | 12.3 | 0.0  | 0.0  | 2.4  |
| <i>Filenchus</i>          | 4.4     | 5.9  | 0.0  | 0.0  | 4.1  | 0.0  |
| <i>Helicotylenchus</i>    | 1.8     | 5.9  | 4.9  | 14.4 | 5.1  | 4.7  |
| <i>Hirschmanniella</i>    | 18.1    | 0.0  | 8.6  | 11.7 | 6.3  | 0.0  |
| <i>Macroposthonia</i>     | 2.6     | 1.2  | 0.0  | 0.0  | 4.2  | 4.7  |
| <i>Neothada</i>           | 0.0     | 0.0  | 0.0  | 3.6  | 3.1  | 1.1  |
| <i>Paratylenchus</i>      | 1.7     | 0.0  | 0.0  | 4.5  | 0.0  | 2.4  |
| <i>Pratylenchus</i>       | 0.0     | 20.0 | 0.0  | 0.0  | 0.0  | 3.5  |
| <i>Psilenchus</i>         | 0.0     | 0.0  | 0.0  | 2.7  | 12.5 | 4.7  |
| <i>Scutylenchus</i>       | 6.0     | 0.0  | 9.9  | 3.6  | 0.0  | 0.0  |
| 捕食杂食线虫 Omnivore-predators | 11.2    | 16.4 | 8.6  | 11.7 | 14.6 | 7.1  |
| <i>Aporcelaimellus</i>    | 0.0     | 0.0  | 0.0  | 0.0  | 0.0  | 4.7  |
| <i>Discolaimus</i>        | 0.0     | 0.0  | 6.2  | 0.0  | 0.0  | 2.4  |
| <i>Dorylaimoides</i>      | 5.2     | 4.7  | 0.0  | 6.3  | 7.3  | 0.0  |
| <i>Epidorylaimus</i>      | 4.3     | 2.4  | 0.0  | 5.4  | 0.0  | 0.0  |
| <i>Thonus</i>             | 0.0     | 2.4  | 2.5  | 0.0  | 4.2  | 0.0  |
| <i>Tylencholaimus</i>     | 1.7     | 7.0  | 0.0  | 0.0  | 3.1  | 0.0  |

表 4 抚顺市西露天矿西舍场矸石山周围不同样点土壤线虫群落多样性和生态指数

Table 4 Diversity and ecological indices of nematodes in the different sampling sites around the Gangue hill of Fushun West Open-pit mine

| 样点<br>Site | 线虫生态指数 Nematode ecological indices |       |        |       |           |       |       |       |       |
|------------|------------------------------------|-------|--------|-------|-----------|-------|-------|-------|-------|
|            | S                                  | WI    | f/b    | TD    | $\lambda$ | H'    | MI    | J'    | SR    |
| 1          | 20a                                | 1.45b | 0.22b  | 2.95a | 0.09a     | 2.70a | 2.73a | 0.90a | 8.20a |
| 2          | 16ab                               | 1.09b | 0.28b  | 3.20a | 0.10a     | 2.50a | 2.88a | 0.90a | 3.38b |
| 3          | 15ab                               | 1.39b | 0.43a  | 3.16a | 0.09a     | 2.54a | 2.76a | 0.94a | 3.19b |
| 4          | 16ab                               | 1.11b | 0.18bc | 2.87a | 0.09a     | 2.54a | 2.68a | 0.91a | 3.18b |
| 5          | 13b                                | 1.38b | 0.15bc | 2.94a | 0.11a     | 2.37a | 2.69a | 0.92a | 2.64b |
| 6          | 18a                                | 2.95a | 0.09c  | 2.14b | 0.12a     | 2.52a | 2.58a | 0.87a | 3.83b |

每一列数字后同一字母表示无显著差别,不同字母表示有显著差别

表 5 抚顺市西露天矿西舍场矸石山周围土壤成分线虫指数之间相关关系

Table 5 Correlation coefficients between community indices of nematodes and soil component around the Gangue hill of Fushun West Open-pit mine

| 指数<br>Indices | pH        | 矿化度<br>Degree of<br>mineralization | $\text{CO}_3^{2-}$ | $\text{HCO}_3^-$ | $\text{Cl}^-$ | $\text{SO}_4^{2-}$ | $\text{NO}_3^-$ | $\text{Ca}^{2+}$ | $\text{Mg}^{2+}$ |
|---------------|-----------|------------------------------------|--------------------|------------------|---------------|--------------------|-----------------|------------------|------------------|
| <i>S</i>      | 0.254     | 0.867 *                            | -0.575             | .901 *           | -0.089        | 0.333              | -0.588          | 0.577            | 0.71             |
| <i>WI</i>     | 0.672     | 0.386                              | 0.438              | 0.272            | .854 *        | .868 *             | 0.423           | 0.456            | 0.373            |
| <i>f/b</i>    | -0.938 ** | -0.339                             | -0.312             | -0.096           | -0.509        | -.833 *            | -0.296          | -0.736           | -0.543           |
| <i>TD</i>     | -0.79     | -0.331                             | -0.507             | -0.17            | -0.862 *      | -0.904 *           | -0.49           | -0.517           | -0.376           |
| $\lambda$     | 0.779     | 0.156                              | 0.57               | -0.031           | 0.792         | 0.866 *            | 0.567           | 0.459            | 0.295            |
| <i>H'</i>     | -0.161    | 0.637                              | -0.705             | 0.755            | -0.394        | -0.116             | -0.717          | 0.244            | 0.434            |
| <i>MI</i>     | -0.685    | -0.065                             | -0.608             | 0.123            | -0.761        | -0.687             | -0.578          | -0.372           | -0.188           |
| <i>J'</i>     | -0.757    | -0.691                             | -0.007             | -0.582           | -0.482        | -0.854 *           | -0.006          | -0.725           | -0.681           |
| <i>SR</i>     | 0.166     | .838 *                             | -0.792             | .850 *           | -0.447        | 0.104              | -0.815 *        | 0.618            | 0.769            |

\* 显著性  $P=0.05$ ; \*\* 显著性  $P=0.01$ 

#### 4 讨论

本研究共鉴定出线虫 29 属,其中 *Acrobeloides* 为优势属。随采样点距矸石山距离的增加线虫的优势属也有所变化。研究区域土壤线虫中食细菌类群和植物寄生类群绝对丰度较高,而食真菌类群和捕食-杂食类群绝对丰度较低。线虫学研究表明数量最多的营养类群是食细菌线虫,前人在对不同条件下线虫群落的研究也有同样的发现<sup>[28-31]</sup>。这是因为食细菌线虫被认为是干扰环境的耐受种,它对变化的环境反映不敏感<sup>[32-33]</sup>,并且采矿地区的重金属含量往往较高,这使得食细菌线虫的捕食者的数量降低,而一定含量的重金属能够刺激细菌生物量的增加;植物寄生线虫含量高是由于研究区域主要的植被类型是草本植物,其植株小,根系发达,植物寄生线虫很容易刺破植物根系的表皮来获取养分,从而间接提高了植物寄生线虫的生物量。Nkem 等<sup>[34]</sup>对南极土壤线虫 *Scottinema* 和 *Plectus* 对不同盐分 ( $\text{NaCl}$ ,  $\text{MgSO}_4$ ,  $\text{KNO}_3$  和  $\text{NaCl} + \text{MgSO}_4$ ) 的反应进行评估,结果发现线虫对盐分的耐受度是明确的,在低浓度的  $\text{NaCl}$  和  $\text{MgSO}_4$  下能够生存。

在线虫生态指数中,*WI* 指数反映线虫群落结构和土壤健康状况,当  $WI = 1$  时,表明有益的非植物寄生线虫数量与有害的植物寄生线虫数量相当,土壤健康状况一般;当  $WI > 1$  时,*WI* 值越大土壤健康程度越高,当  $WI < 1$  时,*WI* 越小土壤健康程度越低。本研究 *WI* 值在 1.09 与 2.95 之间,这与梁文举等<sup>[35]</sup>对马铃薯田和 Pen-Mouratov 等<sup>[36]</sup>对沙漠线虫群落的研究相似(表 4),表明研究区域土壤健康状况良好,特别是样地 6,距矸石山最远,有最大的 *WI* 值。微生物群落的结构能够通过指数 *f/b* 表示出来,它反映和指示了由岩屑形成的食物网中分解途径的状况<sup>[37]</sup>。本研究中 *f/b* 值在 0.09 和 0.43 之间,高于在长期试验田中土壤经有机肥料处理后所得的 *f/b* 值<sup>[38]</sup>,表明有大量细菌存在并且分解途径以细菌为主(表 4);另外酸性环境适合食真菌线虫的生长,而中性条件更有利于食细菌线虫的增加<sup>[39-40]</sup>,本研究区域 pH 值 7.58—8.25 适合食细菌线虫繁殖,也是造成食细菌线虫数量要远大于食真菌线虫的原因。Simpson 指数( $\lambda$ )和 Shannon 多样性指数( $H'$ )它们都是属的丰富度和多度在属间分配的数学表达式,二者可以相互替代,本研究中  $\lambda$  (0.09—0.12) 低于 Pen-Mouratov 等<sup>[41]</sup>对非污染地区的调查研究 (0.14—0.22) (表 4),并且也低于中国其他同样受污染地区的报道<sup>[42]</sup>;相反, $H'$  从 2.37 到 2.70 高于 Tomar 等<sup>[42]</sup>对高速公路附近污染区的研究所得的值(表 4)。 $\lambda$  与  $H'$  变化趋势相反, $\lambda$  与  $\text{SO}_4^{2-}$  正相关,而  $H'$  与盐离子则无相关性,产生这种现象的原因是 Simpson 指数( $\lambda$ )侧重于常见属,而 Shannon 多样性指数( $H'$ )赋予稀有属更多的权重<sup>[43]</sup>,两者侧重点不同,所以其变化情况与土壤盐离子的相关程度也不同。线虫成熟指数(*MI*)越高说明干扰的影响程度越小,反之干扰的影响程度就越大,由表 4 可以看出,随着距矸石山距离的增加 *MI* 值有降低的趋势,这是由于土壤受到了人为因素的影响,矸石山附近的土地大多被开垦为农田,离矸石山远的土地开垦的比较早,而较近的土地开垦的比较晚有的甚至才开垦,刚被用做农田的土地受干扰的程度比较大,因此 *MI* 值比较低。



Barrett 报道盐性土壤与土壤后生动物存在负相关或是正交的关系<sup>[44]</sup>,本研究中除硬度、 $\text{Ca}^{2+}$ 、 $\text{Mg}^{2+}$ 之外其他土壤成分与线虫生态指数间存在或多或少的相关关系,结果表明,矸石山周边土壤盐离子会对线虫群落产生重大影响,反过来线虫群落能敏感的指示该地区土壤环境状况的变化及土壤盐化程度。

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