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Bryophyte communities as biomonitors of environmental factors in the Goujiang karst bauxite, southwestern China

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HIGHLIGHTS

- Bryophyte communities as biomonitors of heavy metal pollution in karst bauxite.
- Single-species communities grow in locations with high levels of heavy metals.
- Bryophyte communities are affected by slope, altitude and heavy metals in the soil.
- Bryophyte communities respond differently to concentrations of Fe, Cu, Zn and Ni.
- Approximately 36% of bryophyte taxa on Goujiang karst bauxite reproduce asexually.

GRAPHICAL ABSTRACT

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ABSTRACT

Bauxite mining on karst results in several ecological and environmental issues including heavy metal pollution, soil erosion and the destruction of vegetation. In turn, these may affect the distribution of plant communities and endanger human health. In general, bryophytes (mosses, liverworts and hornworts) are pioneer plants, lacking roots, vascular systems and well-developed cuticles. Due to their high sensitivity to the environment, they are often used to monitor air and soil pollution. A total of 25 bryophyte taxa from 19 genera and 9 families were recorded on Goujiang karst bauxite near the city of Zunyi in the Guizhou Province of southwestern China. Eleven principal bryophyte communities were identified, most of which consisted of only one species (monospecific assemblage), although the proportion of these single-species communities differed at the six locations. The levels of heavy metals also differed in soil from the six locations: iron, 8748.9–10,023 μg/g; zinc, 146.7–240.9 μg/g; copper, 24.6–60.4 μg/g; and nickel, 35.6–95.1 μg/g. A canonical correspondence analysis (CCA) of the bryophyte communities and environmental variables revealed the effect of gradient (slope), altitude and heavy metals in the soil on the distribution of the principal bryophyte communities. More than 36% of bryophyte taxa identified reproduced asexually by gemmae, as gemmiferous bryophyte communities tolerate substrates with high levels of heavy metals more readily than non-gemmiferous communities do. The distribution of heavy metals in the soil is reflected in the distribution of the bryophyte communities. The distribution characteristics of the principal

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bryophyte communities and of the gemmiferous bryophyte communities are useful in monitoring heavy metal pollution in karst bauxite.

1. Introduction

Located in southwestern China, the Guizhou Province is characterized by distinctive karst landforms, a great diversity of biological species (plant and animals) and high levels of metal minerals in the soil. The karst bauxite reserves of the Guizhou Province account for about 17% of the total reserves in China (Wen, 2004). Goujiang karst bauxite deposits are located in Goujiang Town, 30 km south of Zhunyi City (Fig. 1). Karst bauxites are found above carbonate rocks (usually limestone or dolomite); those found at the study sites contain high levels of iron oxide (haematite) (Li and Zhu, 2007; Liu and Liao, 2013). Although this region was mostly covered by woodlands and shrubs originally, bauxite mining activities have led to a series of environmental problems such as vegetation degradation, sometimes leading to desertification, soil erosion and groundwater pollution. Heavy metals enter the atmosphere through dust produced by bauxite ore mining and processing (Smirnov et al., 2004; Zhang, 2000). These activities have had adverse effects not only on the environment surrounding the mine but also on the health of nearby residents. However, the impact of mining operations extends beyond the local area. Goujiang karst bauxite is located in the catchment area of the Wujiang River (Li and Zhu, 2007), a tributary of the Yangtze River, which flows into the Yangtze River basin. Strip mining of surface deposits and processing of ores with high-intensity precipitation lead to soil erosion and to the movement of heavy metal ions downstream, first into the Wujiang River and subsequently into the Yangtze River basin. Consequently, the water quality of the agricultural and urban areas of the central and lower reaches of the Yangtze River is seriously affected. Hence, it is important to monitor the heavy metal pollution arising from the Goujiang karst bauxite deposits.

Although few vascular plants can survive the poor soil conditions and aridity near the mine, some bryophyte taxa grow and flourish in this challenging environment (Wu, 1998). Bryophytes are plants with relatively simple morphology. Due to their one-cell-thick (unistratose) leaves and lack of a waxy, waterproof cuticle, bryophytes pose no resistance to ion exchange. Thus, they are extremely sensitive to changes in the surrounding environment and are ideal effect indicator plants for monitoring the surrounding environment (Bates, 2000; Hu, 1987; Pesch and Schröder, 2006). The unistratose leaves and uniseriate rhizoids of bryophytes also provide a large surface area for cation exchange, allowing the free uptake of dust particles and droplets of moisture. As they lack stomata, bryophytes are unable to screen airborne pollutants by closing stomata at night or during stress (Bates, 2000; Glime, 2007). Some moss taxa can be used as indicators of specific heavy metals in the substrate (Wilkie and La Farge, 2011).

Many bryophyte communities play an important role in water retention and pedogenesis (Glime, 2015; Jia et al., 2014). Further, as they facilitate colonization by higher plants, they play an important pioneering role in the process of community succession (Wu, 1998).

In recent years, there has been a marked increase in biological monitoring of the environment, using organisms that are continuously exposed to pollution and easy to collect (Cymerman et al., 2006; Wilkie

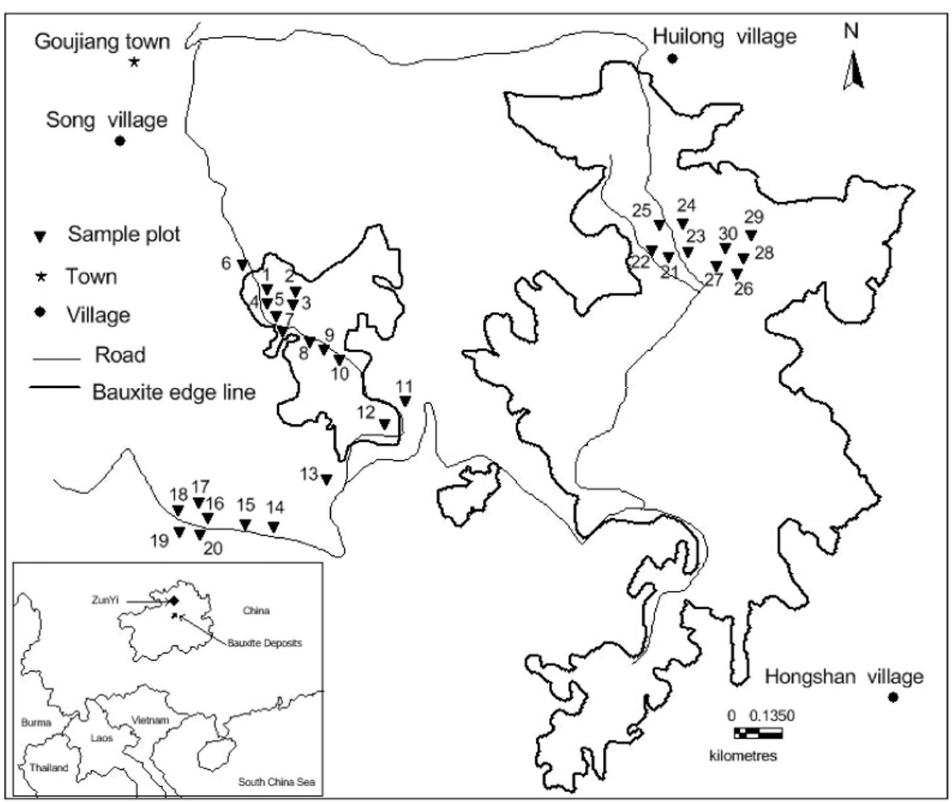

Fig. 1. Six locations: aluminum mill (1–5), vicinity of miners' living quarters (6–10), aluminum ore sintering plant and waste rock pile (11–15), orchards (16–20), ore stockpile (21–25) and bauxite mine (25–30).

and La Farge, 2011; Yang et al., 2011). Bryophytes have been used to monitor the atmospheric deposition of heavy metals in Europe and North America (Berg and Steinnes, 1997; Cymerman et al., 2006; Grodzińska et al., 1999; Jules and Shaw, 1994; Økland et al., 1999; Pakarinen and Tolonen, 1976; Pesch and Schröder, 2006; Shaw, 1994; Smirnov et al., 2004), but they have rarely been used to indicate physiological effects and subsequent abundance changes of moss species. In China, several studies have been conducted on heavy metals present in bryophytes associated with gold, zinc, copper and mercury production (Bi et al., 2006a, 2006b; Jia et al., 2014; Yang et al., 2011). However, the characteristics of bryophyte communities associated with karst bauxite deposits have rarely been studied in relation to environmental conditions or to vegetation gradients (Økland et al., 1999). The aims of this study are as follows: (I) to break ground by examining the characteristics of bryophyte communities (species composition (methods in Section 2.3.1 and results in Section 3.1.1), abundance index (methods in Section 2.3.2 and results in Section 3.1.1), the classification of the principal community (methods and results in Section 3.1.2) and community structure (methods and results in Section 3.1.2)) growing on karst bauxite deposits; (II) to determine the concentration of heavy metals in the soil matrix from different locations (methods in Section 2.3.3 and results in Section 3.2); and (III) to determine whether bryophyte communities can be used to monitor environmental conditions (heavy metals, altitude and angle of slope (gradient)) in karst bauxite areas known to harbor bryophytes (methods in Section 2.3.4 and results in Sections 3.3.1 and 3.3.2). This study aims to bridge the knowledge gaps of bryophyte community characteristics as biomonitors of environment factors.

Table 1
Geographic coordinates of sample plots ($n = 30$).

Locations	Plots	Longitude	Latitude	Altitude (A)
1	1	106° 51′ 19.0″ E	27° 27′ 28.7″ N	941.9 ± 7.7 m
	2	106° 51′ 18.7″ E	27° 27′ 28.4″ N	926.7 ± 7 m
	3	106° 51′ 19.5″ E	27° 27′ 29.3″ N	909.7 ± 15 m
	4	106° 51′ 19.5″ E	27° 27′ 29.3″ N	910.7 ± 19.4 m
	5	106° 51′ 19.5″ E	27° 27′ 29.4″ N	927.6 ± 5 m
2	6	106° 51′ 17.1″ E	27° 27′ 31.2″ N	917.2 ± 7.9 m
	7	106° 51′ 18.8″ E	27° 27′ 27″ N	922.3 ± 7.9 m
	8	106° 51′ 22.2″ E	27° 27′ 26″ N	925.4 ± 18.6 m
	9	106° 51′ 23.4″ E	27° 27′ 25″ N	933.5 ± 15.5 m
	10	106° 51′ 24″ E	27° 27′ 26″ N	936.5 ± 10.2 m
3	11	106° 51′ 31.8″ E	27° 27′ 20.5″ N	909.8 ± 35.9 m
	12	106° 51′ 29.6″ E	27° 27′ 19.3″ N	952.1 ± 6 m
	13	106° 51′ 25.9″ E	27° 27′ 15.1″ N	963.9 ± 6 m
	14	106° 51′ 14.2″ E	27° 27′ 10.3″ N	937 ± 4.1 m
	15	106° 51′ 11.5″ E	27° 27′ 10.5″ N	935.2 ± 4.5 m
4	16	106° 51′ 11.4″ E	27° 27′ 11″ N	935.6 ± 5.6 m
	17	106° 51′ 11″ E	27° 27′ 10.8″ N	936.1 ± 4.3 m
	18	106° 51′ 11.3″ E	27° 27′ 10.5″ N	935 ± 5.8 m
	19	106° 51′ 11.6″ E	27° 27′ 10.7″ N	936.5 ± 5.8 m
	20	106° 51′ 11.3″ E	27° 27′ 10.8″ N	935.9 ± 6.3 m
5	21	106° 52′ 00.7″ E	27° 27′ 33.7″ N	916.7 ± 17.5 m
	22	106° 52′ 00.4″ E	27° 27′ 34″ N	906 ± 7.9 m
	23	106° 52′ 01.3″ E	27° 27′ 34.1″ N	917.3 ± 6.1 m
	24	106° 52′ 01.5″ E	27° 27′ 33.7″ N	917.4 ± 6.5 m
	25	106° 52′ 01.5″ E	27° 27′ 34.3″ N	914.6 ± 6.1 m
6	26	106° 52′ 03.4″ E	27° 27′ 31.2″ N	908.4 ± 6.1 m
	27	106° 52′ 04″ E	27° 27′ 31.3″ N	910.2 ± 11.5 m
	28	106° 52′ 04.9″ E	27° 27′ 31.2″ N	925.6 ± 7.5 m
	29	106° 52′ 06.2″ E	27° 27′ 30.9″ N	927.9 ± 12.1 m
	30	106° 52′ 04.3″ E	27° 27′ 31.4″ N	918.1 ± 10.5 m

2. Material and methods

2.1. Study area

The Goujiang karst bauxite deposits (27° 27′ 10.5″ to 27° 26′ 34.3″ N, 106° 51′ 11″ to 107° 52′ 06.2″ E) are located in the northeastern region of the Yunnan–Guizhou plateau (Fig. 1) at altitudes ranging from 906 to 964 m. Goujiang karst bauxite deposits are located in Goujiang Town, 30 km south of Zhunyi City. This region has a complex geomorphology, generally dominated by karst landforms (include karst peak cluster, karst hills, karst depression and karst cave). The study area experiences mild summers and winters with a mean annual temperature of 15.1 °C; the annual precipitation varies from 1000 to 1150 mm, which can be significantly affected by the monsoon. The Goujiang area has a bauxite yield 100,000 tons/year, with the average mineral sheer segment ore containing 65.2% of Al_2O_3 and 6.8% of Fe_2O_3 (Liu and Liao, 2013).

2.2. Sampling procedure

Sampling was carried out on 3 October 2014. The area surrounding the mine on the Goujiang karst bauxite deposit was divided into six locations (aluminum mill, the vicinity of the miners' living quarters, the aluminum ore sintering plant and waste rock pile area, orchard, ore stockpile and bauxite mine). At each location, five plots each of 1×1 m^2 area were established (Table 1 and Fig. 1). Within these plots, five 10×10 cm^2 quadrats were set out (i.e., a total of 25 quadrats at each location). The entire surface layer of the bryophyte cover present in each quadrat was removed down to the soil surface using a sampling knife, which was washed between samplings. The samples were carefully packed into an envelope and sent to a laboratory to determine the species and the corresponding statistics. The location, habitat, percentage cover on the ground and substrate gradient (slope) were recorded (Table 2). A total of 150 bryophyte samples were collected from the six locations. At each plot (total 30), a layer of surface soil (10×10 cm$^2 \times 3$ cm) was removed for heavy metal analysis following the protocols of Smirnov et al. (2004).

2.3. Sample preparation and analytical methods

2.3.1. Specimen identification

Bryophyte taxa were identified with classical morphological identification techniques, using an HWG-1 anatomical lens and a XSZ-107TS microscope, and referring to *Flora Bryophytarum Sinicorum* Vol.1–4, Vol. 7 and Vol. 8 (Gao, 1994, 1996; Hu and Wang, 2005; Li, 2000, 2006; Wu and Jia, 2004) and *Flora Yunnanica* Vol. 17 (Institutum Botanicum Kunmingense Academiae Sinicae Edita, 2000).

2.3.2. Abundance index

In order to assess the species richness at each location, the species abundance was calculated from three factors: families, genera and species. The abundance index (Zuo, 1990) was calculated as follows:

$$S_j = \sum_{j=1}^{n} \frac{X_{ij} - \overline{X}_{ij}}{\overline{X}_{ij}} \qquad (1)$$

Here, X_{ij} is the data of the j taxon among n taxa from the i region among k regions, $\overline{X}_{ij}$ is the average value of the j taxon among n taxa of the k region and n is the taxa number.

2.3.3. Analysis of heavy metals

In the laboratory, the soil samples were dried and homogenized using a 0.149-mm cell sieve, as described by Smirnov et al. (2004). A subsample of 0.2 g was removed from each soil sample, to which were added 12 ml of nitric acid and 3 ml of perchloric acid before digestion in an electric furnace. During digestion, 1 ml of hydrofluoric acid was added to the sample. For each of the 30 soil samples, three parallel and two sample blanks were prepared similarly for analysis (Økland

Table 2
Habitat parameters of six locations.

Location	Intensity of human interference	Altitude (*A*)	Gradient (*G*)
1. Aluminum mill	Strong	923.3 m	33.4°
2. Vicinity of miners' living quarters	Light-degree disturbance	927.0 m	67.6°
3. Aluminum ore sintering plant and waste rock pile area	Moderate-intensity interference	939.6 m	33°
4. Orchards	Light-degree disturbance	935.6 m	5.2°
5. Ore stockpile	Moderate-intensity interference	914.4 m	43.2°
6. Bauxite mine	Strong	918.0 m	64.6°

et al., 1999). After completion of digestion, the samples were allowed to cool to room temperature and then transferred to 50-ml volumetric flasks. Deionized water was added to bring the total volume to 50 ml. The concentrations of Cu, Zn, Fe and Ni were analyzed by flame atomic absorption spectrophotometry using a Rayleigh WFX-210 Atomic Absorption Spectrophotometer (Jia et al., 2014).

2.3.4. Canonical correspondence analysis

The correlation between the distribution of bryophyte communities and environmental factors was analyzed using Canoco for Windows 4.5. Further, the sorting function of Canoco for Windows can provide insight into the correlation among the structure of biological community, plant communities and the environment. Detrended correspondence analysis (DCA) is an analytical method that obtains an indirect gradient of the overall community data. Canonical correspondence analysis (CCA) is a unimodal linear gradient-sorting method that sorts the sample plots and the object, along with multiple environmental factors, which are sorted together in the same figures. An 'arch effect' may be observed, which can be avoided if the highly correlation-redundant variables are removed at primary. First, the species information of the bryophyte communities was subjected to DCA, obtaining lengths of gradient (the length of the gradient of each sort axis) of 3.580, suitable for CCA (Li et al., 2014; Wu, 1998). The generated data file was drawn using CanoDraw for Windows. For data analyses, the following two conditions must be met: (i) the frequency of bryophyte populations at the sample plots was > 15% and (ii) at least one of the locations must have a relative abundance of > 1%. The normal distribution for the environmental factor data was obtained by log-transforming $(x + 1)$ the environmental matrix (Li et al., 2014; Ou et al., 2014; Yang et al., 2010, 2011).

3. Results and discussion

3.1. Characteristics of the bryophyte communities

3.1.1. Species composition of bryophyte communities

A total of 25 bryophyte taxa in nine families and 19 genera were recorded from the 150 samples collected from Goujiang karst bauxite. These included one liverwort taxon together with 24 moss taxa from eight families and 18 genera. Acrocarpous mosses (short, erect and tufted, with a capsule terminal on the stem) dominated the bryoflora and accounted for 91.7% of the moss taxa. Each of the dominant families included at least three genera such as Pottiaceae, Bryaceae and Ditrichaceae. More species of *Bryum* (three taxa) were found compared with other genera.

Pottiaceae and Bryaceae are found across the globe. They are well suited to the drought, high temperatures, disturbance, air pollution and minimal protection provided by the sparse vegetation of the Goujiang bauxite mine sites due to their reproductive strategies, life forms and ecophysiological tolerance of sometimes extreme xeric conditions (Lo Guidice et al., 1997). By contrast, taxa of Brachytheciaceae and Hypnaceae are usually restricted to relatively humid locations, with less disturbance and more vegetation cover (Lo Guidice et al., 1997); they are mostly found in grass on the margins of Goujiang karst bauxite. The sole liverwort, *Marchantia papillata* Raddi subsp. *grossibarba*, is limited to sheltered sites with high humidity and relatively low light levels and therefore not common in the dry environment of the mine.

At the family level, all six sample locations included taxa from four to six families (Fig. 2), with no significant difference among them. The maximum of six families was recorded at the aluminum ore sintering plant and waste rock pile (location 3). At the level of genus and species, relatively few bryophytes were recorded either in the vicinity of miners' living quarters (location 2) or at the bauxite mine (location 6), with seven species in seven genera and five species in five genera, respectively. More genera and species were recorded at each of the other four location categories: aluminum mill (one), aluminum ore sintering plant and rock pile (three), orchards (four) and ore stockpile (five). The abundance index (Eq. 1) was similar to the characteristic of genera and species for the six locations.

The average angle slope (gradient) of the plots in the vicinity of the miners' quarters (location 2) and at the bauxite mine (location 6) was 67.6° and 64.6°, respectively (Table 2), considerably steeper than the gradients recorded at the other four sites. The slope may influence the number of genera and species recorded at each site, as steeper slopes may accelerate soil erosion and limit the survival of bryophytes. According to the vegetation coverage of six locations and the intensity of human activities, the human disturbance intensity of the Goujiang karst bauxite area was divided into three levels (Table 2). Human disturbance may have a negative impact on bryophyte communities.

3.1.2. Classification of bryophyte communities

Bryophyte communities comprising numerous species can reflect the nature of the substrate and environment (Hu, 1987). Based on the classification system of ecological communities of Chen (1963), 11 principal bryophyte communities were identified in the Goujiang karst bauxite area (Table 3).

Six single-species (monospecific) communities were identified in the area (Table 3). The most commonly occurring communities that included only one species were *Pleuridium subulatum*, *Barbula constricta* var. *Constricta* and *Ditrichum heteromallum*. Five communities included

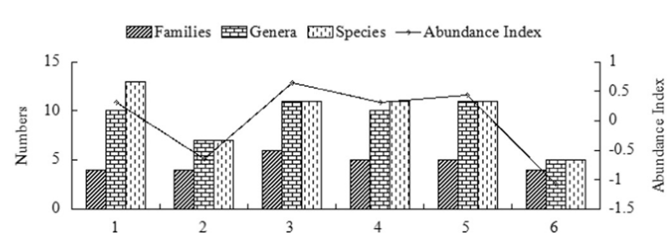

Fig. 2. Absolute numbers of bryophyte families, genera and species together with abundance index for the six locations: 1, aluminum mill; 2, vicinity of miners' living quarters; 3, aluminum ore sintering plant and waste rock pile; 4, orchards; 5, ore stockpile; and 6, bauxite mine.

Table 3
The principal bryophyte communities of the Goujiang karst bauxite area.

Number	Community names	Community composition	Habitat
C1	*Pleuridium subulatum*	*P. subulatum* (Hedw.) Rabenh.	Soil, thin soil
C2	*Barbula constricta* var. *constricta*	*B. constricta* Mitt. var. *constricta*	Thin soil
C3	*Ditrichum heteromallum*	*D. heteromallum* (Hedw.) Britt.	Soil, thin soil
C4	*Brachythecium glaciale*	*B. glaciale* B.S.G.	Soil, thin soil
C5	*Pogonatum inflexum*	*P. inflexum* (Lindb.) lac.	Soil
C6	*Bryum apiculatum*	*B. apiculatum* Schwaegr.	Thin soil
C7	*Ditrichum heteromallum–Hydrogonium consanguineum*	*D. heteromallum* (Hedw.) Britt. *H. consanguineum* (Thwait. et Mitt.) Hilp.	Soil
C8	*Hydrogonium consanguineum–Ditrichum heteromallum*	*H. consanguineum* (Thwait. et Mitt.) Hilp. *D. heteromallum* (Hedw.) Britt.	Soil, thin soil
C9	*Pleuridium subulatum–Pogonatum inflexum*	*P. subulatum* (Hedw.) Rabenh. *P. inflexum* (Lindb.) lac.	Thin soil, rock
C10	*Funaria muhlenbergii–Brachymenium exile*	*F. muhlenbergii* Turn. *B. exile* (Doz. et Molk.) Bosch et Lac.	Soil
C11	*Ditrichum heteromallum–Molendoa japonica–Anoectangium clarum*	*D. heteromallum* (Hedw.) Britt. *M. japonica* Broth. *A. clarum* Mitt.	Soil

more than one bryophyte taxon; the two most commonly occurring communities were *D. heteromallum–Hydrogonium consanguineum* and *P. subulatum–Pogonatum inflexum*.

Single-species communities are dominant in three locations in this area, all of which are affected by human activities (Zhang et al., 2013). The bryophyte communities are most abundant in soil to a lesser extent in thin soil over rock and rarely grow on rocks. Characteristically, bryophyte communities are most abundant in the soil of this region of China.

Sites in the vicinity of the aluminum milling area (one), the aluminum ore sintering plant and waste rock pile (three) and the bauxite mine (six) are principally composed of single-species communities (Fig. 3), which may reflect high levels of heavy metals, intense human disturbance (Table 2) and soil erosion. Roadside areas adjacent to the miners' living quarters (two), orchards (four) and ore stockpiles (five) were characterized by communities with several bryophyte taxa. In general, these three locations with mixed communities were more sheltered and less disturbed, and they retained higher levels of moisture than the three locations with only a single-species community. Multi-species communities grow under conditions more favorable than those dominated by single-species communities. The ore stockpile (five) remained undisturbed for a long time, was in the initial stage of vegetation succession and had a relatively high proportion of mixed-species community. Thus, single-species communities have greater potential for use as biomonitors in karst bauxite mine areas, as their presence reflects the presence of heavy metals in the soil matrix, disturbance and erosion.

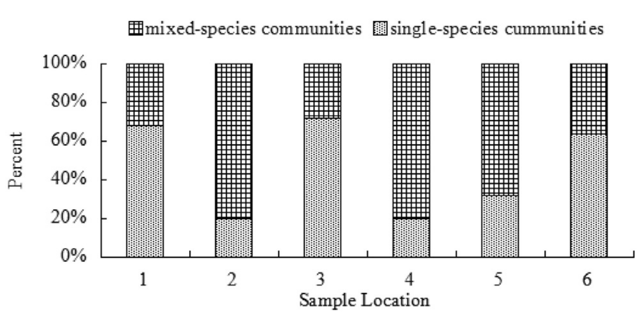

Fig. 3. Community structure of six sample locations: 1. aluminum mill; 2. vicinity of miners' living quarters; 3. aluminum ore sintering plant and waste rock pile; 4. orchards; 5. ore stockpile; and 6. bauxite mine.

3.2. Heavy metals present in soil substrate underlying bryophytes

The total heavy metal concentrations of copper, nickel, zinc and iron were evaluated in soil samples collected from 30 sample plots on the Goujiang karst bauxite (Fig. 1). The concentration of heavy metals in soil reported from each location is the mean of five sample plots (Table 4).

Fe: The total Fe concentration in the collected soil samples was very high, ranging from 8748.9 to 10,023 μg/g. Our results for this Fe-rich bauxite are similar to those recorded by Li and Zhu (2007) and Liu and Liao (2013). The highest concentration of total Fe was recorded at location 1, the aluminum mill, at 10,023 μg/g, as expected with Fe being a major by-product of the smelting process. The lowest level was found near miners' living quarters (location 2) at 8748.9 μg/g, which may have been caused by the leaching of rainwater down a relatively steep slope (Table 2).

Zn: The concentration of zinc fluctuated widely. The highest concentration of 755.1 μg/g was recorded from the aluminum mill (location 1). The concentrations recorded from the other five locations were relatively low, varying from 146.7 to 240.9 μg/g, which were higher than the background value of Zn in the Guizhou Province, as recorded by Jia et al. (2014) and by the National Environmental Monitoring Station (1990). The high concentration of zinc in the soil surrounding the aluminum mill may have been caused by the dust pollution from the powder processing of the aluminum ore. As all locations were adjacent to major transport roads, automobile tires may have contributed to the concentration of zinc in the soil (Jia et al., 2014; Pesch and Schröder, 2006).

Table 4
Heavy metal concentrations (μg/g) for six categories of locations of Goujiang karst bauxite (mean of five sample plots).

	Iron/Fe	Zinc/Zn	Copper/Cu	Nickel/Ni
1. Aluminum mill	10,023	755.1	46.6	68.7
2. Vicinity of miners' quarters	8748.9	146.7	40.9	57.5
3. Aluminum ore sintering plant and waste rock pile	9292.2	162.1	36.4	35.6
4. Orchards	9731	240.9	60.4	95.1
5. Ore stockpile	9650.6	180.5	24.6	43.3
6. Bauxite mine	9251.5	106.7	49.5	79.5
Mean value of 30 sample plots	9449.5	265.3	43.1	63.3
Background value for Guizhou Province	4170	99.5	32	66.7

Cu: The concentration of copper in the soil from six locations was relatively low, varying from 24.6 to 60.4 μg/g. The copper concentration was the highest in the orchards (four), resulting from deciduous humus, chemical fungicide and prevailing wind blowing from the aluminum ore sintering plant to the orchards. Only the ore stockpile (five) showed a Cu concentration lesser than the recorded background value (32 μg/g) for the Guizhou Province (Jia et al., 2014; National Environmental Monitoring Station, 1990; Pesch and Schröder, 2006). The original levels of Cu in the ore stockpile may have been similar to those of the other sites, as copper is known to be weakly related to environmental factors compared with other elements (Økland et al., 1999).

Ni: The concentration of nickel in the soil varied significantly among the six locations (Table 4). At the aluminum mill (one), the Ni concentration was very close to that of the background value of Ni recorded in soil for the Guizhou Province (66.7 μg/g). The Ni concentration from the orchards (four) and the bauxite mine (six) easily exceeded the background value of Ni recorded in soil for Guizhou (Jia et al., 2014; Pesch and Schröder, 2006). The concentrations near the miners' quarters (two), at the aluminum ore sintering plant and rock pile (three) and the ore stockpile (five) were well below this value. The lowest levels (35.6 μg/g) were observed at the sintering plant and rock pile (three) and the highest (95.1 μg/g) at orchards (four). Ni may be affected not only by the mineral content of the soil matrix but also by human activities.

On analysis, the total Fe and Zn mobility in our study area was found to be very high, which probably indicated its geogenic and anthropogenic origins (Bi et al., 2006a). Except for the aluminum mill (under strong human disturbance), the orchards have the highest levels of the four heavy metals. This may be caused by their proximity to major transport roads, the use of fungicides and wind blowing from the aluminum ore sintering plant to the orchards (field investigation). Wind speed, direction and distance from the sintering plant may also affect the heavy metal concentrations in the soil matrix (Bi et al., 2006b; Cymerman et al., 2006).

3.3. Distribution patterns of bryophyte communities

3.3.1. The distribution patterns of principal bryophyte communities

Bryophytes are efficient capture organisms for wet and dry deposition of heavy metals (Cymerman et al., 2006; Schofield, 2001; Wilkie and La Farge, 2011). In this fine-scale survey of bryophytes on Goujiang karst bauxite, each location received the same input of heavy metal ions from precipitation. However, the concentrations of heavy metals in bryophytes differed because of dust deposition on the substrate, directly resulting from human activities (field investigation). Dust-borne mineral particles can easily reach the surfaces of moss leaves (Økland et al.,

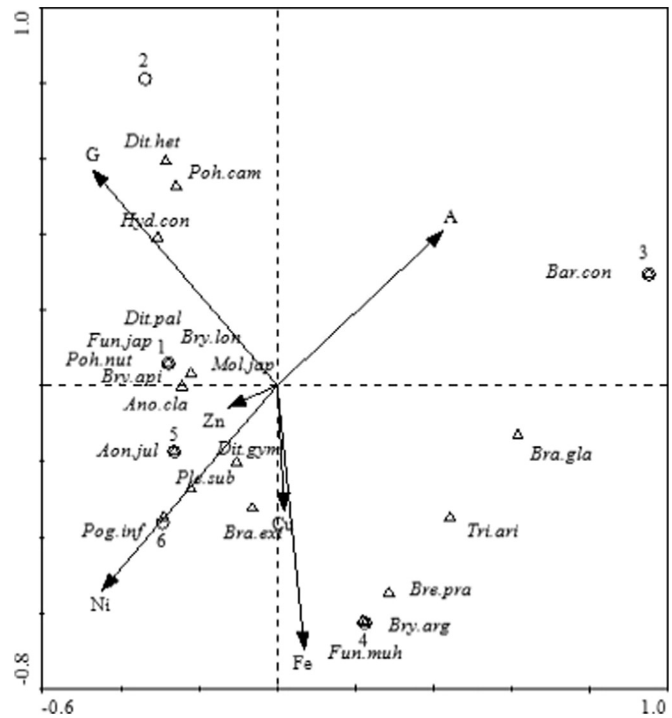

Fig. 4. Canonical correspondence analysis of bryophyte community data with the projection of species, variables and locations. *A*, altitude; *G*, gradient (slope); Fe, iron; Cu, copper; Ni, nickel; and Zn, zinc. 1. aluminum mill; 2. vicinity of miners' living quarters; 3. aluminum ore sintering plant and waste rock pile; 4. orchard; 5. ore stockpile; and 6. bauxite mine. The abbreviations of bryophyte are listed in Table 5.

Table 5
Relative abundance of bryophyte species from the six location categories ($n = 5$ sample plots).

Species	Abbreviation	Relative abundance					
		Location 1	Location 2	Location 3	Location 4	Location 5	Location 6
*Hydrogonium consanguineum**	*Hyd.con*	0.098	0.171	0	0	0.069	0
*Molendoa japonica**	*Mol.jap*	0.124	0.104	0.01	0.045	0.279	0
Anoectangium clarum	*Ano.cla*	0	0.053	0.001	0.017	0.152	0.018
*Trichostomum aristatulum**	*Tri.ari*	0	0	0.03	0.07	0	0
Barbula constricta Mitt. var. *constricta*	*Bar.con*	0	0	0.678	0	0	0
*Bryum lonchocaulon**	*Bry.lon*	0.038	0	0	0	0	0
*Bryum apiculatum**	*Bry.api*	0.179	0	0	0	0	0
*Bryum argenteum**	*Bry.arg*	0	0	0	0.055	0.001	0
*Pohlia camptotrachela**	*Poh.cam*	0.006	0.018	0.001	0	0.003	0
Pohlia nutans	*Poh.nut*	0.028	0	0	0	0	0
Brachymenium exile	*Bra.exi*	0.066	0	0	0.114	0.066	0.023
Ditrichum heteromallum	*Dit.het*	0.083	0.653	0.028	0.001	0	0.093
Ditrichum pallidum	*Dit.pal*	0.015	0	0	0	0	0
Pleuridium subulatum	*Ple.sub*	0.124	0.001	0.019	0.098	0.356	0.6
Ditrichopsis gymnostoma	*Dit.gym*	0.132	0	0.001	0.085	0.037	0
Funaria japonica	*Fun.jap*	0.106	0	0	0	0	0
Funaria muhlenbergii	*Fun.muh*	0	0	0	0.285	0	0
*Aongstroemiopsis julacea**	*Aon.jul*	0	0	0	0	0.013	0
Pogonatum inflexum	*Pog.inf*	0	0	0	0	0.023	0.265
Breidleria pratensis	*Bre.pra*	0	0	0.003	0.032	0	0
Brachythecium glaciale	*Bra.gla*	0	0	0.23	0.197	0	0

Note: '*' indicates gemmiferous species.

1999), which are highly capable of adsorbing and retaining many heavy metals from both precipitation and dry deposition (Berg and Steinnes, 1997). Thus, different environmental factors were found to affect each of the six locations. Bryophyte communities differ in their tolerance of environmental factors, such as heavy metals, some of which are uniform, single-species communities, while others are more complex multi-species communities.

The correlation between bryophyte communities and environmental factors was analyzed using the relative abundance index (Table 5) and heavy metal concentration (Table 4), as presented in Fig. 4 (in terms of the concentration of heavy metals present in the soil; gradient (angle of slope), *G*; and altitude, *A*). Locations 1, 4, 5 and 6 were mainly affected by the heavy metal concentration in the soil; location 2 was mainly affected by gradient; and location 3 was mainly affected by altitude.

Fig. 4 shows that the principal single-species bryophyte communities, *P. subulatum* community (*Ple.sub*) and *P. inflexum* community (*Pog.inf*), are primarily distributed in regions with high soil concentrations of nickel, zinc, iron and copper. The *B. constricta* var. *constricta* community (*Bar.con*) is distributed at relatively higher altitudes with lower concentrations of nickel, zinc, iron and copper. The *D. heteromallum* community (*Dit.het*) is chiefly found on steeper slopes with considerably lower concentration of iron and copper. The *B. glaciale* community (*Bra.gla*) is primarily distributed at higher altitudes, with high concentrations of iron and copper and lower concentrations of nickel and zinc. The *B. apiculatum* community (*Bry.api*) is mostly distributed at relatively higher-altitude areas with higher concentrations of nickel and zinc.

The principal mixed-species communities of *D. heteromallum*–*H. consanguineum* (*Dit.het*–*Hyd.con*) and *D. heteromallum*–*Molendoa japonica*–*Anoectangium clarum* (*Dit.het*–*Mol.jap*–*Ano.cla*) were primarily distributed on steeper slopes. *Funaria muhlenbergii*–*Brachymenium exile* (*Fun.muh*–*Bra.exi*) was mostly distributed on gentler slopes with high concentrations of nickel, zinc, iron and copper.

The ground of steep terrain is readily scoured and eroded by fast-flowing storm water. Thus, soil particles, the result of natural weathering, cannot be retained easily. On gentle slopes, rainwater can be retained for longer periods of time, enhancing the survival of bryophytes in otherwise harsh, dry conditions. Field studies have demonstrated that soil moisture is the main factor influencing the distribution of bryophyte communities (Cymerman et al., 2006; Glime, 2015; Sun et al., 2013). Jules and Shaw (1994) found that populations of *Ceratodon purpureus* growing on heavy metal-contaminated soils near mine and smelter sites were significantly more tolerant of heavy metals than those growing on uncontaminated soils. Many studies have found that bryophytes with high levels of tolerance to heavy metals are often restricted to contaminated environments (Jules and Shaw, 1994; Økland et al., 1999; Shaw, 1987, 1994). Therefore, just as the presence of copper moss indicates copper reserves so also can the appearance of different bryophyte communities and their distribution patterns associated with environmental factors be utilized to monitor heavy metals in karst bauxite.

3.3.2. The distribution patterns of bryophyte communities with gemmiferous species

The distribution of bryophyte communities with gemmiferous species is shown in Fig. 4. *Aongstroemiopsis julacea* (*Aon.jul*) is mainly distributed in regions with high concentration of nickel and zinc. *Bryum argenteum* (*Bry.arg*) and *Trichostomum aristatulum* (*Tri.ari*) are found on gentle slopes with high soil concentrations of nickel, iron and copper. *H. consanguineum* (*Hyd.con*) and *Pohlia camptotrachela* (*Poh.cam*) are mainly distributed on steep gradients with high concentrations of iron and copper. *B. apiculatum* (*Bry.api*), *Bryum lonchocaulon* (*Bry.lon*) and *Molendoa japonica* (*Mol.jap*) chiefly occur on medium slopes, with high soil concentrations of nickel and zinc.

Sexual reproduction appears to be inhibited in mosses growing in polluted environments, which instead successfully reproduce asexually (Shaw, 1994). Many bryophytes reproduce asexually from gemmae, and nine species from a total of 25 bryophytes found on Goujiang karst bauxite were found to produce gemmae. This accounts for >36% of the species recorded in this study, three times higher than in the Tianhetan karst wetlands (12%) in Guizhou (Wang et al., 2015). Shaw (1994) also commented that the total number of gemmiferous bryophytes recorded at heavy metal-contaminated mine sites was three to five times greater than that recorded in uncontaminated soils. Thus, the distribution of gemmiferous bryophyte communities may be used to monitor heavy metal pollution in the Goujiang karst bauxite area.

4. Conclusion

The Goujiang karst bauxite mining operations have resulted in heavy metal pollution and destruction of native vegetation in the surrounding area. No significant difference was found among the six sample locations at the family level. At the level of genus and species, the average angle slope of sample plots influences the quantity of bryophyte genera and species. Slope may influence the number of genera and species recorded at each site, as steeper slopes may accelerate soil erosion and limit the survival of bryophytes. Characteristically, bryophyte communities are composed of fewer bryophyte species than found elsewhere in the province. Eleven principal bryophyte communities were identified in the Goujiang karst bauxite area. The principal communities have a relatively simple structure; mixed-species communities are dominant on more sheltered, less disturbed locations with higher levels of moisture than single-species communities. Single-species communities may reflect intense human disturbance and soil erosion.

The total heavy metal concentrations of copper, nickel, zinc and iron were evaluated in soil samples collected from 30 sample plots on the Goujiang karst bauxite. The total iron content of the collected soil samples was very high, ranging from 8748.9 to 10,023 μg/g. Iron is a major by-product of the smelting process, and its concentration may be affected by rainwater and siope. The content of zinc from the six locations was higher than its background value in the Guizhou Province. Powder processing and automobile tires may contribute to the concentration of zinc in the soil. The concentration of copper in the soil from six locations was relatively low, varying from 24.6 to 60.4 μg/g. The concentration of nickel in the soil varied significantly among the six locations. Nickel may be affected not only by the mineral content in the soil matrix but also by human activities.

CCA revealed the effect of heavy metals concentration, slope and altitude on the distribution of the principal bryophyte communities and the gemmiferous bryophyte communities. Ore processing and human activity such as growing produce also have a negative impact on distribution. The appearance of different bryophyte communities is well related to environmental factors. The distribution of bryophyte communities was influenced by the concentration of heavy metals in the environment. Thus, it appears that the characteristic distribution patterns of the principal bryophyte communities and the gemmiferous bryophyte communities can be used as ecotopes conveniently and effectively to monitor heavy metal pollution in Goujiang karst bauxite.

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Appendix A

Environment and principal bryophyte community of Goujiang karst bauxite

Goujiang Karst Bauxite: 1. Typical appearance of karst bauxite deposits; 2. soil erosion on karst bauxite.

Study locations: 3. Location 1, aluminum mill; 4. location 2, vicinity of miners' living quarters; 5. location 3, aluminum ore sintering plant and waste rock pile; 6. location 4, orchard; 7. location 5, ore stockpile; and 8. location 6, bauxite mine.

Bryophyte communities on karst bauxite:

Single-species communities: a. *Brachythecium glaciale*, b. *Pogonatum inflexum*, c. *Funaria muhlenbergii* and d. *Pohlia camptotrachela*.

Multi-species communities: e. *Molendoa japonica*–*Brachythecium glaciale* and f. *Bryum argenteum*–*Molendoa japonica*.

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