云南石林碳酸盐岩表面气生蓝藻(蓝细菌)研究

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摘要:云南石林的黑石头及其颜色会随着天气的变化而变化的自然景观,是由于其碳酸盐岩表面长满黑色气生蓝藻(蓝细菌)之故。经鉴定,气生蓝藻共 4 目,11 科,31 属,188 种。种类十分丰富。其优势种主要为寄生微囊藻、红色星球藻、伯氏伪枝藻和皮壳伪枝藻等;寄生微囊藻和红色星球藻呈面状分布,相对均衡;伯氏伪枝藻和皮壳伪枝藻呈点状分布,相对集中。这些气生蓝藻的胶被色泽鲜艳,宽厚而坚硬,是适宜高山岩石表面生活的典型进化特征。在野外肉眼观察时,气生蓝藻还表现出不同形态的微群落;发现气生蓝藻能溶解石灰石,形成钻孔,加速岩石的溶蚀与风化。这些现象表明,气生蓝藻与云南石林岩石表面的微形态及整个石林景观的形成都有着十分密切的关系。

关键词:气生蓝藻(蓝细菌);碳酸盐岩表面;云南石林;中国云南

A Study on Aerial Cyanophyta (Cyanobacteria) on the Surface of Carbonate Rock in Yunnan Stone Forest, Yunnan Province, China

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Abstract: The well-known Yunnan Stone Forest is located in the Shilin County (former Lunan county, "Shilin" means the Stone Forest in Chinese.) and 24°30′~25°03′N and 103°10′~103°40′E, 85km southeast of Kunming, provincial capital of Yunnan, China. It is not only a great tourist attraction, but also of important scientific and aesthetic value. In the Yunnan Stone Forest National Park, there are variety shapes of stones such as blade-shape, tower-shape and mushroom-shape. The best of all amazements is the color of these stones in changable with weather. When it is raining, offwhite stones become black. When it is fine, their black color returns original offwhite.

After the field work on the Stone Forest, we found the black on the surface of stone results mainly form the living cyanophyta (cyanobacteria). These cyanophyta living on the dry surface of carbonate stone belong to typical aerial algae, which can live in the air or on rock surface lacking water and only obtain available water is from rain or fog. A great deal of the blue-green algae often appears when weather is warm and moist, but a few appear when weather is dry and cold at a long time. Causations of abundance aerial blue-green algae distributing on the surface of carbonate rock at the Yunnan Stone Forest are five points: First, In the Yunnan Stone Forest area, the mean annual air temperature is 16.3 C, annual precipitation is 800~850mm, the mean annual humidity is 75%, the mean sunlight of past years is 2318 hours, sunlight rate is 53%, and altitude is about 1700~1950m. It belongs to the sub-tropic altiplano

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climate of warmth, humidity, raininess and sunny, so this kind of climate is of great benefit to algae living. Second, the Yunnan Stone Forest is typical stone forest karst landscape and is named as the stone forest karst museum of the world. There are a lot of pure carbonate rocks there. Limestone is more abundant with CaO content more than 50%. Many algae favor calcium and live in hard water or on the limestone. Third, the blue-green algae, as a kind of prokaryotic organism from 30 hundred million years ago, are greatly adaptable and can live in any place of the world such as ice mountain, hot spring, blue water and deserted rock. Fourth, protoplasm of the blue-green algae is denser than that of other algae and higher plant, and is colloid and flow less and have few vacuoles with liquid. Protoplasm of the blue-green algae gives out water very easily, but rehabilitate soon after sopping water. These characters of blue-green algae make them more likely to live on the places lacking water and rock surface. They can survive by little water supply. Fifth, the blue-green algae are most bullheaded pioneer plant and produce organic matter on stone surface for later biologic activities.

Cyanophyta often extend in the same direction as downstream on the surface of carbonate rock and form many black strips named "ink-strap" or different black small communities which distribute and live on almost whole surface of carbonate rock, so that the carbonate rock appear black. During a long time dry weather, the blue-green algae grow comparatively slowly and shrink their cells to keep water in cell, appear offwhite. In wet weather, blue-green algae grow quickly and its cells dilate, appear black. The phenomenon of color change may be observed clearly by stereomicroscope. These ecological characters of the blue-green algae result in the formation of nature landscape of the black stone at Yunnan stone forests. The black color is changeable with weather change.

For a further understand to these black aerial algae, this paper had studied in detail about the species community, dominant species, distribution and biological characteristics etc.

Research methods include field collection, identification and statistic analysis of "Volume relative quantity" and "Appearance relative frequency". Volume relative quantity is the sum of homology algae volume percentages to be estimated in all microscope slides. A kind of algae volume (generally, the area of a kind of algae in the microscope slide is larger, the volume of a kind of algae in a microscope slide is bigger) percentage in a microscope slide is the volume of this kind alga to the volume of all kinds algae in a microscope slide. The volume relative quantity of algae is a relative numerical value and dose not represent actual volume quantity and only have comparative meaning and reflect relative biomass of a kind alga in the rseach area. Appearance relative frequency, if a kind of algae appears in a microscope slide, we name one time of appearance of this kind alga at the research area, then in all microscope, the times of appearance of a kind alga is the times of appearance of this kind alga at the research area, that is, the appearance relative frequency of this kind alga.

Sixty-three bottles of algal samples and 253 pieces of microscope slides have been obtained. By identifying the algae by optics microscope, aerial algae are mainly cyanophyta that belong to of 188 species of 31 genera of 11 families of 4 orders. Among them, a new species *Nephrococcus Shilin* Y. P. Tian and three new varieties *Asterocapsa rubra* var. *crassa* Y. P. Tian, *Asterocapsa changbaishanensis* var. *rubra* Y. P. Tian and *Asterocapsa purpurea* var. *minor* Y. P. Tian were recognizd. These new species and new varietie all belong to *Chroococcaceae*.

Cyanophyta on the surface of carbonate rock in the Yunnan Stone Forest is very abundant. It is suggested that the ecological environment of the Yunnan Stone Forest is very good.

According to statistic analysis, we had worked out: (A) Volume relative quantity of *Scytonema bohneri* and *Scytonema crustaceum* are the highest, but their appearance relative frequencies are relatively lower. It

can be explained that *Scytonema bohneri* and *Scytonema crustaceum* take on centralized and punctiform distribution on the rock surface. (B) Volume relative quantity and appearance relative frequencies of *Asterocapsa rubra* and *Microcystis parasitica* are higher. It can be explained that this two kind of algae take on uniform distribution. (C) The algae whose sum of volume relative quantity and appearance relative frequencies is higher are dominant species. The dominant species are *Microcystis parasitica*, *Asterocapsa rubra*, *Scytonema bohneri*, *Scytonema crustaceum* and *Gloeocapsa atrata* etc at the research area.

Color of aerial cyanophyta's sheath in the Yunnan Stone Forest is gorgeous such as red, yellow, purple and black. This is an important characteristic of algae living on the rock surface at alpine. Moreover, its sheath is thick and hard. These charcteristics are evolution results, which protect water in algae from evaporation.

Aerial cyanophyta not only make rock in the Yunnan Stone Forest in black color and form black rock landscape, but also play a important effect in the formation of stone forest shape. It was found that many aerial cyanophyta groups micro-communities of different shapes and erode carbonate rock into pits. The growth and distribution of micro-communities closely related to the formation of micro-morphology on the surface of stone forest rock. These actions of cyanophyta had been confirmed and researched on many literatures. Aerial cyanophyta accelerate the process of corrosion and weathering of the Yunnan Stone Forest, as a proper role, and take part in figuring of the Stone Forest shape, mechanisms of which need to be studied by biologists, geologists and geomorphologists together.

At present, little research to micro-community ecology of cyanophyta has been worked out, and the research to its adopting ration statistic means is more less. This paper is a attempt study to this field. Many topics have been discussed for further research.

Key words: aerial cyanophyta (cyanobacteria); surface of carbonate rock; Stone forest; Yunnan, China
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著名石林国家级风景区位于云南省石林彝族自治县(原路南彝族自治县)境内,地处北纬 24°30′～25°03′,东经 103°10′～103°40′,在海内外享有很高的声誉。景区内,石林形态丰富多样,造型美妙,有剑状、塔状、磨菇状等奇峰怪石。"青牛戏水"、"凤凰梳翅"、"母子携游"、"漫步从容"等著名景点,形态微妙微肖,令人惊喜流连。最让人惊异的是,这些石峰石柱还会随天气改变颜色,阵雨之时,灰白色的石柱竟成了浓墨色,宛如一幅泼墨山水(图版 Ⅰ-1)。雨过天晴,数十分钟内,无数石峰又魔幻般自峰脊边刃开始,由黑变灰(图版 Ⅰ-2,3),还其本来面目,让人叹为观止。黑色的石头不仅在这里作为一种独特而壮丽的自然景观,而且还深深地融入了当地彝族撒尼人的文化之中。路南一词源于彝语"鲁乃",鲁即石头,乃即黑色,鲁乃意为长满黑石头的地方。黑色,成为当地撒尼人崇高的象征。撒尼人自称"尼",即黑颜色的意思;《阿诗玛》史诗中的阿黑哥是撒尼人崇敬的英雄;在撒尼人的民族服装中最主要的颜色就是黑色[1]。

通过在石林近半个月的考察,发现石头表面的黑色主要是由于其表面长满黑色藻类植物之故,其中,95%以上的藻类是蓝藻(蓝细菌)。这些生长在干燥岩石上的蓝藻,属于典型的气生藻类。气生藻类(Luftalgen , Aerophytische , Atmophytische algen)是离开水的环境而在空气中生活的,其所需的水是从下雨或蒸气中获得[2]。它通常在温暖而潮湿的气候里大量出现,而在长期干燥寒冷的地方数量很少。云南石林碳酸盐岩表面分布着大量的气生蓝藻,原因有 5 点:①云南石林一带,年平均气温 16.3℃,年降水量在 800～ 850mm 之间,平均湿度 75%,历年平均日照时数为 2318h,日照率 53%,海拔约在 1700～1950m 之间[1],属于温暖潮湿,雨量充沛,阳光充足的亚热带高原气候。所以,该地区的气候条件十分有利于气生藻类的生长。②云南石林是典型的石林喀斯特景观,被誉为世界石林喀斯特博物馆,分布有大量较纯的碳酸盐岩,其中,以石灰岩较多,岩石含 CaO50%以上,而许多藻类都偏爱于钙质和生活在硬水或石灰石基质上。③蓝藻作为一类早在 30 亿年前就出现的原核生物,具有极大的适宜性。它在世界任何地方都有出现,

从两极到赤道，在冰山，热泉，深海，荒芜的岩石上都能生存。④蓝藻的原生质比其他藻类和高等植物的原生质浓厚，它是胶质的，不流动，也很少含有具水溶液的液泡；蓝藻的原生质很容易放出水来，但吸水后又恢复原状。这些性质使蓝藻最有可能生活在象岩石表面这样干燥无土的地方，即是它有短时间的供水就能生活[2]。⑤蓝藻是最顽强的先锋植物，它首先在岩石上形成有机质，使后来的生物的生活成为可能。

蓝藻常在碳酸盐岩表面，顺着雨水流动的方向扩展，形成一条条黑色带状的外观，称为“墨水带”(图版Ⅰ-1；见书后彩版)；或以不同黑色小群落的方式分布和生活在几乎整个碳酸盐岩的表面(图版Ⅱ-1)，使其表现为黑色。当天气久干无雨时，生活在岩石上的蓝藻生长相对缓慢，细胞处于收缩状态，以保持体内的水分，其颜色成为灰色。一旦下雨，蓝藻细胞扩张，生命活动旺盛，其颜色成为黑色。在体视显微镜下，能清楚地观察到这一特征，将岩石标本移到体视显微镜下，观察岩石标本表面的藻体，由于标本经过包装运输，挥发失水，其表面的藻体已经干缩，颜色呈灰色(图版Ⅱ-2)，用滴管将少许水，滴到这些已经干缩的藻体上，观察藻体的变化，发现原来已经干缩的藻体，一旦遇水便立刻吸水膨胀，膨胀体积可达到原来干缩体积的3～6倍，同时颜色加深，呈黑色(图版Ⅲ-1)。蓝藻的这些生态特征，形成了云南石林的黑石头和这些石头的颜色会随天气的变化而变化的自然景观。

为了对这些黑色气生蓝藻有更深入的了解，本篇文章作了更详细的研究，内容包括云南石林气生蓝藻的种类组成，优势种类及分布特点，生物学特征等。

1 研究方法

1.1 野外采集

用小刀将岩石表面不同形态的藻类群落划取，放入盛有4%甘油＋4%富尔马林的固定液的采集瓶中[3]，编号，拍照，并进行描述和记下日期、地点。采集范围覆盖整个研究区不同生境和地貌的典型部位。

1.2 室内鉴定和统计

将样品从采集瓶中取出，于解剖镜下选取少量藻类，制备微片。将微片于光学显微镜下镜检，鉴定藻类[4～8]，拍照。

为了了解藻类在岩石表面的分布情况，本文对以下两个数值进行规定和统计：

(1) 体积相对数　对每张微片中每一种藻类占该微片中总藻类体积(在微片中，每一种藻类占该微片的面积越大，则该种藻类的体积越大)的百分数进行估计，即得该种藻类在该微片中的体积估计百分数。将研究区所有微片中相同藻类的体积估计百分数相加，即得该研究区该种藻类的体积相对数。这里的体积相对数，并不代表实际的体积数，它是一个估计的相对数值，只具有比较意义，它反映了该种藻类在该研究区的相对生物量。

(2) 出现相对次数　将一种藻类出现于一张微片中，认定为该种藻类在研究区出现一次，则同一种藻类出现于多张微片中的微片数，为该种藻类在研究区的出现相对次数。

2 结果与分析

2.1 云南石林气生蓝藻的种类组成

野外采集藻类标本，共63号。室内制备藻类微片，共253张。显微鉴定表明，藻类主要为蓝藻门蓝藻纲的属种，共4目11科31属188种，其中，发现一新种(石林肾胞藻 *Nephrococcus Shilin* Y. P. Tian)和3个新变种(红色星球藻大型变种 *Asterocapsa rubra* var. *crassa* Y. P. Tian、长白山星球藻红色变种 *Asterocapsa changbaishanensis* var. *rubra* Y. P. Tian 、紫色星球藻小型变种 *Asterocapsa purpurea* var. *minor* Y. P. Tian)[17]。可以看出，云南石林碳酸盐岩表面的蓝藻种类是十分丰富的，说明云南石林一带的自然生态环境非常好。

2.2 云南石林气生蓝藻的优势种类及分布特点

藻类体积相对数和出现相对次数，见表1，根据表1，分别作出藻类体积相对数对比图(图1)和藻类出现相对次数对比图(图2)。据此，可得出如下结论：

(1) 伯氏伪枝藻和皮壳伪枝藻在研究区的体积相对数较高，但其出现相对次数却偏低。这说明，伯氏伪枝藻和皮壳伪枝藻在研究区的岩石表面，不出现则罢，一出现数量就较多，呈点状分布，相对集中。

表 1　云南石林碳酸盐岩表面蓝藻体积相对数和出现相对次数

Table 1　Volume relative quantity (VRQ) and appearance relative frequency (ARF) of Cyanophyta on the surface of carbonate rock in Yunnan Stone Forest, Yunnan Province, China

编号 No.	镜检结果 Result of differentiating by optics microscope	体积相对数 VRQ	出现相对次数 ARF	体积相对数与出现相对次数之和 VRQ+ARF	编号 No.	镜检结果 Result of differentiating by optics microscope	体积相对数 VRQ	出现相对次数 ARF	体积相对数与出现相对次数之和 VRQ+ARF
1	笔状裂须藻 *Schizothrix penicillata*	110.2	40	150.2	103	内卷翅线藻 *Petalonema involvens*	44	20	64
2	边缘微囊藻 *Microcystis marginata*	96	200	296	104	纳氏隐杆藻 *Aphanothece Naegelii*	5	10	15
3	伯氏伪枝藻 *Scytonema bohneri*	1090	230	1320	105	拟单歧伪枝藻 *Scytonema tolypothrichoides*	131	30	161
4	薄膜粘球藻 *Gloeocapsa crepidium*	3	20	23	106	拟色球粘囊藻 *Myxosarcina chroococcoides*	293	130	423
5	不定腔球藻 *Coelosphaerium dubium*	1	10	11	107	捏团粘球藻 *Gloeocapsa magma*	369	490	859
6	不定微囊藻 *Microcystis incerta*	10	20	30	108	纽曲单歧藻 *Tolypothrix distorta*	36	40	76
7	层片微囊藻 *Microcystis lamelliformis*	170	20	190	109	帕氏伪枝藻 *Scytonema pascheri*	448	70	518
8	长白山星球藻 *Asterocapsa changbaishanensis*	21.5	80	101.5	110	泡状平盘藻 *Placoma vesiculosa*	10	20	30
9	长突星球藻 *Asterocapsa longipapilla*	15	20	35	111	膨胀色球藻 *Chroococcus turgidus*	22.2	90	112.2
10	尘埃微囊藻 *Microcystis pulverea*	20	10	30	112	膨胀伪枝藻 *Scytonema dilatatum*	40	10	50
11	池生念珠藻 *Nostoc piscinale*	750	150	900	113	皮果藻 *Dermocarpa* sp.	5	20	25
12	稠密粘球藻 *Gloeocapsa compacta*	17	30	47	114	皮壳伪枝藻 *Scytonema crustaceum*	874	200	1074
13	次裂隙颤藻 *Oscillatoria subbrevis*	1	10	11	115	皮色粘球藻 *Gloeocapsa dermochroa*	11	30	41
14	翠绿微囊藻 *Microcystis viridis*	317	280	597	116	皮氏集胞藻 *Synechocystis Pevalekii*	9	30	39
15	大型集胞藻 *Synechocystis crassa*	15	10	25	117	珀氏裂须藻 *Schizothrix Purcellii*	20	10	30
16	滴岩粘球藻 *Gloeocapsa stegophila*	249.5	540	789.5	118	栖石色球藻 *Chroococcus lithophilus*	5	10	15
17	滴岩粘球藻大型变种 *Gloeocapsa stegophila* var. *crass*	50	10	60	119	栖石土席藻 *Phormidium rubroterricola*	286	70	356
18	普通念珠藻 *Nostoc commune*	76	50	126	120	栖石隐杆藻 *Aphanothece saxicola*	10	10	20
19	点形念珠藻 *Nostoc punctiforme*	10	10	20	121	栖霞鞘丝藻 *Lyngbya digueti*	240	50	290
20	点形粘球藻 *Gloeocapsa punctata*	86	160	246	122	栖藓鞘丝藻 *Lyngbya mucicola*	9	40	49
21	东方席藻 *Phormidium orientale*	183	40	223	123	其它 Others	96	290	386
22	多管鞘丝藻 *Lyngbya polysiphoniae*	105	20	125	124	墙壁眉藻 *Calothrix parietina*	184	80	264
23	多形管孢藻 *Chamaesiphon polymorphus*	55	40	95	125	鞘丝藻 *Lyngbya* sp.	41	60	101
24	多育颤藻 *Oscillatoria prolifica*	33	40	73	126	球纹星球藻 *Asterocapsa trochiscioides*	47	140	187
25	多枝伪枝藻 *Scytonema multiramosum*	85	10	95	127	软席藻 *Phormidium molle*	74	20	94
26	二型隐球藻 *Aphanocapsa biformis*	360	340	700	128	瑞士色球藻 *Chroococcus helveticus*	4	40	44
27	佛氏绿胶藻 *Hydrogloea Fritschi*	150	40	190	129	塞斯西雅隐球藻 *Aphanocapsa sesciacensis*	160	50	210

续表 1

28	弗氏眉藻 *Calothrix Flahaultii*	40	10	50	130	色球藻 *Chroococcus* sp.	7	30	37
29	弗氏伪枝藻 *Scytonema Fritschii*	60	30	90	131	沙生裂须藻 *Schizothrix arenaria*	173	70	243
30	浮游念珠藻 *Nostoc planctonicum*	25	10	35	132	山地色球藻 *Chroococcus montanus*	2	20	22
31	福氏单歧藻 *Tolypothrix Foreauii*	65	30	95	133	山地隐球藻 *Aphanocapsa montana*	221	200	421
32	盖氏伪枝藻 *Scytonema Geitleri*	10	20	30	134	山地隐球藻小型变种 *Aphanocapsa montana* var. *micrococcus*	12	40	52
33	高山粘球藻 *Gloeocapsa alpina*	37	60	97	135	山地粘球藻 *Gloeocapsa montana*	95	40	135
34	格氏隐球藻 *Aphanocapsa Grevillei*	23	30	53	136	舍氏异球藻 *Xenococcus Schousboei*	2	10	12
35	硅藻 Bacillariophyta	13	10	23	137	埃氏单歧藻 *Tolypothrix Elenkinii*	15	10	25
36	果实管孢藻 *Chamaesiphon carpaticus*	90	10	100	138	石生粘球藻 *Gloeocapsa rupestris*	15	30	45
37	哈氏念珠藻 *Nostoc Hatei*	120	40	160	139	束缚色球藻 *Chroococcus tenax*	46.5	160	206.5
38	旱生微囊藻 *Microcystis orissica*	101	170	271	140	水生集胞藻 *Synechocystis aquatilis*	47	20	67
39	褐黑粘杆藻 *Gloeothece ustulata*	9	30	39	141	丝状鞘丝藻 *Lyngbya confervoides*	70	30	100
40	褐黑粘杆藻小型变种 *Gloeothece ustulata* var. *minor*	8	10	18	142	四体粘球藻 *Gloeocapsa quaternata*	7	40	47
41	黑色胶须藻 *Rivularia atra*	49	20	69	143	梭形粘球藻 *Gloeocapsa shuttleworthiana*	30	10	40
42	黑色鞘丝藻 *Lyngbya nigra*	240	30	270	144	铁锈管孢藻 *Chamaesiphon ferrugineus*	60	20	80
43	黑色星球藻 *Asterocapsa atrata*	208	310	518	145	铜绿粘球藻 *Gloeocapsa aeruginosa*	47	90	137
44	黑色粘球藻 *Gloeocapsa atrata*	444.8	510	954.8	146	透明星球藻 *Asterocapsa hyalina*	258.3	380	638.3
45	黑紫粘球藻 *Gloeocapsa nigrescens*	170.3	140	310.3	147	土栖隐球藻 *Aphanocapsa muscicola*	2	10	12
46	红被粘杆藻 *Gloeothece rhodochlamys*	13	40	53	148	椭孢念珠藻 *Nostoc ellipsosporum*	26	10	36
47	红色星球藻 *Asterocapsa rubra*	780.7	680	1460.7	149	微孢绿胶藻 *Chlorogloea microcystoides*	28.3	70	98.3
48	红网鞘丝藻钙质变种 *Lyngbya martensiana* var. *calcarea*	290	70	360	150	微孢隐杆藻 *Aphanothece microspora*	4	20	24
49	红紫微鞘藻 *Microcoleus purpureus*	13	20	33	151	微囊藻 *Microcystis* sp.	3	10	13
50	厚膜色球藻 *Chroococcus turicensis*	37	140	177	152	微小色球藻 *Chroococcus minutus*	2	10	12
51	湖泊鞘丝藻 *Lyngbya limnetica*	2	20	22	153	微小微囊藻 *Microcystis minutissima*	91	60	151
52	黄色鞘丝藻 *Lyngbya lutea*	461	100	561	154	微小隐杆藻 *Aphanothece microscopica*	9	30	39
53	喙突粘球藻 *Gloeocapsa coracina*	33.1	100	133.1	155	伪枝藻 *Scytonema* sp.	53	50	103
54	霍氏裂须藻 *Schizothrix Heufleri*	242	160	402	156	未知 *unknow*	50	50	100
55	极小集胞藻 *Synechocystis minuscula*	17	30	47	157	埃哥念珠藻 *Nostoc elgonense*	95	20	115
56	极小色球藻 *Chroococcus minimus*	3	20	23	158	希氏鞘丝藻 *Lyngbya Hieronymusii*	35	10	45
57	寄生微囊藻 *Microcystis parasitica*	978.5	610	1588.5	159	锡兰鞘丝藻 *Lyngbya ceylanica*	140	20	160
58	假格圆伪枝藻 *Scytonema guyanense*	319	80	399	160	席藻 *Phormidium* sp.	2	10	12

续表 1

59	坚实微囊藻 *Microcystis filrma*	45	60	105	161	喜钙念珠藻 *Nostoc calcicola*	104	40	144
60	胶质粘球藻 *Gloeocapsa gelatinosa*	15	40	55	162	细巧隐球藻 *Aphanocapsa delicatissima*	12	30	42
61	金枝藻(金藻门) *Phaeothamion confervicola* (*Chrysophyta*)	370	50	420	163	细小隐球藻 *Aphanocapsa elachista*	243	170	413
62	晶粒粘球藻 *Gloeocapsa crepidinum*	514	410	924	164	细叶裂须藻 *Schizothrix mascarenica*	40	20	60
63	居氏腔球藻 *Coelosphaerium Kuetzingianum*	4	10	14	165	纤细伪枝藻 *Scytonema tenellum*	55	10	65
64	巨大鞘丝藻 *Lyngbya majuscula*	419	120	539	166	纤细席藻 *Phormidium tenue*	135	50	185
65	巨大粘球藻 *Gloeocapsa gigas*	32	70	102	167	藓 *moss*	101	20	121
66	菌丝 hypha	52	20	72	168	小形色球藻 *Chroococcus minor*	1	10	11
67	卡氏鞘丝藻 *Lyngbya Kashyapii*	154	90	244	169	小型念珠藻 *Nostoc minutum*	111	50	161
68	卡氏隐杆藻 *Aphanothece Castagnei*	33	20	53	170	小粘球藻 *Gloeocapsa minutula*	14	30	44
69	康氏粘囊藻 *Myxosarcina Concinna*	10	70	80	171	亚麻色单歧藻 *Tolypothrix byssoidea*	73	60	133
70	颗粒粘球藻 *Gloeocapsa granosa*	70	200	270	172	亚麻色单歧藻岩生变种 *Tolypothrix byssoidea f. saxicola*	180	40	220
71	客氏异球藻 *Xenococcus Kerneri*	13	30	43	173	亚丝鞘丝藻 *Lyngbya subconfervoides*	120	30	150
72	枯萎 *withered*	50	10	60	174	岩生粘杆藻 *Gloeothece rupestris*	13.5	50	63.5
73	枯萎粘球藻 *Gloeocapsa deusta*	88	110	198	175	盐生伪枝藻印度变种 *Scytonema salayeriense* var. *indica*	298	70	368
74	库氏链鞘藻 *Sirocoleus Kurzii*	32	20	52	176	眼点伪枝藻 *Scytonema ocellatum*	50	10	60
75	库氏隐球藻 *Aphanocapsa Koordersi*	155	90	245	177	依氏粘球藻 *Gloeocapsa Itzigsohnii*	24	30	54
76	拉氏鞘丝藻 *Lyngbya Lachneri*	154	40	194	178	易脆裂须藻 *Schizothrix fragilis*	120	30	150
77	拉氏粘球藻 *Gloeocapsa Ralfsiana*	60	30	90	179	易碎单歧藻 *Tolypothrix fragilis*	145	30	175
78	莱氏裂须藻 *Schizothrix Lenormandiana*	65	10	75	180	隐杆藻 *Aphanothece* sp.	5	10	15
79	蓝色粘球藻 *Gloeocapsa livida*	10	30	40	181	蝇色伪枝藻 *Scytonema myochrous*	125	60	185
80	莉氏念珠藻 *Nostoc Letestui*	455.5	180	635.5	182	有须伪枝藻 *Scytonema stuposum*	120	20	140
81	立氏单歧藻 *Tolypothrix Rechingeri*	99	20	119	183	玉红裂须藻 *Schizothrix rubra*	50	40	90
82	沥青色球藻 *Chroococcus bituminosus*	31	20	51	184	原型微鞘藻 *Microcoleus chthonoplastes*	42	70	112
83	联结鞘丝藻 *Lyngbya connectens*	285	50	335	185	圆胞束球藻 *Gomphosphaeria aponina*	3	10	13
84	裂褶念珠藻 *Nostoc verrucosum*	13	20	33	186	粘附单歧藻着色变种 *Tolypothrix conglutinata* var. *colorata*	60	30	90
85	林氏念珠藻 *Nostoc Linckia*	185	30	215	187	粘杆藻 *Gloeothece* sp.	5	10	15
86	绿色隐球藻 *Aphanocapsa virescens*	10	10	20	188	粘黑粘球藻 *Gloeocapsa bituminosa*	9	20	29
87	马拉维伪枝藻 *Scytonema malaviyaensis*	85	10	95	189	粘连色球藻 *Chroococcus cohaerens*	90	100	190
88	玫瑰红皮果藻 *Dermocarpa rosea*	50	10	60	190	粘球藻 *Gloeocapsa* sp.	20	90	110
89	煤黑厚皮藻 *Dermocarpa fuliginosa*	67.2	80	147.2	191	植内隐球藻 *Aphanocapsa endophytica*	12	40	52

续表 1

90	美丽颤藻 *Oscillatoria formosa*	5	10	15	192	朱氏蓝枝藻 *Hyella Jurana*	40	20	60
91	美丽隐球藻 *Aphanocapsa pulchra*	111	200	311	193	爪哇伪枝藻 *Scytonema javanium*	185	60	245
92	美丽粘囊藻 *Myxosarcina spectabilis*	211	210	421	194	着色裂须藻 *Schizothrix tinctoria*	53	20	73
93	美丝鞘丝藻 *Lyngbya perelegans*	41	50	91	195	紫管鞘丝藻 *Lyngbya porphyrosiphonis*	85	30	115
94	米氏伪枝藻 *Scytonema Millei*	245	40	285	196	紫色平盘藻 *Placoma violacea*	12	20	32
95	密集微囊藻 *Microcystis densa*	20	20	40	197	紫色微囊藻 *Microcystis amethystina*	45	30	75
96	缅甸伪枝藻 *Scytonema burmanicum*	509	100	609	198	紫色星球藻 *Asterocapsa purpurea*	73.3	150	223.3
97	缅甸粘囊藻 *Myxosarcina burmensis*	103	170	273	199	棕黄微囊藻 *Microcystis fusco-lutea*	325.6	280	605.6
98	膜状色球藻 *Chroococcus membraninus*	55	110	165	200	棕黄粘杆藻 *Gloeothece fusco-lutea*	6.5	30	36.5
99	石林肾胞藻 *Nephrococcus Shilin*	60	30	90	201	长白山星球藻红色变种 *Asterocapsa changbai-shanensis* var. *rubra*	50	30	80
100	红色星球藻大型变种 *Asterocapsa rubra* var. *crassa*	70	90	160	202	紫色星球藻小型变种 *Asterocapsa purpurea* var. *minor*	60	20	80
101	地衣 *lichen*	90	60	150	203	棕色眉藻 *Calothrix fusca*	12	30	42
102	巴拉里隐球藻 *Aphanocapsa banaresensis*	20	30	50	204	棒状皮果藻 *Dermocarpa clavata*	50	20	70

* 为了比较之便，这里的出现相对次数均在原来实际出现相对次数的基础上乘 10。For more convenient contrast, actual appearance relative frequency times ten is ARF in the table.

(2)红色星球藻和寄生微囊藻的体积相对数和出现相对次数均偏高，说明，两种藻类在研究区的岩石表面，呈面状分布，相对均衡。

(3)藻类体积相对数和藻类出现相对次数之和较高的，即为该研究区的优势藻类。由图 3 可知，研究区的优势藻类为寄生微囊藻、红色星球藻(图版Ⅲ-2)、伯氏伪枝藻、皮壳伪枝藻(图版Ⅲ-3)和黑色粘球藻等。

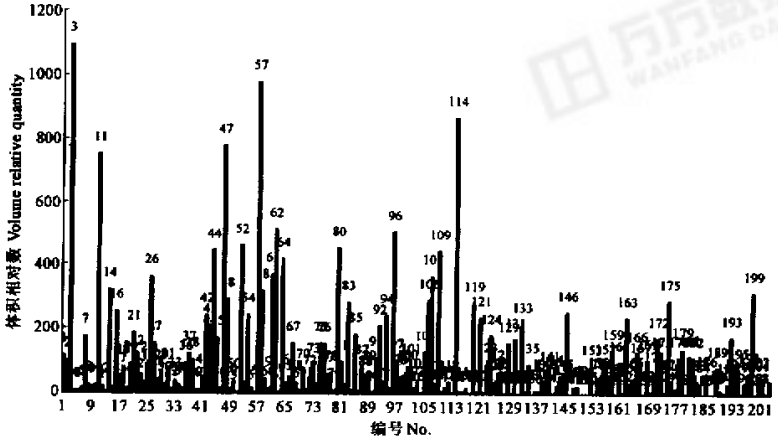

图 1 云南石林碳酸盐岩表面的藻类体积相对数对比图

Fig. 1 Contrast of volume relative quantity of Cyanophyta on the surface of carbonate rock in Yunnan Stone Forest, Yunnan Province, China

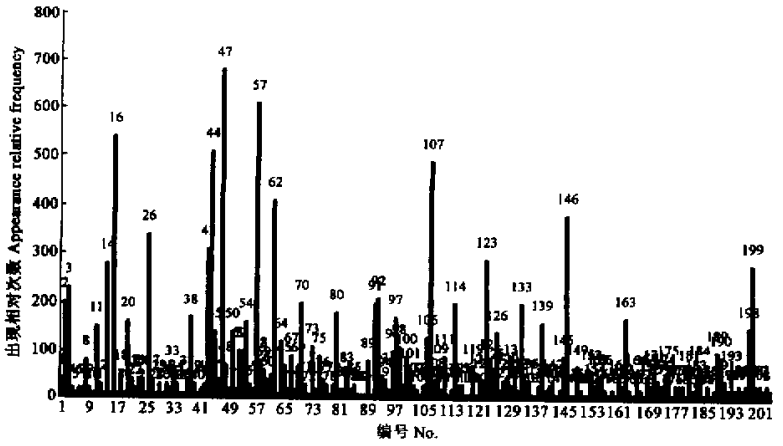

图 2　云南石林碳酸盐岩表面的藻类出现相对次数对比图

Fig. 2　Contrast of appearance relative frequency of Cyanophyta on the surface of carbonate rock in Yunnan Stone Forest, Yunnan Province, China

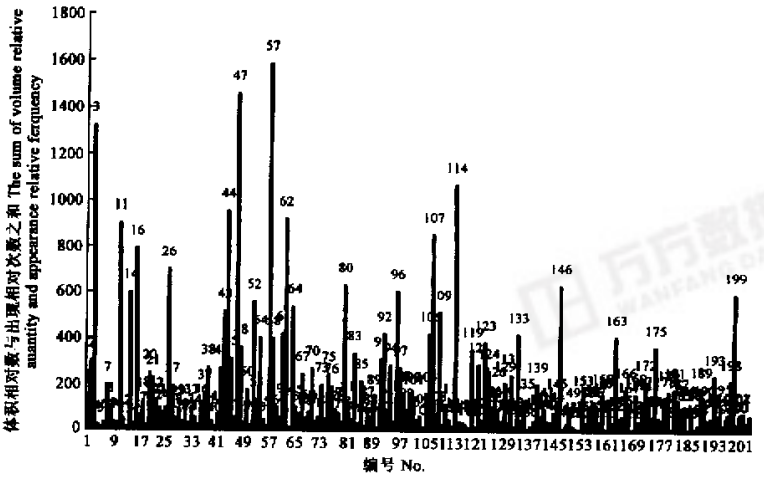

图 3　云南石林碳酸盐岩表面的藻类体积相对数与藻类出现相次数之和对比图

Fig. 3　Contrast of the sum of volume relative quantity and appearance relative frequency of Cyanophyta on the surface of carbonate rock in Yunnan Stone Forest, Yunnan Province, China

2.3　云南石林气生蓝藻的生物学特征

(1) 云南石林气生蓝藻的胶被或胶鞘色泽鲜艳,具有特别强烈的色彩(红,黄,紫或黑)。例如,寄生微囊藻、红色星球藻(图版Ⅲ-2)、伯氏伪枝藻、皮壳伪枝藻(图版Ⅲ-2)、黑色粘球藻和粘黑粘球藻等。这是生长在岩石表面的高山藻类的重要特征[2]。

(2) 气生蓝藻的胶被或胶鞘宽厚且坚硬,可防止藻体内水分过度蒸发,是适宜高山岩石表面生活的典

型进化特征。

2.4 气生蓝藻与石林景观的形成

气生蓝藻不仅使石林的石头成为黑色，形成黑石头景观，而且还对石林形态的形成有着十分重要的作用①。野外观察发现，许多蓝藻溶解石灰石，形成钻孔；蓝藻微群落的生长分布与石林岩表的微形态形成有密切关系。蓝藻的这些作用，在许多文献里已得到充分的证实和研究[9～16]。气生蓝藻加速了石林的溶蚀和风化过程，以它特有的角色，参与着石林形态的塑造，其机理，需要生物学者、地质学者、地貌学者携起手来，共同研究。

3 小结与讨论

云南石林的黑石头及这些石头的颜色会随着天气的变化而变化的自然景观，是由于其碳酸盐岩表面长满黑色的气生蓝藻之故。它们的胶被色泽鲜艳，宽厚而坚硬，是适宜高山岩石表面生活的典型进化特征。野外肉眼观察时，还发现它们表现出不同形态微群落，能溶解石灰石，形成钻孔。这些现象表明，气生蓝藻与云南石林碳酸盐岩岩石表面的微形态及整个石林形态景观的形成都有着十分密切的关系。

目前，对蓝藻微群落生态进行研究的工作很少，采用定量统计方法研究的就更少，本文的研究是大胆尝试，许多问题值得探讨。

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田友萍一文图版说明

图版 Ⅰ Plate Ⅰ

1. **大石林狮子亭，示阴雨时碳酸盐岩表面浓黑色的墨水带**。At Shiziting in the Great Stone Forest, showing the dark black ink belt on the surface of carbonate rock while it is raining. (Ⅰ$_{00}$)[SL-99001][①]

2. **大石林东侧，示晴天时碳酸盐岩表面呈灰色**。On the east of the Great Stone Forest, showing the gray surface of carbonate rock while it is sunny. (Ⅵ$_{19}$)

3. **大石林“民族娱乐中心”路边，工人给草坪浇水时，左侧石面被水淋湿，呈黑色，与右侧没有被水淋湿的呈灰色的石面形成鲜明对比，石面上均覆盖有一层蓝藻**。Beside the center of minority nationality amusement in the Great Stone Forest, the surface of carbonate rock on the left was soaked by water and appears black when worker irrigated the grassland. However, the surface of carbonate rock on the right was not soaked by water and appears gray. The blue-green algae communities cover all of the surfaces of carbonate rock. (Ⅵ$_{5}$)[SL-99044, Y-99021]

图版 Ⅱ Plate Ⅱ

1. **大石林“石林”刻字右侧，示生活在碳酸盐岩表面的黑色蓝藻小群落**。On the right of “Shilin” carve in the Great Stone Forest, showing the black blue-green algae communities living on the surface of carbonate rock. (Ⅲ$_{29}$)[SL-99034]

2. **乃古石林，在体视镜下观察碳酸盐岩表面蓝藻群落干缩时的情况，与图版 Ⅱ-1 对比，其色泽较后者浅**。At the Naigu Stone Forest, showing the blue-green algae communities dry and contract by stereo microscope. Compare to Plate Ⅱ-1, this is lighter than that. (13)[Y-99008]

图版 Ⅲ Plate Ⅲ

1. **乃古石林，在体视镜下观察碳酸盐岩表面蓝藻群落遇水时的情况，蓝藻群落吸水膨胀，其膨胀体积能达到干缩时的 3～6 倍，与图版 Ⅱ-2 对比，其色泽加深变黑**。At the Naigu Stone Forest, showing the blue-green algae communities meet with water by stereo microscope. The blue-green algae communities expand when its absorb water. The expanse volume is 3 to 6 times of the dry that. Compare to Plate Ⅱ-2, its color become black. (14)[Y-99008]

2. **石林景区的优势藻类，红色星球藻** *Asterocapsa rubra* C. Z. Wang，×640(Ⅻ$_{12}$)[SL-99017①] The dominant species in the Stone Forest : *Asterocapsa rubra* C. Z. Wang，×640(Ⅻ$_{12}$)[SL-99017①]

3. **石林景区的优势藻类，皮壳伪枝藻** *Scytonema crustaceum* Ag.， The dominant species in the Stone Forest: *Scytonema crustaceum* Ag.，×640(Ⅹ Ⅲ 0)[SL-99020⑤]

①**小括弧内为相片编号，方括弧内为标本编号** That in parenthesis is number of photos and that in brackets is number of samples

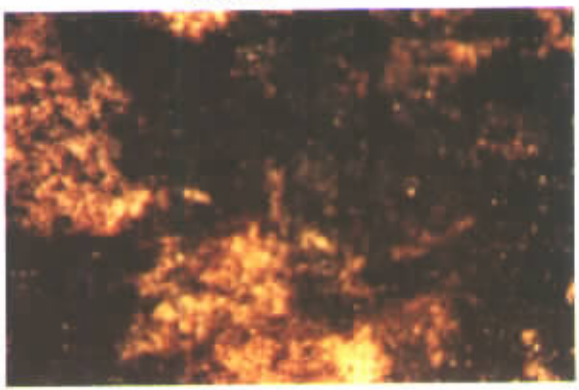
图版 I Plate I

1

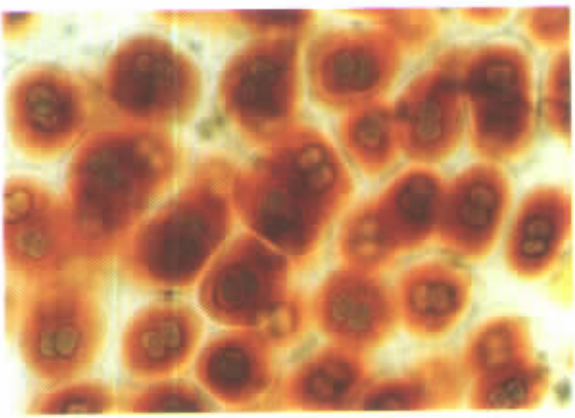
2

3

图版 III Plate III



5mm

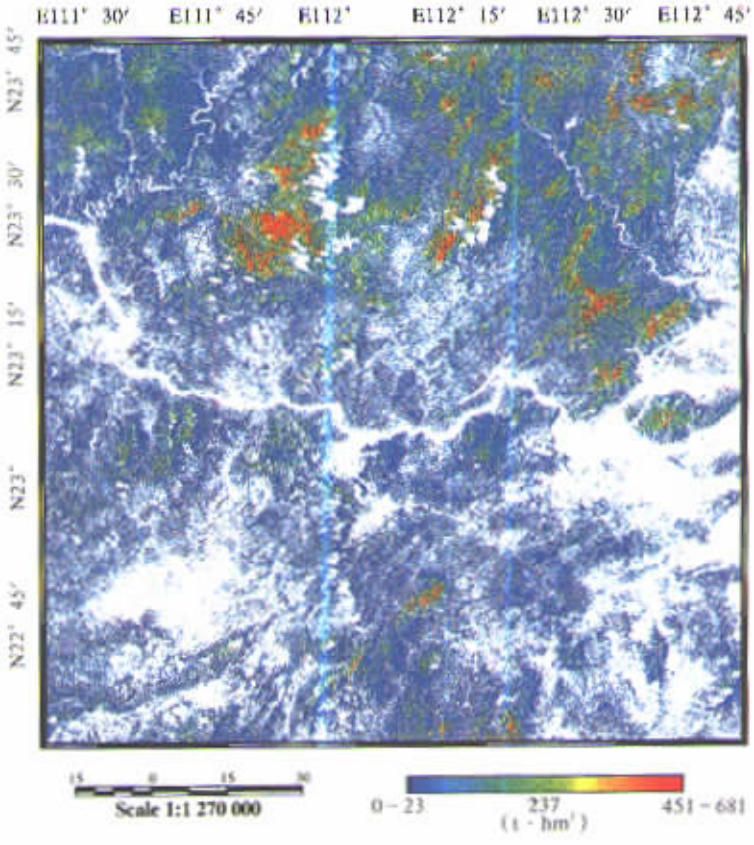


×640

×640

郭志华，等：利用TM数据提取粤西地区的森林生物量

GUO Zhi -Hua ,*et al*:Retrieving Forest Biomass in Western Guangdong Using Landsat TM Data

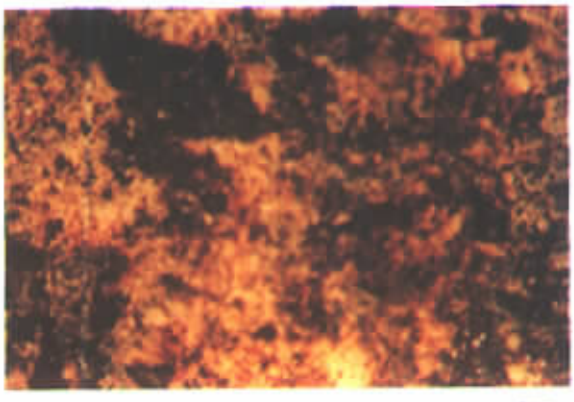


图版Ⅰ　基于模型(4)、(7)的粤西地区森林生物量

Plate Ⅰ　Coniferous biomass of western Guangdong Province based on model(4)、(7)

田友萍，等：云南石林碳酸岩表面气生蓝藻（蓝细菌）的研究

TIAN You-Ping, *et al*: A Study on Aerial Cyanophyta (Cyanobacteria) on the Surface of Carbonate Rock in Yunnan Stone Forest, Yunnan Province, China



1　　图版 Ⅱ　Plate Ⅱ　　2