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封面图说:秋色藏野驴群——秋天已经降临在海拔4200多米的黄河源区,红色的西伯利亚蓼(生于盐碱荒地或砂质含盐碱土壤)铺满大地,间有的高原苔草也泛出了金黄,行走在上面的藏野驴们顾不上欣赏这美丽的秋色,只是抓紧时间在严冬到来之前取食,添肥增膘以求渡过青藏高原即将到来的漫长冬天。

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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采石场废弃地的生态重建研究进展

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摘要:采石场的开采严重破坏了植被和土壤,形成了大量的裸露岩石斜坡,造成宏观景观支离破碎和极端的环境条件,限制了植物的生长。由于自然恢复所需时间长久,人工恢复被广泛应用于采石场废弃地的生态重建。自然演替过程是采石场生态重建的理论基础,自然演替理论可以为人工恢复措施提供指导。植物群落演替的早期阶段,非生物因素起主要作用,随着演替的推移,生物因素的重要性增强。邻近自然植被的土壤和繁殖体通过外力的扩散,对恢复起重要作用。除了非生物和其他的限制,先到达恢复地的物种竞争能力的变化能决定了演替过程。演替过程中的干扰因素往往成为演替重要的驱动力。裸露岩石斜坡的物理稳定性对植被恢复有重要影响,有机废物的使用和施肥可以影响恢复演替的方向和生物多样性。播种一定的植物能够改变恢复演替方向,加速演替过程。乡土物种适应了当地气候,能够促进演替。随着修复时间的延长,土壤有机质含量,植被覆盖度和物种丰富度不断增加,土壤微生物生物量随之增加。开展不同地区采石场植物种类的选育、研究乡土物种的功能特性、土壤微生物群落和酶的变化、植被演替过程的定位研究、植物种间的竞争关系、自然演替和人工恢复的比较研究、探索经济高效的采石场生态重建方法是未来的研究方向。

关键词:采石场废弃地;生态重建;人工恢复;生物因素; 非生物因素

Advances in ecology restoration of abandoned quarries

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Abstract: Many quarries are exploited to provide construction material due to rapid progress of urbanization and industrialization. Exploitation of quarries causes lots of bare rock slopes, resulting in complete removal of vegetation and propagules, soil depletion, and landscape fragmentation. The soil erosion causes an impoverishment of nutritional and hydric status, hindering natural germination and establishment of young plants. As a result, the reutilization of abandoned quarries becomes quite difficult. The destruction of vegetation is the major factor that leads to the ecosystem degradation. Revegetation of abandoned quarries is the key to improving the ecological environment. Low water and nutrient availabilities are the primary factors limiting plant development at quarries. The establishment of a plant community is often quite low and limits the success of revegetation. Natural restoration is a very slow process, which may take hundreds of years. As a result, artificial revegetation methods have been widely used in ecology restoration of abandoned quarries. Soil management, slope stabilization, species selection, seed collection, seeding and planting strategies and techniques are recommended practices. Treatments with fertilizer may promise procedures to improve plant performance in the site with low water and nutrient availabilities. Artificial restoration of abandoned quarries should be based on spontaneous succession, which could guide artificial practices. At the early stages of vegetation succession, abiotic factors play a key role, and biotic factors become

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more important as the succession proceeds. Soil accumulation on the rocky slope face is a key factor for vegetation establishment at the early successional stages, but it is very difficult to retain soil on a rocky slope surface due to high rates of water erosion resulting from rainfall influence. In addition, extreme low and high temperatures and drought are the most limiting factors on these sites for plant establishment. Whether there are soil and propagulum being spread through external forces from neighboring natural vegetation will decide the success at starting stage of the succession. Besides the abiotic factors and other constraints, the arrival of some species before other species determines the course of succession through shifts in competitive abilities. Disturbances often become the important driving force of succession process. Physical stability of bare rock slopes could affect the vegetation restoration significantly, and addition of organic waste and fertilization may change or determine the direction of biodiversity of restoration succession. Sowing or planting certain plants could potentially modify the restoration successional direction, and speed up restoration succession. Native species, which has adapted to the local climate, can promote restoration succession. Organic matter, vegetation coverage, species richness and soil microbial biomass increase with increasing restoration age. Future research should focus on the studies of selection and breeding of species which applied in the abandoned quarries restoration in different regions, functional characteristics of native species, dynamics of soil microbial community and soil enzyme, positioning studies of vegetation succession process, interspecific competition among restoration vegetation, comparison of spontaneous succession and artificial restoration, exploring cost-effective methods of abandoned quarries restoration, and so on.

Key Words: abandoned quarries; ecology restoration; artificial restoration; biotic factors; abiotic factors

随着经济的发展和城镇建设的加快,人类对石材资源的开发利用加强[1]。有些采石场临时性关停,还有的开采规划不规范,没有考虑采后恢复措施,造成部分采石场没有按照国家法律规定进行复垦,形成了大量的裸露岩石斜坡,带来了植被破坏、土壤流失、自然景观破坏等生态环境问题,威胁着社会经济的可持续发展[2-3],在景观上形成美学缺陷。同时,裸露岩石斜坡的不稳定性(岩崩、滚石),严重的威胁了居民的生命财产安全。因此,采石场的生态重建受到广泛的重视[3-4],成为恢复生态学研究的重要内容之一。采石场废弃地的环境条件十分恶劣,特别是裸露岩石斜坡恢复难度较大,众多研究者对不同类型岩石斜坡的恢复进行了研究,主要涉及恢复策略[1,5]、工程措施[3,6-7]、恢复演替[8-11]、土壤改良[11-13]、植物物种[9]等。对采石场废弃地的生态重建进行研究,总结采石场废弃地恢复的理论与技术、不同恢复技术下植被和土壤的变化过程,能够指导采石场废弃地的生态恢复,减少其水土流失、景观缺陷及安全隐患,这对我国生态环境建设具有重要意义。因此,本文对采石场废弃地生态重建的研究进行综述,以期为采石场生态重建提供参考。

1　废弃采石场环境特点

采石场采用露天开采的方式极端浪费土地资源,极大地改变了地质结构与外貌特征,严重破坏生态环境[3],恢复难度较大。开采后形成的采石场废弃地由岩石斜坡、悬崖、台地、采矿坑、废石堆放场及排土场等地形组成[14-15],且大部分岩石斜坡未形成规则的阶梯状开采面,坡度一般在 40°—90°,甚至存在反倾石壁,岩石斜坡表面遍布着开采留下的不规则凹陷和缝隙,部分采石场废弃地上层有遗留的土壤层[4,8,14,16]。露天采矿去除了采石场表土覆盖层[5,17-18],破坏了采石场的生物学特征,使采石场原来的植被及植物繁殖体全部丢失[2,5,17,19],微生物群落发生巨大变化,降低了物种的数量,恶化了野生动物的生存条件,威胁当地的物种多样性[14,19]。未治理的采石场废弃地破坏自然环境,造成宏观景观支离破碎,降低了其观赏性[1-2,14]。恶劣的环境条件促进了岩石的风化,部分坡面的石头风化程度高,形成碎石坡面[4],甚至呈现出不断的山崩和岩崩[20],岩石中的有毒物质流失,污染周围环境,严重威胁了周围的居民点和街道[7]。

采石场废弃地立地条件十分恶劣,不是深坑、石壁, 就是坚硬的地表[21]。由于缺少表土覆盖,岩石斜坡的温差增大,易形成极端温度;侵蚀和表面径流增强,保水能力差,干旱是岩石斜坡上植物定居的最主要限制因子[5,7,21-22]。Oliveira 等[11]发现恢复地植物死亡大概都是由于干旱引起的。另外,岩石斜坡养分含量很

低[7],低的养分可利用性与干旱的相互作用限制植物的生长[23]。

2 废弃采石场恢复策略

生态重建是在一定立地条件下,在恢复地上创造一个维持需求低,具有一定的生产力,生物相互作用较强,生态功能较齐全的生态系统[5,24]。生态恢复指将废弃地恢复到原有的生态系统[5]。采石场废弃地的生态重建可以定义为在人的干预下,修复采石场废弃地被破坏的环境,使废弃地重新可以被利用[2,25]。通常,采石场废弃地恢复的主要目的是控制水土流失和提供绿化[11,18],减少其在视觉上的影响,使其重新融入到周围景观中[2,5,11]。采石场废弃土地利用的优化配置,要根据其周围环境特点及城市建设规划来制定,恢复后的采石场一般用来作为开放空间、景观或作为多种用途的土地[2,16]。环境条件恶劣使采石场废弃地难以恢复为生产性用地,应用景观再造法进行植被重建后,可以将其开辟成公园、游乐园、野生动物栖息地、生态廊道、雕塑、地质公园等[14,16],而将采石场废弃地的恢复与保护区建设相结合[26-27],能更好地保护生物多样性[26,28]。例如,Neri 等报道,恢复的石灰石采石场或被遗弃的采石场可以作为许多动物和植物[29],例如蜂[30], 蝴蝶[28]、蜘蛛[31]和鸟类[32]重要的生境。一些裸露岩石地区,如岩溶地貌[33-34],本身是自然美景[29,35],可以通过模拟自然的外貌来改善废弃地对景观的影响,提供了一个经济且被社会接受的采石场恢复途径[29]。

采石场废弃地的生态重建及土地的再利用要建立在一定的土壤-植被系统上[5],植被重建对于采石场废弃地生态重建至关重要。过去采石场关闭后,形成的采石场废弃地的生态重建往往属于自然恢复[5,12]。自然恢复的植被组成接近原来植被[36]或半自然的植被[27,37]。相对于昂贵的土壤改良措施[26,38],自然演替的采石场恢复成本较低[39]。因此,在有些地方可以通过自然演替恢复植被[40-42]。自然恢复所需要的时间与岩石特性、植物和气候有关。自然恢复过程极其缓慢[5],往往要花费几十年到一个世纪以上[26,38]。Novak 等[38]的研究表明,在采石活动停止 20a 后,采石场废弃地上会自发形成灌木草原,在坡度较大的裸露岩石斜坡,恢复时间更为长久。

自然恢复所需时间长久,无法短期改善环境。因此,人工恢复被广泛应用于采石场废弃地的生态重建,特别是在裸露的岩石斜坡[12,15]。人工恢复复垦能够实现采石场废弃地表面岩石的稳定和复绿[5],减少其对安全和景观的负面影响[5,43]。但在环境条件恶劣和微生境差异较大的采石场废弃地,人工恢复成本较高,模拟自然恢复成为重要途径[5]。

3 植被演替过程

在自然演替和人工措施下的生态重建中,植被会不断的变化。自然演替过程是采石场的生态重建的理论基础,了解自然演替过程,可以为人工恢复措施提供依据。

3.1 演替限制因子

植物群落的定居和演替过程取决于生态系统中特定生物因素和非生物因素限制的变化[1]。在演替早期阶段,非生物因素起主要作用,不良的土壤条件排除了许多物种;随着演替的进行,物理条件改善了,适宜更多的物种定植和生长,增加了物种间的竞争,生物因素的重要性增强[1,44]。自然演替恢复过程中,采矿废弃地的植被动态是一种原生演替类型[17],在演替的初始阶段非生物和生物因素都具有重要作用[27,38]。露天采石场表土完全丢失,非生物的限制因子限制了植物的定植(干旱、增强的温差和侵蚀作用),仅有一些抗逆性强的物种在裸露岩石上定植,所以植被的种类可能较少[21,45]。

不同条件下的立地和小气候的差异,使得采石场的植被恢复过程呈现不同的植被演替模式和速率[1,17,46]。立地初始条件决定植物群落的多样性和组成结构[11,47],如贫瘠的玄武岩阻止了木本植物的定居[26]。生物因素方面,由于采石场废弃地的土壤种子库丢失[5],使得原有生态系统中依靠土壤种子库与地下繁殖体更新的植物缺少繁殖体来源,因此具有独特的演替特点[5]。自然植被是采石场生态重建的重要物种库[5,26],但物种的定居受物种扩散限制的影响[26-27]。繁殖体到达一个地方的概率与源种群的大小和距离相关[48],也与其扩散能力、种源质量和繁殖体的丰富度相关[26,49]。种源距离较远会降低物种的扩散能力,从而影响的群落结构[17,26]。例如,Moreno- De Las Heras 等[17]的研究发现,由于灌木种子(*Genista scorpius* 和

Dorycnium pentaphyllum)存在传播限制,仅在邻近植被斑块附近的斜坡上出现。

3.2　邻近自然植被的作用

物种扩散机制影响了废弃地上物种的定植,因而废弃采石场邻近的自然植被对恢复的作用变得重要,往往决定了废弃采石场自然恢复的演替方向[26-27]。邻近自然植被下的土壤和繁殖体通过外力的扩散作用,不断地扩散到采石场废弃地,驱动着废弃地的恢复演替。在环境条件限制相对较少的地方,邻近的繁殖体决定了演替模式,是演替主要的驱动力[17]。恢复区中自然定植的物种组成与邻近自然植被相似[27]。邻近的自然植被的比例和适宜程度影响了演替的速度[27]。对于那些传播能力差的物种,大面积的近距离天然植被尤为重要。Novák 等[26]的研究表明,如果周围存在大面积草地,草地物种的繁殖体就会相对较早地到达恢复地并且数量会相对较多。在周围没有干旱草地的采石场,物种扩散限制成为采石场次生干草原植被发育的重要因素[27,50]。具有很好散布能力的植物,能通过很远的种源入侵定植[26]。

3.3　物种的竞争

除了非生物和其他的限制,先到达恢复地物种的竞争能力变化能决定了演替过程[26-27]。若先到达的物种竞争不过后来入侵的物种[26],则通常对后者的定植有促进作用,推动演替的发展。Wang 等[22]指出攀援植物在岩石斜坡上形成小的“植被岛”,能够改善岩石斜坡上微生态系统和小气候,增加了其他乡土物种的定居可能。在废弃地种植植物后,侵入的杂草强烈吸收了有限的土壤水分和养分,明显地限制种植物种的存活[51-52]。若先到达的物种竞争能力强[26],则群落保持稳定。例如,人工恢复中利用快速生长的草本物种重建植被后,其竞争能力强于自然定植者[26,53],阻止了植被的演替。杂草与木本竞争能力的差异决定了木本植物的定居[26],Tamanga 等[54]指出,由于白茅(*Imperata cylindrica*)的竞争优势,在白茅占优势的恢复地,其他物种的入侵受到限制。

3.4　干扰因素与演替的偶然性

演替过程中会受到多种干扰因素的影响,因此生态重建演替存在巨大的偶然性,而这些偶然因素往往成为演替重要的驱动力,降低了演替的可预见性[55]。Moreno-de Las Heras 等[17]的演替模式和驱动力研究表明,在土壤条件不受严重限制时,小气候的差异影响物种库的变化。在恢复的矿山生态中一些偶然因素的影响尤为重要。采矿后土地的利用以及局部干扰是推动演替变化的重要驱动力,控制了抑制机制[56]。如 Moreno-de Las Heras 等[17]发现,紫花苜蓿(*Medicago sativa*)的偶然真菌性疾病和放牧羊群的取食增加了新物种,特别是风播灌木种子银灰菊(*Santolina chamaecyparissus*)和百里香(*Thymus vulgaris*)的发芽和定居机会,使得的草本群落转化为多样化的灌木群落[56]。另外,放牧的动物毛皮携带和消化道保留的种子数量巨大[57],是种子散布的携带者。因此,羊群可以作为一种恢复工具,促进了种子散布,控制播种的优势物种[17]。干扰会造成立地退化,阻碍采石场废弃地的恢复演替。例如 Meira-Neto 等[5]发现,采石场植被恢复 21a 后的火灾干扰可能妨碍采石场废弃地的群落演替。Oliveira 等[11]的研究表明,在废弃采石场的植被恢复演替过程中,极端干旱的天气导致种植的角豆树(*Ceratonia siliqua*)、橄榄树(*Olea europaea*)、黄连木(*Pistacia lentiscus*)大量死亡,减缓了恢复速度。

3.5　土壤变化

植物的生长有利于改善土壤性质。随着修复时间的延长,植物通过持续的枯落物生产和根系的腐烂促进了有机质积累[18,58],采石场土壤的有机 C 和全 N 都有所增加[59]。另外,植被的存在改善了采石场的小气候,有助于枯落物的分解,也促进了有机质的积累[18,60]。固氮的豆科植物较多的采石场土壤 N 含量可能较高[17-18]。植被的发育吸收阴离子基团,并将其在土壤中重新分配,能够酸化土壤[61],有机质的积累过程也促进了土壤酸化[62]。

微生物生物量能衡量土壤中微生物群落的总量。植被覆盖率[63]和物种丰富度[64-65]的变化与土壤微生物生物量密切相关。不断增加的植物群落的覆盖度能改善立地的微生境(例如,温度、湿度和光强度),并对根系的形态特征(例如根系的密度和结构)和化学性质(例如根系分泌物和组织质量)有积极的影响[18]。这些

都使微生物的食物资源和生境多样性增大,产生了支持多种多样微生物群落的生态位[66]。随着林龄的增加,植被覆盖度和物种丰富度不断增加,土壤微生物生物量也增加,特别是乡土物种丰富度的增加尤为明显[67]。

4 生态重建技术

4.1 坡面稳定

采石场的地质结构与外貌特征发生了巨大的变化。由于植被在裸露岩石或斜坡上自然定居非常困难,人为改良措施非常必要[1,16]。通常,采石场废弃地恢复的人为改良措施首先要考虑矿坑、废弃岩石堆和岩石斜坡的物理稳定性[29]。所谓坡面生态工程技术即是一种利用植物进行坡面保护和侵蚀控制的途径和手段。在坡度平缓的采石场斜坡可以采用挂网客土喷播或喷混植生技术,而在坡度较大的地方往往要通过开凿或爆破等手段对坡面进行整理,构筑阶梯平台、燕巢或通过悬挂种植盆等[16,18,68]。周顺涛等[6]等认为,挂网客土喷播由于网面与基质结合不紧密以及无法控制土体内部渗透水的方向与流速,渗透侵蚀的防护作用较弱性, 混凝土型框技术影响生态重建的美观性,挡土翼工法适用于石质边坡的生态重建。

爆破斜坡是坡面稳定的重要措施[22],特别对坡度较大的岩壁尤其必要。但爆破作业操作困难并有潜在的危险,由此产生的碎片清理需要大量的时间和费用[7,22]。为了避免大规模的爆破,金属网种植筐被广泛应用于稳定斜坡[7,69] Beikircher 等[7]在此基础上将独立的种植筐技术应用于陡峭岩石斜坡,不仅能改进景观,而且独立的金属网种植筐可以充当挡板,防止落石、侵蚀和地表径流。另外,Neri 等[29]在研究石灰岩采石场的植被恢复时提出,应模拟岩溶地形[33-34]来代替直线造型和岩石其他工程特征,缓和视觉上冲击;Wang 等[22]也提出了在岩石斜坡表面钻垂直的洞穴,客土种植攀援植物以克服在岩石斜坡表面植被恢复的困难。

4.2 基质改良

废弃地人工恢复的实质上是人为加快生态演替的过程[23]。由于演替过程中的初始立地条件决定了恢复演替的方向和生物多样性[23],对采石场废弃地的基质进行改良是非常必要的。

4.2.1 有机废物的使用

失去表土的采石场废弃地极端的土壤条件和小气候限制了植被恢复,导致采石场废弃地的人工恢复往往需要大量的土壤或替代基质[7,11]。购买土壤不仅费用高昂,而且会给取土地点造成不利影响[13]。因此,在采石场废弃地的植被重建中,添加有机废物,如污水污泥逐渐成为一种常用技术[12]。在地中海地区,有机废物经常被应用于火灾后土地的恢复[13,70],有机废物也被直接应用于尾矿[71-72]。有机废物的添加能够提高基质中有机质含量,促进 C、N 等大量元素及一些微量养分的循环,改善土壤结构[12-13],因而能促进采石场和采矿地区的恢复[13]。有机废物中微生物起源的碳水化合物是构建稳定土壤聚合体的重要因素[12],可以维持并提高土壤微生物生物量,促进采石场废弃地上植被的定居[12]。杨晓亮等[73]在岩石边坡植被恢复的人工土壤中添加鸡粪有机肥和泥炭土, 提高了人工土壤的抗蚀性。大量应用有机废物时产生的污染可能会引起公共健康问题,因此,各类有机废物在应用前进行一定的处理,对土壤的改良效果更佳[13]。例如,脱水的污泥需要进行堆肥处理或者是烘干,不仅去除了有机废物的气味,而且也避免了卫生问题和有机污染的发生[12,74],还能有效的控制植物真菌病害[75]。Marando 等[12]研究中发现,热力干燥和堆肥处理可以加强脱水污泥对两个石灰石土壤的生物化学和微生物性质的促进作用,并且前者促进污泥有机物质分解的作用更显著。Larchevêque 等[76]的研究表明,堆肥处理减少了叶片枯落物上真菌的定居但没有减少细菌的定居,所以使用有机废物后废弃地的微生物生物量的增加主要来自细菌,这可能与有机质含量高有关。不同有机废物的肥效各异。对城市垃圾产生的有机废物和修剪的植物枝叶+家禽粪肥+麦壳进行堆肥发现,粪肥比植物残体的腐败速度快,提高了矿化作用[12]。很多有机废物含有某些具有毒性的微量金属元素,阻碍了植物群落的恢复[1]。因此,使用有机废物,特别是污泥时必须要仔细的筛选[1],有机废物的添加对土壤性质和植物产量的作用与其成分以及数量有关[77]。有机废物的作用也受时间影响,较易分解的有机物碎片减少后,促进养分循环的作用也相应降低[13]。

4.2.2 施肥的作用

施肥能够迅速补充植物所需要的矿物营养元素,短期内促进植物的生长,积累较多的生物量,是植被重建

初期常见的基质改良措施。有关学者报道,施肥提高了养分缺乏的原生演替立地的养分可利用性[23,78],短期内改善植物在恢复地上的生长和生物量[11],增加了植被覆盖和生物量的积累,增加地面植被的物种丰富度和生物多样性[23]。施肥后树木的快速生长,凋落叶和根系更替的数量将会增加,产生更多的种子,N 含量相对较高和多酚含量相对较低的凋落叶的分解速度会更快[79],提供更多的生态位。同时树木生长后会拦截更多的风吹来的凋落物、尘土和种子,并降低了极端条件的影响[23]。

施肥措施的作用受到立地和物种特性的影响。例如在严重退化的采石场废弃地,施肥促进了快速生长的硬叶物种角豆树(*C. siliqua*)和黄连木(*P. lentiscus*)的生长,而对生长相对缓慢的橄榄树(*O. europaea*)没有作用[11],对黄连木(*P. lentiscus*)和橄榄树(*O. europaea*)的存活也没有作用[80]。施肥的短期促进作用对不同演替阶段植被的生物多样性影响各异。在已有植被覆盖的废弃地上,施肥在短期内可以显著的提高优势植物物种的生产力,促进具竞争力的优势物种的生长[23]。Rajaniemi 等[81-82]的研究表明,在样方中施肥引起了植物多样性的降低。Suding 等[83]对北美超过 900 个物种施 N 肥的结果进行分析,发现随着生产力的增加,稀有物种比丰富物种更可能消失。

4.3 植物种类

播种也可以增加植物种类,通过提高植被覆盖率而改善采石场废弃地上的观赏性[27]。播种一定的植物能够改变恢复演替方向,加速了向预定阶段的演替过程[27]。在恢复演替的不同阶段添加目标植物种子,可以克服物种扩散的限制[84],促进其朝向理想的植被发育[27]。Novák 等[27]的研究发现,通过播种演替后期的典型植物种子,如 *Stipa pulcherrima* 和 *Stipa pennata*,使其能够在恶劣条件下的废弃采石场的初级演替阶段生长。Meira-Neto 等[5]种植的演替后期物种[85]促进了采石场恢复地火灾后的植被恢复。

了解植物的功能特性,可以预测其对环境因素的反映[5],这对植被重建非常重要。一些植物能够通过某种机制和生长习性适应裸露岩石斜坡的严酷环境[22]。例如种植适应干旱的植物在水分条件不足的采石场废弃地恢复中是必需的[7,12],攀援植物在垂直岩石表面的植被恢复中应该优先考虑[22],豆科植物往往用于贫瘠的废弃地恢复中[17]。根据采石场废弃地斜坡的特征和气候条件选择适宜的植物种类是植被恢复演替的关键所在[22]。采石场的岩石斜坡坡面陡峭,缺少土壤,种植耐胁迫物种有利于恢复初期的植被重建[22]。

采石场恢复中应用的草本、灌木和藤本居多[7,12]。因为采石场的土壤结构差,水分和养分含量低,大部分都是早期演替或 R-对策种,如耐干旱、繁殖能力强的禾本科[1,8-9,86]。束文圣等[21]在研究中发现,自然恢复的采石场的干旱边坡,以禾本科的白茅(*Imperata cylindrica*)、五节芒(*Miscanthus floridulus*)等为优势物种,袁剑刚等[8]发现采石场悬崖生态系统中,自然演替早期定居的植物主要是禾本科和菊科的草本植物,其中红毛草(*Rhynchelytrum repens*)和类芦(*Neyraudia reynaudiana*)在群落中占绝对优势。一些植物的生物学特性有利于其用于采石场的植被恢复[1,7,87]。例如,金发草(*Pogonatherum paniceum*)对极端干旱的岩石表面适应性强,被开发用于采石场的斜坡的生态重建[88-90]。爬山虎(*Parthenocissus tricuspidata*)、常春藤(*Hedera helix*)和扶芳藤(*Euonymus fortunei*)3 种攀援植物能够抵抗贫瘠、高温和干旱环境胁迫,能很好地覆盖垂直面,可以用于采石场的绿化[12,22,91]。黄荆(*Vitex negundo*)是一种在人工岩石斜坡自然恢复中普遍应用的木本先锋植物,其根系对阻止植物的倒伏具有重要作用,从而能提高了斜坡的稳定性[92]。

外来植物种类的群落复杂性和多样性较低[18,65],甚至对环境产生不利影响。例如,桉树人工林可能降低土壤肥力和对微生物群落有害[18,93]。乡土物种适应了当地气候,能够与当地的其他物种形成稳定的群落,并促进演替,所以常被推荐用于废弃地的生态重建[1,27]。地中海植被类型的形态和功能上适应了极端的环境条件,在采石场植被恢复的演替前期种植 R 物种(依靠发芽更新的物种)能促进 S 物种(依靠种子更新的物种)的引入[5,85]。另外,而植物的抗旱性也受驯化作用的影响,对生长在采石场植物进行抗旱驯化能够增强其抗旱性[7]。

5 展望

采石场废弃地的环境恶劣,缺少表土,干旱贫瘠,温度变化剧烈,只能适合以抗旱和耐贫瘠植物的生存。

寻找经济可行,生态环保的基质,选育我国不同地区采石场植被恢复物种,对于不同地区采石场的植被恢复有重要意义。有机添加物能够在短期内促进植物的生长,而植物生长是个长期的过程,研究长期有效的有机添加物,对于植被恢复具有重要意义。乡土物种适应了当地气候,能够形成稳定的群落。因此,研究乡土物种的功能特性,模拟具有一定功能的乡土物种的种子雨或种子库组成对生态重建具有重要意义。大多数采石场废弃地种植植物后,植物生物多样性、组成和结构产生变化。目前,采石场废弃地植被恢复的研究仅考虑植被的结构、多样性和生产力,而对于采石场废弃地的植物根系生长的研究较少。有些采石场采用的垂直开采方式,形成了高低不同的直立石质开采面,植物难以恢复。开展岩石斜坡上植物的根系生长、攀援植物的长期生长研究具有重要的应用价值。目前,对植被演替过程中的生态系统结构、功能和动态研究规模小,缺乏长期的定位研究,植物种间的竞争关系和化感作用尚不清楚,几乎没有开展对植被演替的模拟和预测恢复效果的研究,对植被恢复过程中产生的土壤微生物群落和酶的变化也缺乏研究。在同一气候区内的植物自然演替模式往往为采石场恢复重建提供了有用的模版,对自然演替和人为重建的比较研究能进一步了解采石场的恢复过程。这些内容有待于在今后的研究中取得进展。

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