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Natural recovery of different areas of a deserted quarry in South China

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Abstract

A quarry is a surface mining operated place, which produces enormous quantities of gravel, limestone, and other materials for industrial and construction applications. Restoration and revegetation of deserted quarries are becoming increasingly important. Three areas of a typical quarry in South China: terrace for crushed materials (terrace), spoiled mound, and remaining side slope, were investigated, to compare the existing plant species and to study the relationship between environmental factors and revegetation. The plant species composition of these three areas was found to differ significantly after eight years of natural recovery. The typical plant communities found over them were composed of gramineous herbs, ferns, and shrubs. Soil organic matter, soil moisture, and soil bulk density were considered to be the major determining factors for vegetation succession. There existed abiotic and biotic thresholds during quarrying restoration. Suggestions had been presented that could have accelerated the process of natural recovery in quarries.

Key words: natural recovery; quarry; vegetation; environment-vegetation relationships

Introduction

Limestone is an important raw material that is widely used for cement production, metallurgy, agriculture, glass, and steel production (Pamukcu and Simsir, 2006). Rapid economic development and the growth of urban areas in many countries have fueled an ever increasing need for limestone. Accordingly, many “mined-out” or low-production quarries have been created and deserted, presenting a challenge for environmental managers and engineers to adequately restore these degraded habitats (Yuan *et al*., 2006). There is often substantial pressure from governments and citizen groups to restore old quarries, as they can not only impose a significant negative visual impact, but may also pose serious soil erosion and degradation (Clemente *et al*., 2004). However, the restoration of limestone quarries has generally been considered difficult because of the residual coarse substrate, bad soil structure, and nutrient deficiencies (Wheater and Cullen, 1997; Clemente *et al*., 2004; Price *et al*., 2005).

Substantial research has been conducted on rehabilitation and ecological restoration of mined lands. Most of this research has been focused on large mines where valuable materials, including gold, copper, and zinc, have been extracted, and operators have set aside funds specifically for rehabilitation study. Very little attention has been paid to quarries producing low-value materials (Hobbs and Norton, 1996; Price *et al*., 2005). Moreover, most studies of quarry restoration have concentrated on the selection of suitable engineering methods to improve microhabitats or to introduce a pioneer species that can survive on harsh substrates (Panagopoulos *et al*., 1997; Correia *et al*., 2001; Harrouni *et al*., 2003; Riley *et al*., 2003). The authors have a limited understanding of the feasibility of natural recovery (Novak and Prach, 2003; Khater *et al*., 2003). It has been claimed that natural recovery can be more efficient than human efforts for the recovery of degraded land and its restoration to the original substrate and vegetation conditions (Prach *et al*., 2001; Rebele and Lehmann, 2002). Natural recovery has become a favored and promoted method in several countries, as funding requirements are much lower than active remediation and thus more easily approved by the decision-makers. Since 2000, the scientists have begun to pay attention to the processes and mechanisms of the recovery of abandoned quarrying.

In 1994 there were an estimated 12,000 working quarries in the Guangdong Province of South China (Yuan *et al*., 2006), most of which were overexploited without any consideration to the potential negative environmental consequences. Because of the numerous environmental issues resulting from this, most of the quarries were compelled to close and revegetation efforts were initiated. Government plans called for the imposition of regulations on 1,200 quarries by the end of 2006, meaning as many as 90%

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of the existing quarries would be abandoned. Restoring so many quarries through engineering technologies alone seemed improbable because of the potential cost.

In this study, we have studied the spontaneous regeneration of an abandoned quarry, to examine the possibility of an economical and affordable technology for quarry restoration. Specifically, they address the following questions: (1) are there spatial heterogeneity of species diversity and distribution in the quarry? (2) if yes, what factors affect species diversity and heterogeneity in the quarry; and (3) how to make use of the results to accelerate the natural recovery of quarries.

1 Methods

1.1 Study site

The study was conducted at a quarry in Longmen Mountain which is about 2 km from Heshan Hilly Land Interdisciplinary Experimental Station (112°54′E, 22°41′N), located in Heshan County, Guangdong Province, China. This station is one of the core stations of the Chinese Ecological Research Network (CERN) of the Chinese Academy of Sciences (CAS). The quarry was abandoned in 1998. The climate is subtropical monsoon and the elevation varies from 0 to 50 m above mean sea level. The original soil is lateritic, a heavy acid soil. The mean annual temperature is 21.7°C, the mean annual rainfall is 1,700 mm, and the mean annual evaporation is 1,600 mm. Regional vegetation is dominated by evergreen broad-leaved forests, typical of the subtropics. Representative plant families of a climax community include *Lauraceae*, *Euphorbiaceae*, and *Fagaceae*.

The major experimental quarry has an area of about 15 hm^2 and consists of five different sections: workout area, cliff, spoiled mound (C), terrace for crushed material (called "terrace" in this article) (A), and the remaining is side slope (B). Because the cliff holds no vegetation and the workout area is flooded by rainwater, only the remaining three areas have been investigated in this study.

1.2 Field and laboratory methodology

To compare the vegetation and evaluate factors that determine vegetative growth in the spoiled mound, terrace, and remaining side slope, 36 quadrats were sampled. In each area, quadrat samples of two crossed transects were established at a 5-m interval. To quantify the shrub and grass species, quadrats of 5 m × 5 m and 1 m × 1 m, respectively, were established. Three of the smaller grassland quadrats were situated inside each large shrub quadrat. In each large, 5 m × 5 m quadrat, the height, density, and basal diameter of all shrub species, as well as the height, density, and coverage of all grass species were determined. To more accurately quantify the areal coverage of grasses, the authors used a 1 m × 1 m frame that included a small pane measuring 5 cm × 5 cm. The grass cover was determined by counting the number of panes covered by grasses.

Soil samples were randomly collected from five points in each quadrat using a 5-cm diameter soil corer, inserted to a depth of 20 cm, after removing the surface litter. A composite soil sample of approximately 1 kg was collected from each point; subsamples were air-dried and sieved for analysis of soil chemical characteristics including pH, N, P, K, Ca, Mg, Na, and soil organic matter (Institute of Soil Science, CAS, 1978; Liu, 1996). All sampling equipment was cleaned between collections to ensure no cross-contamination occurred. To measure the physical characteristics of the soil, nine intact soil cores were collected randomly in each quadrat, using ring knives, after removing the litter and humus layer. Three of these samples were used to determine soil bulk density, soil saturate moisture, and soil capillary moisture, respectively. Soil cores for soil bulk density were oven-dried at 105°C for 24 h, prior to measuring the bulk density.

1.3 Data analysis

Thirty-two species were recorded in 36 plots (Table 1). The importance values (IV) of the species in each sample were calculated using the following eqations:

$$IV_{shrub} = (d_R + f_R + D_R)/3 \quad (1)$$

$$IV_{herb} = (C_R + H_R)/2 \quad (2)$$

where, d_R is relative density, f_R is relative frequency, D_R is relative dominance, C_R is relative coverage, H_R is relative height. Relative frequency is the percentage of the quadrat containing a shrub species over the total number of quadrats in the same quarry area. Relative dominance is the sum of the basal areas of a shrub species within a quadrat.

Detrended correspondence analysis (DCA; Hill and Gauch, 1980), Canonical correspondence analysis (CCA; Ter Braak, 1986), TWINSPAN (Two-Way Indicator Species Analysis; Gauch and Whittaker, 1981) and Cluster analysis (CA; Sneath and Sokal, 1973) were completed using PC-ORD4 for Windows (MjM, USA).

Analysis of variance (ANOVA) analysis was conducted using SPSS 13.0.

Table 1 Species in Longmen quarry

Code No.	Latin name of species	Code No.	Latin name of species
S1	*Dicranopteris linearis*	S17	*Eupatorium catarium*
S2	*Cynodon dactylon*	S18	*Panicum repens*
S3	*Imperata cylindrical*	S19	*Desmodium heterocarpon*
S4	*Ageratum conyzoides* L.	S20	*Murdannia triquetra*
S5	*Melastoma dodecandrum*	S21	*Tephrosia candida*
S6	*Miscanthus sinensis*	S22	*Herba Hedyotidis*
S7	*Blechnum orientale*	S23	*Embelia laeta*
S8	*Rubus alceaefolius*	S24	*Clerodendron fortunatum*
S9	*Paederia scandens*	S25	*Eurya chinensis*
S10	*Mussaenda pubescens*	S26	*Melastoma normale*
S11	*Ischaemum ciliare*	S27	*Gardenia sootepensis*
S12	*Lycopodium cernnum*	S28	*Rhodomyrtus tomentosa*
S13	*Adiantum flabellulatum*	S29	*Ilex asprella*
S14	*Neyraudia neyraudiana*	S30	*Polygonum chiensis*
S15	*Urena lobata*	S31	*Mimosa pudica*
S16	*Desmodium triflorum*	S32	*Cynosurus viridis*

2 Results

2.1 Classification of the plant community

On the basis of TWINSPAN analysis, 32 species have been classified into four plant communities, representing natural revegetation in three different areas of the quarry (Fig.1). The communities are described as follows.

Community A-1: this community mostly appeared in the terrace. More abundant species included *Neyraudia neyraudiana*, *Miscanthus sinensis*, and *Lycopodium cernum*. The dominant species were tall, gramineous herbs. These species could resist arid conditions and nutrient-poor, low organic carbon substrate. Seeds from these plants were also light and easy to disperse.

Community A-2: this community also appeared in the terrace. Representative species were *Cynodon dactylon*, *Imperata cylindrical*, *Ischaemum ciliare*, *Cynosurus viridis*, and *Mimosa pudica*. Most of these species were short gramineous and leguminous herbs. Some of them tended to send out horizontal runners and could reproduce asexually from those runners. These species were easy to find in the early natural successional stages.

Community B: this community appeared on the remaining side slope of the quarry. The representative species were *Ilex asprella*, *Rhodomyrtus tomentosa*, *Eurya chinensis*, and *Melastoma normale*. These species were heliophytes and were typical shrubs found throughout South China. During natural succession, these species commonly appeared during the transition from the shrub stage to the tree stage.

Community C: this community encompassed nearly all the spoiled mound area in the quarry. Two ferns, *Dicranopteris linearis* and *Blechnum orientale*, dominated this community. Some shrubs, such as, *Melastoma normale*, *Clerodendron fortunatum* were also present, but had only sparse distribution.

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             465890733458126567901123494278235601

24   S24     5555455-5444555--453-----------------   111
23   S23     -4------555--------------------------   111
7    S7      ---4--55555555555555-----------------   111
1    S1      5555555555555545555555------5--------   111
30   S30     5444--15444-------------------5-5----   1101
26   S26     55555555555555555--------------------   1101
8    S8      4441--34555--------------------------   1101
29   S29     -5555555------------5----------------   1100
28   S28     55555555----5------------------------   1100
27   S27     --4---44-----------------------------   1100
25   S25     -5555555-----------------------------   1100
10   S10     541---44555-4-----------------5454-4-4  10
6    S6      51435445----------------------5555----  10
9    S9      4------3---4---------44-1--5---------   01
17   S17     -----------33-----4---------3-4-45454   001
14   S14     -------------5----------------5555----  001
12   S12     --------------4-----4---------4444----  001
4    S4      5-----------------------------4545----  001
19   S19     -----------------------------54343----  00011
15   S15     -------------------------------4-45-5-  00011
13   S13     --------------------3-----------------  00010
3    S3      5-------------------55555555555-5-5     00010
2    S2      ---------------------555544-44445555    00010
16   S16     ---------------33-------------4-44343   000011
32   S32     --------------4---55---1444-4-4-----    000010
31   S31     ---------------3-----51-------------    000010
18   S18     -------------------54-44-5----2-2----   000010
11   S11     ---------------55555-4345555555555-5-   000010
22   S22     --------------------4-554455-4444----   00000
21   S21     -------------4---------52--33---------  00000
20   S20     -------------------4---5---445--------  00000
5    S5      ---------------------------3---------   00000

             000000000000000011111111111111111111
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             011111110001111000110000000001111111
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Fig. 1 TWINSPAN analysis of 36 plots and 32 plant species from Longmen quarry. The S+ numbers on the left are the species code (Table 1) and the upper numbers are the serial number of plots. The number (0 and 1) indicate the partition of species and plots.

From the ordination diagram, the relationship between the four communities and the distribution of species can be visualized (Fig.2). In this diagram, the number of shrub species decreases moving from left to right on axis 1, whereas, the number of herbs increases in the same direction. As the succession proceeds, opportunistic pioneer species are gradually replaced by later colonizing species. This process resembles the early stages of natural succession on a degraded hillside.

2.2 Comparison of the vegetation in different areas of the quarry

Cluster analysis provides a means to differentiate vegetation among the three areas of the quarry (Fig.3). By establishing a “cut-off” line at approximately 58%, the different areas can be distinctly separated. Moreover, the plots of the terrace (A) can be further separated into two groups that generally possess different plant communities. Some plots from the remaining side slope (B) do not clearly fall in with other B plots, but are instead intermingled with A and C plots. This indicates that the vegetation from the side slope plots may be more diverse than either A or C plots and, in some cases, more similar to the vegetation in these latter areas.

Relationships between plots in different areas can be visualized in the ordination diagram (Fig.4). The diagram indicates that data points from the same area tend to concentrate together. Not surprisingly, these results are reflective of the DCA analysis of the plant species themselves (Fig.2). The degree of vegetation recovery tends to decrease moving from left to right on axis 1.

2.3 Analysis of environmental factors

In the CCA diagram, the length of a line represents the importance of an environmental variable and the angle

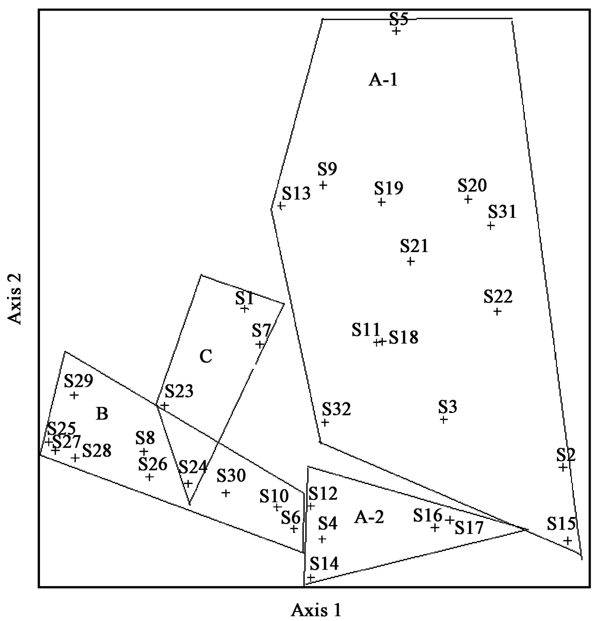

Fig. 2 DCA diagram of 32 species from Longmen quarry. S + number are the species code (see Table 1).

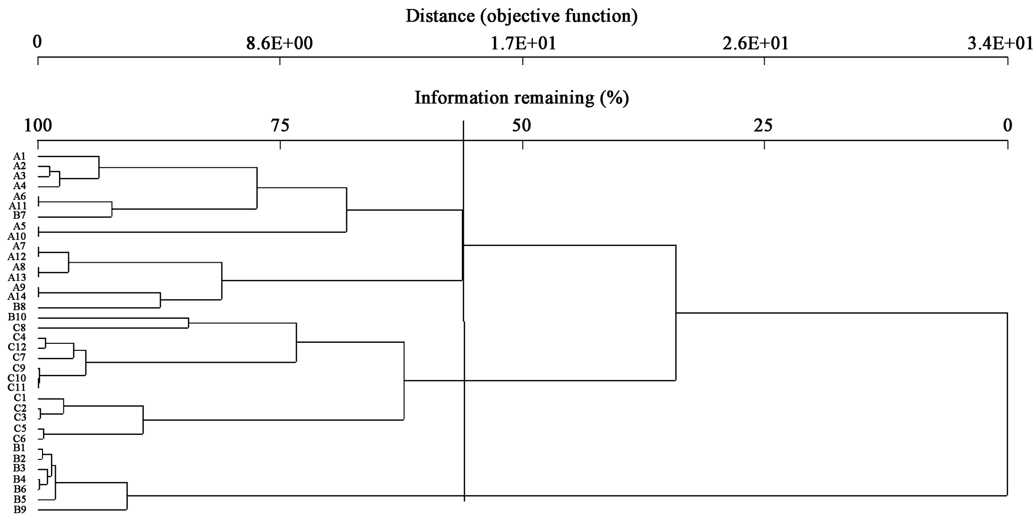

Fig. 3 Cluster analysis of 36 plots in Longmen quarry. A, B, C + number represent plots of different communities.

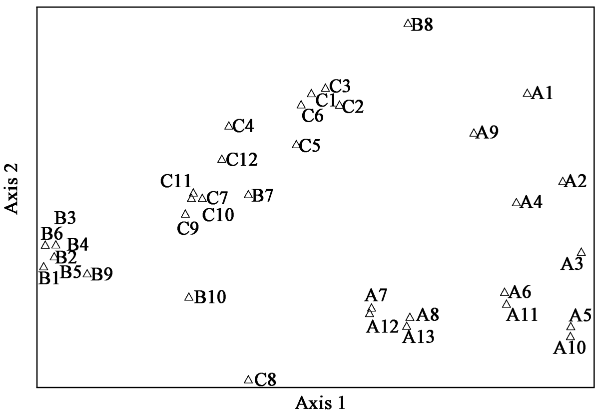

Fig. 4 DCA analysis of 36 plots in Longmen quarry.

between two lines denotes the relationships of these two variables. In this study, soil bulk density, soil moisture, and soil organic matter are determined to be the most important environmental factors affecting vegetation (Fig.5). Soil organic matter is critical in determining soil structure, which in turn affects the soil water holding capacity. It is also apparent that increasing soil organic matter enhances soil moisture and causes a decrease in soil bulk density. Soil organic matter, therefore, plays a key role in the natural restoration of quarries (Table 2).

The quarry spoiled mound is where removed but unusable soil, rock and so on, is placed. The material is unconsolidated and usually loosely packed, allowing for easy infiltration by rain water. However, because the primary soil structure of this area has been disturbed, there is an increase in noncapillary porosity and a decrease in capillary porosity. Accordingly, its soil capillary action declines after disturbance and its water holding capacity increases.

In this experiment, the soil saturation moisture of the spoiled mound (33.31%) was higher than the remaining side slope (30.97%) and terrace (23.97%). Soil capillary moisture for these three areas was 20.96%, 23.38%, and 16.87%, respectively. The terrace area was compressed through impaction and combined with gravel. Its soil bulk density was significantly higher. As a result, rain water did not infiltrate well, surface moisture was easily lost through evaporation and soil moisture levels were low. Most of the plants in the terrace areas were gramineous species, with minimal litter that did not decompose rapidly. Accordingly, soil organic matter content was low. The spoiled mound and remaining slope had a better soil structure, which positively influenced the nutrient holding ability. Most of the soil nutrient concentrations in these two areas were higher than in the terrace areas. However, a few mineral elements, such as, K, Ca, and Mg were actually higher in the terrace soil. Higher concentrations of these elements in terrace areas could be associated with leaching or residue from stockpiled gravels.

3 Discussion

The pace of spontaneous succession was different in different parts of the quarry even though recovery began at essentially the same time. Before recovery and vegetative succession began, all three these areas in the quarry were essentially bare. After eight years of natural recovery, different plant communities became established in different areas. These three areas differed in resource availability and carrying capacity.

In the terrace, available resources are low and soil structure is poor; most of the species are early successional or r-selected. These plants tend to be tolerant to chemical and physical perturbations and have a high reproductive output. In this area of the quarry, more than 90% of the species are gramineous and drought-tolerant. Moreover, because the soil is highly compacted, most of the large plant species cannot root successfully. These conditions result in a stagnant succession process. In the spoiled mound, the original substrate and seed bank have been buried by spoil soil. The soil is relatively loose, unconsolidated, and moist. It also tends to be acidic (pH ≈ 4.3), which provides a perfect environment for the growth of ferns. As a result, ferns, through their high reproductive output and adaptability, colonize this area before other species can

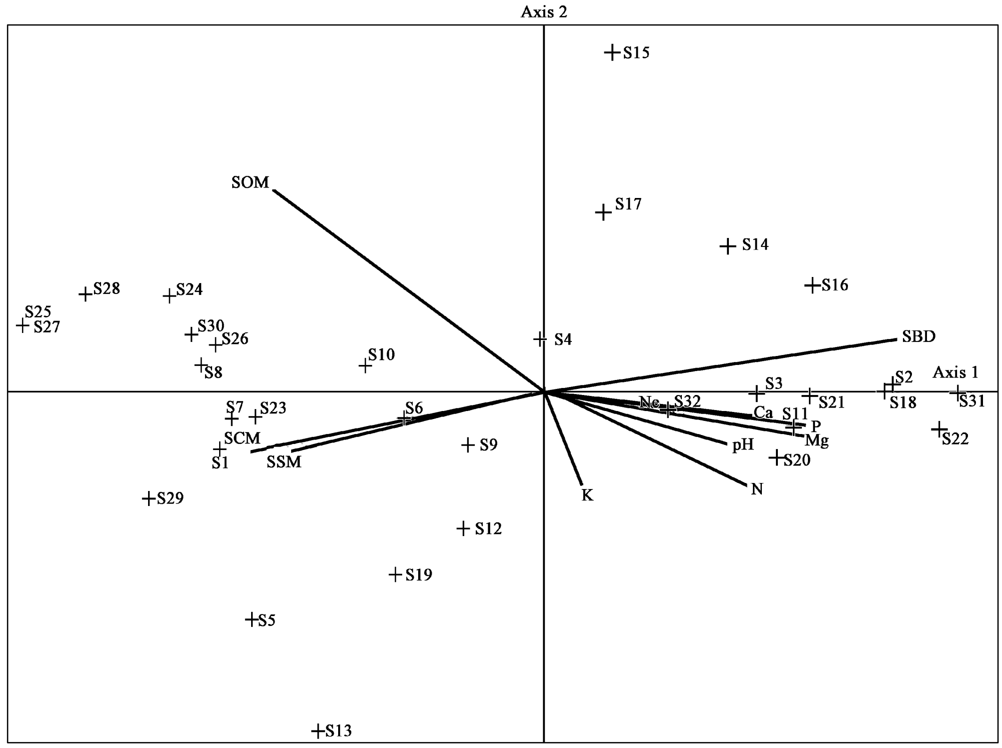

Fig. 5 CCA diagram of 32 plant species in Longmen quarry. SBD: soil bulk density; SOM: soil organic matter; SCM: soil capillary moisture; SSM: soil saturation moisture.

Table 2 Soil nutrient concentrations and bulk density (mean ± SE) of material from three areas of Longmen quarry

Parts of the quarry	Soil organic matter (g/kg)	Hydrolyzed nitrogen (mg/kg)	Available phosphorus (mg/kg)	Exchanged kalium (mg/kg)	Soil bulk density (g/cm^3)
Spoiled mound	19.48±2.13[a]	68.52±15.21[b]	1.55±0.14[a]	67.68±6.38[b]	1.15±0.08[c]
Terrace	9.02±1.31[b]	13.37±4.31[c]	1.38±0.61[b]	75.93±10.41[a]	1.59±0.12[a]
Remaining side slope	20.21±2.87[a]	78.11±13.25[a]	1.69±0.49[a]	65.98±13.04[b]	1.24±0.13[b]

For any given parameter, values with the same letter (a, b or c) in each column are not significantly different ($P < 0.05$).

take hold of it. The high degree of coverage by ferns makes it difficult for other species to invade and establish. The authors have found that, in ecosystems of South China, this stage will maintain for about ten years until large shrubs or trees shade out the ferns. In the remaining side slope, the soil structure and seed bank have suffered relatively little disturbance and the process of succession has been rapid. After eight years, herbaceous vegetation has shaded out and the area has entered into the shrub stage. In these permanent plots for studying succession, in Heshan Hilly Land Interdisciplinary Experimental Station, it has been found that this stage will maintain for about twenty years, after which time the shrubs will slowly be replaced by trees.

The progress of succession and establishment of a special plant community is determined by biotic and abiotic filters. In the early stages of succession, abiotic filters play a key role, with adverse soil conditions (texture, nutrients, moisture availability, and retention) excluding many species. As the succession proceeds, the physical conditions improve and more species are able to colonize and grow. As a result, inter-species competition increases and the importance of biotic filters is enhanced (Weiher and Keddy, 1995; Díaz *et al.*, 1998; Whisenant, 1999; Temperton *et al.*, 2004). At this study site, initial conditions in all three areas are harsh and unsupportive of vegetation, resulting in sparse, if any, plant growth. Inter-species competition is low and seeds of all 32 species are relatively easy to disperse and germinate. The seed resource is also abundant because the species pool is relatively intact in the areas surrounding the quarry. Given this availability of seeds, the abiotic filters must be the primary determinants of natural recovery. Soil structure, soil moisture, and soil organic matter are considered to be the most important environmental factors in this study, which is in agreement with the historical research. These three factors are related and dependent upon each other. Soil organic matter affects the structure, which then enhances the water-holding capability (WHC). It also determines the number and variety of microorganisms that commonly play important roles in nutrient circulation. Existing soil organic matter and soil moisture also affect the rate at which soil organic matter decomposes.

There exist two kinds of thresholds during quarrying restoration: the initial threshold characterized by extremely harsh physical environmental conditions and the secondary threshold controlled mainly by a critical level of biodiversity and dispersal facilitating landscape context. For a severely degraded ecosystem to overcome these thresholds, human ameliorative efforts are needed. The most important measure is probably to increase soil organic matter. Sewage sludge is often used as an organic amendment. However, sludge can contain high levels of contaminants, particularly trace metals, which could be toxic and thus discourage recovery of the plant community. If sludge is used, it must be carefully screened, first for phytotoxicity and then amended if needed. In the spoiled mound, ferns flourish and inhibit the establishment of other species. Thus, introducing some shrubs or pioneer trees into the spoiled mound areas will help shade out the herbaceous plants that are present and facilitate the establishment of subsequent species (Lugo, 1992; Guariguate *et al*., 1995; Otsamo, 2000). In the remaining side slope, succession is relatively quick and seed availability may be the next important determinant. In this area, therefore, the introduction of some native tree species may help to accelerate succession (Wunderle and Latta, 1994; Guariguata *et al*., 1995; Healey and Gara, 2003; Lee *et al*., 2005).

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