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Revegetation of extremely acid mine soils based on aided phytostabilization: A case study from southern China

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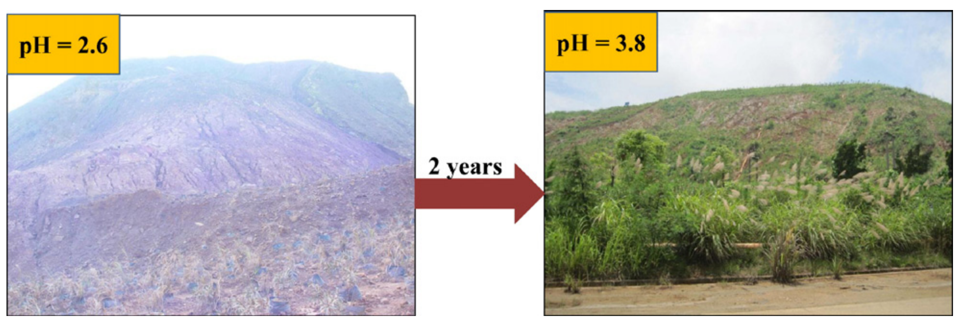
HIGHLIGHTS

- An effort was made to revegetate an extremely acid (pH < 3) mine soil.
- Net acid-generating potential of the mine soil decreased steadily with time.
- Soil pH and acid neutralization capacity increased gradually with time.
- Plants survived, grew and developed a good vegetation cover within 6 months.
- The vegetation development enhanced nutrient accumulation in the mine soil.

GRAPHICAL ABSTRACT



Acidification is a major constraint for revegetation of sulphidic metal-contaminated soils, as exemplified by the lack of literature reporting the successful phytostabilization of mine soils associated with pH < 3 and high acidification potential.

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ABSTRACT

Acidification is a major constraint for revegetation of sulphidic metal-contaminated soils, as exemplified by the limited literature reporting the successful phytostabilization of mine soils associated with pH < 3 and high acidification potential. In this study, a combination of ameliorants (lime and chicken manure) and five acid-tolerant plant species has been employed in order to establish a self-sustaining vegetation cover on an extremely acid (pH < 3) polymetallic pyritic mine waste heap in southern China exhibiting high acidification potential. The results from the first two-year data showed that the addition of the amendments and the establishment of a plant cover were effective in preventing soil acidification. Net acid-generating potential of the mine soil decreased steadily, whilst pH and acid neutralization capacity increased over time. All the five acid-tolerant plants colonized successfully in the acidic metal-contaminated soil and developed a good vegetation cover within six months, and subsequent vegetation development enhanced organic matter accumulation and nutrient element status in the mine soil. The two-year remediation program performed on this extremely acid metalliferous soil indicated that aided phytostabilization can be a practical and effective restoration strategy for such extremely acid mine soils.

1. Introduction

The major environmental issues associated with metalliferous and sulphide-bearing mine wastelands are acidification and the associated metal toxicities (Shu et al., 2001; Yang et al., 2011). Many metals including Fe, Pb, Zn, Cu, Au and Ag occur chiefly as sulphide ores such as

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arsenopyrite (FeAsS), galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$), and sulphur salts of Ag and Au (Baker and Banfield, 2003). The extraction of metal ores unavoidably leads to the release of pyrite-rich deposits into the environment which undergo oxidation and hydrolysis to generate sulphuric acid during weathering and/or exposure to moisture and air. Under strongly acidifying conditions, pH of the mine soils can be lowered rapidly and metal ions including Pb, Zn, Cu, Cd, Fe, Mn and Al will be released at extremely phytotoxic levels (Liao et al., 2007). In general, acidification and heavy metal toxicity act synergistically under the natural conditions, which collectively deteriorate physicochemical properties of mine soils and pose potential hazards to the surrounding terrestrial and aquatic ecosystems (Winter and Redente, 2002; Moreno-Jiménez et al., 2011; Anawar, 2015).

Revegetation of acidic metal-contaminated soils based on aided phytostabilization is recognized as a practical and environmentally sustainable remediation practice (Gray et al., 2006; Madejón et al., 2009; Córdova et al., 2011; Kacprzak et al., 2014). This technique requires both incorporation of adequate amendments and revegetation with suitable plant species (i.e., tolerant plants). During the past few decades, considerable efforts have been made to establish a sustainable vegetation cover in sulphidic metal-contaminated soils. Most of these previous studies carried out in the field have demonstrated that aided phytostabilization (the use of plants together with the application of amendments) is effective for the remediation of moderately to highly acid (pH = 3–5) mine soils (Table 1). For example, Gray et al. (2006) successfully established a good *Festuca rubra* cover on a moderately acid (pH = 4.7) mine site by the addition of lime and red mud (at 3% or 5%). Bleeker et al. (2002) revegetated a highly acid (pH = 3.6) As-contaminated mine spoil tips in Portugal using a combination of three additives (beringite, steel shots and organic matter) and two native grass species (*Agrostis castellana* and *Holcus lanatus*). Pérez-de-Mora et al. (2011) developed a healthy vegetation cover on a highly acid (pH = 3.45) multi-element (As, Cd, Cu, Pb and Zn)-contaminated soil impacted by pyritic wastes after initial application of an amendment. However, on a global scale, there are very limited studies that have been conducted to evaluate the potential of this technique for the remediation of extremely acid (pH < 3) mine soils. Clemente et al. (2006) did attempt to deal with such a problem on a soil contaminated by pyrite waste (pH = 2.91) in Spain based on active phytoremediation using organic materials (cow manure and compost) and lime amendments and growing two successive crops of *Brassica juncea*. Their results showed that the addition of lime and organic materials successfully increased soil pH, led to partial immobilization of pollutants, and allowed plant survival and growth. Nonetheless, it largely remains to be determined as to whether this practice is also efficient for those mine soils with extreme acidity and a high acid-generating potential.

Dabaoshan Pyrite Mine located in Shaoguan, Guangdong Province, southern China (24°37′N, 113°39′E) is a representative polymetallic pyrite ore deposit. The minerals in the ore mainly consist of pyrite, pyrrhotite, and chalcopyrite with minor components of sphalerite, chalcocite, galena, limonite, calaverite, and native bismuth (Zhou et al., 2007). Mining activities during the past five decades have generated large quantities of waste materials that were discarded into the environment without any proper treatment. As pyrite is abundantly present in the overburden materials, oxidation and hydrolytic reactions usually occur under natural conditions upon exposure to moisture and air and so release acid. Generally, the longer the wastes have been deposited, the more acid is released, which is associated with lower soil pH. At present, the topsoil (0–30 cm) of the wastes has been acidified at different levels and shows a wide range of pH (2–6), providing a good opportunity to explore the effectiveness of aided phytostabilization in dealing with moderately to extremely acid mine wastelands having high acid-generating potential.

In 2007, a remediation attempt was initiated to revegetate the sulphide-bearing mine wasteland at the Dabaoshan Pyrite Mine, using a combination of native plant species, lime and chicken manure (Yang et al., 2010). The field experimental was performed at a newly-formed landfill in the centre of the mine site with a moderately low pH (mean, 4.1), high net acid-generation capacity (NAG, 8.86 kg H_2SO_4 t^{-1}) and negative acid-neutralization capacity (ANC, −57.04 kg H_2SO_4 t^{-1}) (Table 1). Our previous study suggested that direct seeding/planting with stress-tolerant plants in combination with lime and manure amelioration is a feasible method for initial establishment of a vegetation cover on this moderately acid metalliferous mine wasteland. Although our earlier attempt has proved successful, it is unclear whether this remediation program is also effective in establishing a stable vegetation cover on an extremely acid mine soil (pH < 3) with higher NAG values and higher metal toxicity. In this study, a revegetation program was therefore performed further on an early-formed metal sulphide-contaminated waste heap at the entrance of Dabaoshan Pyrite Mine with extremely low pH (mean, 2.6), high total S content and high acid-generating potential (Table 1). The associated environmental changes including acidification prevention, trace element stabilization and vegetation development were monitored to address the effectiveness of this remediation technique.

2. Materials and methods

2.1. Experimental design and sampling

A 2 ha remediation trial site was established on the northern slope of a mining waste heap (with a gradient of about 30° and length c. 100 m; see Fig. S1 in Supplementary Materials) at Dabaoshan Pyrite Mine, Guangdong Province, southern China. Two amendments (lime and chicken manure) and five tolerant plant species (*Cynodon dactylon* L., *Pennisetum purpureum* Schum., *Neyraudia reynaudiana* (Kunth.) Keng., *Panicum repens* L. and the non-native *Eucalyptus robusta* Smith.) were selected based on our earlier research (Yang et al., 2010). The revegetation work was initiated in March 2010 and the remediation procedures were performed according to those of Yang et al. (2010): (1) planting strips of 30 × 30 cm (50-cm intervals) along the slope were created on the surface of the remediation site; (2) amendments (lime and chicken manure at a rate of 15 t ha^{-1}) were incorporated into the mine soils and equilibrated for a month; (3) seedlings of *P. purpureum*, *N. reynaudiana* and *E. robusta* (5-month old) were planted into the planting strips at a rate of 1:1:1; (4) a seed mix of *C. dactylon* and *P. repens* (5 g m^{-2}) was sown by hand onto the surface of the amended area; (5) a layer of straw mulch was covered on the plots to prevent excessive water loss by evaporation. Subsequently, plants were allowed to grow under natural conditions, i.e. without further fertilization or irrigation.

Plant surveys and sampling were carried out at 0.5-, 1- and 2-year intervals after planting. Thirty 1 × 1 m quadrats were placed regularly across the remediation site along a transect from the top to the bottom of the slope. For each survey, plant species were recorded and vegetation cover was estimated. Plant biomass was clipped at soil level, dried and weighed. The shoots and roots of the five plant species within each quadrat were sampled for heavy metal analysis at each survey date.

Soil sampling was conducted on four occasions: before remediation, and then at 0.5-, 1- and 2-year intervals after remediation. For each quadrat, five soil samples were collected randomly from the top 30 cm and then mixed to provide one composite sample. Soil samples were air-dried, crushed, homogenized and sieved to <2 mm for chemical analysis.

2.2. Analytical methods

Soil pH was measured in a 1:2.5 (*w*/*v*) aqueous slurry. Net acid generation (NAG) and acid neutralization capacity (ANC) were determined according to the method of Shu et al. (2001). For the NAG analysis, 2.5 g