Management of a Potential Mine Capping for Reclamation of Open-Cut Mines: Responses to Decomposable Organic Treatments

Mark Anglin Harris and Pichu Rengasamy

Abstract Extraction of mineral ores, and some engineering projects commonly entail removal of large tracts of valuable top-soil often called "overburden." A potential mine overburden capping material from an alfisol with different management histories was treated to assess its physical responses to phyto-organic amendments during storage. Although there were small increases in hydraulic conductivity, phyto-organic amendments did not greatly improve the physical properties of the alfisol which had previously been cultivated for several years, as changes in stability and water retention were generally not statistically significant. However, very substantial increases of stability (about 25 %) and water retention (about 40 %) occurred in the same soil which had previously been under a long-term permanent pasture regime. As top-soils can quickly deteriorate when removed and stored, prior soil management should be taken into account where top-soil is to be removed and used as a capping after mineral ore extraction.

Keywords Infiltration · Open-cut mines · Overburden · Mine capping

Highlights

- Mine capping improved with pre-mining treatment of pasture grass
- Substantial increases of stability (about 25 %) and water retention (about 40 %) occurred in the same soil which had previously been under a long-term permanent pasture regime
- Prior soil management should be taken into account where top-soil is to be removed and used as a capping after mineral ore extraction.

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1 Introduction

1.1 Edaphic Problems of Mine Waste Rock

Mining and related activities cause drastic perturbation of terrestrial ecosystem (Das and Maiti 2005), leading to severe soil degradation (Davies et al. 1995). Many mine wastes are structure-less entities (Fig. 1), prone to crusting and low in organic matter and macronutrients (Waygood and Ferreira 2009), with contaminants including salts, metals, metalloids, and radionuclides (Sheoran et al. 2008). Such harsh conditions often prevent colonization by plants (Lottermoster 2003). Mine tailings are a significant health risk to nearby populations and they require novel remediation approaches that are economical and of low input. In arid regions, mine tailings and their associated contaminants are prone to wind-borne dispersion and water erosion. Capping mine tailings sites with soil, gravel, or even cement is an accepted although often impermanent way to reduce wind and water erosion. Revegetation is considered a cost-effective and more permanent alternative to these capping strategies. The challenge is that mine tailings have no nutrients or soil structure.

This is exacerbated by conditions of drought and salinity in arid and semi-arid regions. The end results of mineral ore extraction are commonly mine tailings and waste rock dumps lacking organic matter, and with weak structures prone to surface sealing during rainfall events. In a study assessing the shelf life of mine-soils in India, Ghose (2005) observed a 47 % decrease in SOC in the first year, followed

Fig. 1 Mine waste rocks from a pyrites mine. Note the lack of top-soil and undeveloped soil structure. Adapted from: South Australia Government Documents at: www.minerals.dmitre.sa.gov.au

by gradual decrease until a steady-state level was achieved at 80 % lower SOC than the initial concentration after 6 years. Therefore, the potential to increase the C capital of mine-soils is significant (Ussiri and Lal 2005). Additionally, the mineral separation process is only partially efficient, and after the milling processes, some of the metal-containing minerals are left behind as small tailings particles. As a result of these combined factors tailings do not readily support plant growth and can remain barren for decades or longer.

Research data from other mine-sites demonstrate that in some areas, waste rock weathers rapidly to form suitable materials for revegetation (Sheoran et al. 2008). Some of the important metallic micronutrients that are essential for plant growth are Fe, Mn, Cu, and Zn. These micronutrients are available in the soil due to continuous weathering of minerals mixed with primary minerals. Nevertheless, these metals are more soluble in acidic solution (Sheoran et al. 2010), and therefore can dissolve to form toxic concentrations that may actually hinder plant growth (Barcelo and Poshenrieder 2003; Das and Maiti 2005). Moreover, though many native species are adapted to low nutrient availability, in agricultural land use acidity merely equates to dysfunctional systems, lacking water and high nitrate levels if the rainfall is substantial (Sheoran et al. 2010).

Environmental losses

The effects of mine wastes can be multiple, such as soil erosion, air and water pollution, toxicity, geo-environmental disasters, loss of biodiversity, and ultimately loss of economic wealth (Wong 2003; Sheoran et al. 2008). The overburden dumps include adverse factors such as elevated bioavailability of metals; elevated sand content; lack of moisture; increased compaction; and relatively low organic matter content (Sheoran et al. 2012). Long term mine-spoil reclamation requires the establishment of stable nutrient cycles from plant growth and microbial processes (Singh et al. 2002; Lone et al. 2008; Kavamura and Esposito 2010).

An increase in the concerns for environment has made concurrent post-mining reclamation of the degraded land as an integral feature of the whole mining spectrum (Ghose 1989). For example, in order to avoid soil erosion and to ensure that vegetation is returned to the land, many companies have water drainage practices during mining operations, separate removal of top-soil (50 % reuse it directly after the mining operation) and over 60 % have their own nursery plant facilities (Singh 1994).

The top-soil gets seriously damaged during mineral extraction (Singh et al. 2002). The consequences of physical disturbance to the top-soil during stripping, stockpiling, and reinstatement cause unusually large N transformations and movements, eventually with substantial loss. Management of top-soil is therefore important for reducing N losses and increasing soil nutrients and microbes (Singh et al. 2002). There is severe loss of SOC due to enhanced mineralization, soil erosion, leaching, reduced/lack of inputs of SOM (Fig. 2), mixing and compaction, which decrease physical protection against decomposition (Ussiri and Lal 2005). Losses of SOC of as much as 80 % of the original pool have been observed from scraped top-soils (Ghose 2005).

Fig. 2 Rapid loss of SOM immediately begins on soil sub-aerial exposure due to clearing for mining operations

1.2 Purpose of Mine-Capping

Though the reason for capping is to either (a) increase infiltration to facilitate revegetation, or (b) decrease infiltration to decrease outflow of toxic mine materials, in either case, vegetation directly facilitates the objective (Waygood and Ferreira 2009). This is because the greater proportion of vegetation extraction of moisture by roots reduces the outflow of mine wastes in case (a) above (Waygood and Ferreira 2009). With botanists indicating that most grasses and trees have 80 % of roots within the upper 300 mm of soil with 90 % of biomass being within 600 mm of surface (Waygood and Ferreira 2009), the potency of a well-vegetated top-soil for mine-capping is clear. Nevertheless, this does not preclude vegetation from extracting water from deeper soils where practical.

1.3 The Ideal Mine Capping

For waste rock, infiltration is often so rapid (Fig. 1) as to cause high water stress for any vegetation it supports. The ideal capping should therefore possess adequate water retention and infiltration, and the ability to resist breakdown and erosion from water and wind. Revegetation constitutes the most widely accepted and useful way to reduce erosion and protect soils against degradation during reclamation (Sheoran et al. 2010). However, Mentis (2006) has shown that soil capping systems placed without consideration of the need for additional organic carbon, appropriate additions of nutrients, proper pasture management and detailed planning are often not successful in the longer term. In terms of final land use, he cites several problems on capping systems at various opencast mines associated with disturbed soils, depletion of organic carbon and nutrients and low soil pH. These factors have resulted in limited progression of vegetation to climax species, and a final land use that is less sustainable than before.

Ideally, therefore, to compensate for potential deterioration during storage, the aim should be to sufficiently improve the surface soil prior to its removal of overburden and top-soil. This is critical because top-soil is at times unintentionally mixed with subsoil during the open-cast mining process, thereby depleting the top-soil of nutrients (Harris and Omoregie 2008). On the other hand, mixing with subsoil is at times deliberate. For example, in the Witbank area of South Africa, 600 mm of soil cover would generally be considered adequate, with the stripped material being placed over spoils after they have been levelled, typically as one mixed layer of soils and sub-soils (Waygood and Ferreira 2009). The area is then grassed with a mix of species. The mixing of the soil layers should reduce hydraulic conductivity and lower the influx of water into the subjacent mine-spoil material.

Secondly, there are limits to the efficacious thickness of stored top-soil. At a depth of about 1 m in the stockpile, the number of anaerobic bacteria increases, whereas those of aerobic bacteria decrease (Harris et al. 1989). This inhibits nitrification due to poor aeration within the stockpile, leading to an accumulation of ammonia in the anaerobic zones. If a high level of ammonia is present in a reinstated soil, the amount of nitrate generated is likely to be much greater than the normal. Consequently there is high potential for N loss to the environment via leaching or/and denitrification (Johnson and Williamson 1994). Nitrate leached to water courses is not only a threat to aquatic environment and drinking water supplies (Addiscott et al. 1991) but if nitrogen is lost from soil in the form of gaseous nitrogen or nitrous oxides, this will contribute to degradation of the ozone layer (Isermann 1994; Davies et al. 1995).

1.4 Other Drawbacks of Top-Soil Storage

In addition to a loss in the breakdown of organic matter, stockpiling causes many other deleterious changes (Fig. 3) including a marked drop in the earthworm population (Johnson et al. 1991) which affects soil nutrients, bulk density and water holding capacity (Rana et al. 2007). It has been reported that stockpiling techniques, and the wholesale removal of the top-soil layers, reduce the chances for succession for much of the pre-existing vegetation (Jacobson 1999). Plant fragments from pre-existing vegetation are lost or greatly reduced. The seed bank is

Fig. 3 Untreated top-soil added to this open-cast bauxite mine had been stored (unmaintained) prior to spreading to increase infiltration and facilitate revegetation. Here the process is compromised by wind and water erosion after spreading, and hence is unsuccessful. Adapted from: Google Maps

also reduced, and what does remain must compete for the reduced nutrients with microbes. These microbes become highly competitive as the base of stockpiles become anaerobic (Jacobson 1999).

Fresquez and Aldon of the USDA Forest Service (1984) noted that top-soil stored for years, and, especially the mining overburden material, has little biological resemblance to the undisturbed surface soil and that the resulting reductions to the fungal genera and microorganisms result in an unstable and unbalanced soil ecosystem. Prolonged storage was also a part of the research conducted by Harris and Birch (1989). They concluded that prolonged storage intensifies the loss of the bacterial element of the soil.

In some operations such as bauxite mining, and in keeping with increasingly demanding environmental standards, the removed top-soil is commonly stored, to be used later as a capping for the exposed earth materials. The period between the initial removal of top-soil and final laying of the same over the reclaimed is too often over-extended. Hence, properties of stockpiled soil continually deteriorate and ultimately become biologically non-productive if it is not preserved properly (Ghose 2005). He advised against top-soil storage, especially in the long term, for a time length by which the mine-spoil cannot maintain its sustainability for suitable plant growth without biological reclamation, and, also, maintenance of growth of aerobic bacteria. Often, after a storage period of just six months, top-soil to be used as capping becomes sterile, after heavy losses in organic matter and microorganisms (Hannan 1978; Rana et al. 2007), thereby becoming less effective as a growth medium. Finally, bulk density of productive natural soils generally ranges from 1.1 to 1.5 g cm^3. High bulk density limits rooting depth in mine soils, and at lower levels of thickly stored top-soils (Williamson and Johnson 1991).

1.5 Effects on Mycorrhizae

Arbuscular mycorrhiza fungi are ubiquitous soil microbes occurring in almost all habitats and climates. The hypha network established by mycorrhizal fungi breaks when soils are initially moved and stockpiled (Gould et al. 1996). It is well documented that mycorrhizal associations are essential for survival and growth of plants and plant uptake of nutrients such as phosphorus and nitrogen, especially in P deficient derelict soils (Khan 2005).

According to Six et al. (2004), microbial secretions and fungal hyphae have generally been found to be extremely important components of macro-aggregate development. A study conducted in Derbyshire, England, of the relationship between aggregate stability and microbial biomass in three restored sites, showed a linear relationship between the health of the microbial community and the quality of soil structure (Edgerton et al. 1995). Mycorrhizae hyphae form an extensive network in soil, the hyphae being covered with extracellular polysaccharides that form soil aggregates. These aggregates are held intact by the roots so that they do not collapse in water. This system forms pore spaces and drainage channels. Based on observations in agricultural practices and previous reclamation research, most macro-aggregation is destroyed during top-soil stripping and salvage prior to mining as roots and fungal hyphae holding macro-aggregates together are disrupted (Wick et al. 2008). Soil disturbance associated with surface mining has a negative effect on both saprotrophic and arbuscular mycorrhizal fungal (AMF) populations (Mummey et al. 2002).

Secondly, mycorrhizal symbiosis is documented as protection against pathogenic fungi (Tate and Klem 1985). Moreover, the microbial community is responsible for the development of a soil structure conducive to the various biogeochemical cycles (Tate and Klem 1985). Mycorrhizal fungi are therefore a very important part of the microbial community. These fungi are often reduced or destroyed by stockpiling. They also found that deep stockpiles create both high and low moisture problems, which limits soil microbial respiration. To maintain a healthy microbial community, soil moisture must have some constancy in order for fungal propagules to survive (Tate ans Klem 1985). Thus Rana et al. (2007) found that recovery of the soil microbial community is crucial to successful land reclamation and ecosystem restoration.

1.6 Management History

As long storage is inimical to the integrity of removed top-soils, the nature and prior land use of the top-soil considered for mine waste capping may significantly influence its effectiveness. In models, soil organic carbon (SOC) is often grouped into three conceptual pools to characterize long- and short-term changes in soil C storage and decomposition rates (Schwendenmann and Pendall 2008). Active and slow pools are regarded as being sensitive to land management (McLauchlan and Hobbie 2004) and depth (Fierer et al. 2003).

The passive, resistant, or stable pool is considered to be weakly sorbed C (Schwendenmann and Pendall 2006), composed of aliphatic compounds, often mineral-stabilized, with mean residence time (MRT) in the range of 10^3 years (Paul et al. 2001). As soil management largely determines active and slow pools of organic matter levels in soils, and exposure through storage decreases soil organic matter levels in the short-term, it is important that prior to ore extraction, the management history of the top-soil be ascertained, and its effective treatments upon removal be considered.

Adequate top-soil management is thus considered the most important factor in successful rehabilitation of mining projects if the objective is to restore the native ecosystem of the project area. The top-soil contains the majority of the seeds and other plant propagules (such as rhizomes, lignotubers, roots etc.), soil microorganisms, organic matter and much of the more labile (more readily cycled) plant nutrients. The top-soil from all areas being cleared would ideally be retained for subsequent rehabilitation. However, removal and storage reduces the integrity of top-soil. Therefore, as an abundance of soil organic matter is found under pasture lands (Fig. 4) in humid zones (Schwendenmann and Pendall 2006), the treatment

Fig. 4 Pasture lands contain both active and slow pools of organic matter as short and long-term nutrients for microbial life. After removal as overburden, this helps to maintain soil vigour during storage

and character of the top-soil prior to its removal largely determines its effectiveness as a mine-capping.

1.7 Purpose of Top-Soil In Situ Amendments

Top-soil is a scarce commodity, and it is never stored in the majority of potential sources; instead it is borrowed from nearby areas for the reclamation of the degraded mined-out areas (Sheoran et al. 2010). Also, in a tropical climate where 90 % of rainfall is precipitated within three months of the rainy season, storing of the top-soil and preservation of soil quality remains problematic (Sheoran et al. 2010). The large and relatively rapid decline in SOC pool in mine-soils indicates that there is a potential to enhance the rates of C sequestration in these soils with management practices that reverse the effects of degradation on SOC pools (Ussiri and Lal 2005).

1.8 Problem Area #1: Guyana (Bauxite Mining)

According to the EPA Guyana (2014) report, the East Kurubuka bauxite layer lies approximately 57.8 m below the surface and the West is approximately 38.1 m below the surface (EPA Guyana 2014). During the preparation of a site for open-cast mining, the surface soil is removed to get access to the bauxite. Therefore the local bauxite industry has excavated much more overburden earth to make contact with their bauxite (Fig. 5) than that of Jamaica.

Moreover, whereas the Jamaican ore is physically a soil, the Guyana bauxite exists as a rock (Fig. 6). This presents greater challenges for revegetation due to the lack of permeability, high strength and total absence of organic matter.

1.8.1 Gold Mining Effects in Guyana

An inspection of various mining activities in Guyana—manganese (no longer exploited), bauxite, and gold—shows that invariably mining destroys valuable stands of forest and wildlife habitat. Lang (2014) observes that medium and small-scale gold mining as currently practised and regulated inflict severe environmental, health, and social damage on the areas and people near such mining operations. Areas around mines resembled a moonscape of barren, mounded sand and mud (Fig. 7).

Since small-scale miners typically wash the top-soil away in order to get to the gold-bearing clayey soil underneath, the sites of former mines were very infertile and incapable of supporting regenerated rainforest. Failure to replant immediately after clear-felling of trees has caused the topical clay soils to dehydrate, sometimes irreversibly, and to become very hard and impermeable to water, thereby lowering

Fig. 5 A Guyana bauxite mine. Bauxite is located much more deeply; >3-fold the depth of Jamaica mines. Note the deep lakes formed in the mined out locations, thereby presenting almost insurmountable obstacles to land rehabilitation. *Source* Demarara Bauxite Company (DEMBA)

Fig. 6 Guyana bauxite is often in the form of a pink rock, contrasting with the soft, earthy, easily-worked Jamaican ore. Mine capping therefore is more costly and logistically and edaphically more difficult in Guyana. *Source* Demarara Bauxite Company (DEMBA)

Fig. 7 A gold mine excavation in Guyana. The uneven, pock-marked surface with pools at varying levels presents difficulties for subsequent mine-capping operations. *Source* Barrick Gold 2012

the soil potential to support growth of trees (Singh 1994). On the other hand, high rainfall rapidly erodes the top-soil and creates difficulties for tree establishment. In Guyana, vast tracts of scrubland are burned for cattle ranges. Very soon the soils lose their fertility and new ranges are created by burning more land.

Soils are stripped of their vegetation, scarring the landscape (Fig. 8). According to Lang (2014), large unsightly excavations and stockpiles of overburden are dumped on the top-soil. The loose soils cause dust pollution and affect all living organisms in the area. The heaps of overburden are prone to leaching and erosion, polluting the waters. There are mines where the soil thickness is extremely limited due to poor utilization of soils, or thin soils in the pre-mining environment.

1.9 Problem Area #2: Bauxite Pits in Jamaica

Bauxite-excavated pits in Jamaica exhibit low SOC, soil crusting, and low fertility (Harris and Omoregie 2008). Further, it is known that aluminium is most active in fixing phosphate at a pH of 5.0–5.5. Iron is especially active below pH 4.0 where phosphate is very strongly fixed. This apparently excludes tropical soils where pH exceeds these values, but pH values in soils can vary widely within short distances (Kundu and Ghose 1997), especially with sudden elevations changes as occurs often in Jamaica. Further, calcium is primarily responsible for phosphate fixation in alkaline soils where fixation peaks around pH 8.0. However, of the three major fixation processes—precipitation by iron, aluminium, or calcium—phosphorus is

Fig. 8 Guyana: scarred landscape after bauxite mining has removed soil and overburden. *Source* http://epaguyana.academia.edu

least unavailable when it is fixed by calcium (Ludwick 1998), and the reclaimed bauxite overburdens of Jamaica having karst terra rossa origins, are high in calcium. The structure of a mined-out pit depends largely on the shape and structure of the ore-body, such that the pit can vary from being a shallow saucer-shaped basin to a wide, deep hollow with vertical walls (Sheoran et al. 2010). The shallow basins are graded to a gentle slope ending at the approximate middle of the mined-out area or terraced to that point. Deeper deposits are graded to the toe of the vertical walls and serve as collection ponds for water (Sheoran et al. 2010).

1.10 Improving Stored Top-Soils

Several methods of treatment are known to improve top-soils. One cheap source of organic amendments is green waste or “green manure”. In laboratory trials, Harris and Megharaj (2001) recorded substantial improvements in the physical properties of green manure-treated sludge used as a growth medium in mine-waste dump materials. Courtney et al. (2013) found that within one year, bio-solids-amended and vegetated sites exhibited improved physico-chemical properties and increased aggregate stability. They state that further improvement of these properties in subsequent years and evidence of non-labile carbon and nitrogen accumulation indicate that development of root systems and soil communities drive pedogenesis in restored industrial sites. In this study, the influence of prior management history, period of storage, and decomposing green manure amendments, on the physical properties of potential top-soil capping material are investigated.

1.11 Research Area

The Brukunga Mine of South Australia is a de-commissioned iron pyrites mine where re-vegetation attempts encountered stunted growth and death due to low pH, organic matter, and bacterial levels (Harris 2001; Harris and Megharaj 2001). Elevations range from 150 to 300 m above sea level, and pyrites is geologically the dominant mineral. The climate of the research area is moderately warm (25–35 °C summer, 12–18 °C winter, average), and the average total annual rainfall is 650 mm. The study area is in the Bremer River drainage basin in the Mount Lofty Ranges Watershed which drains to Lake Alexandrina (Fig. 9). The stream supplies irrigation water for various horticultural activities, and facilitates grazing and dairying. The total area of the watershed is approximately 900 km^2.

The Brukunga Mine runs for approximately 2000 m parallel to the western bank of Dawesly Creek. Waste rock is heaped along this area (Fig. 10).

On the eastern side, a large tailings dam has been capped to reduce acidic mine leachate (pH 2.5) generation. Leachate is caught in a number of dams and pumped back to an acid neutralization plant above the tailings dam. Though microbial digested sewage sludge has improved vegetation on some plots, the danger of heavy metal pollution to ground and surface waters, and community resistance to the obnoxious nature of such material (with dwelling houses and the Town Centre less than a kilometer away) discourages its large-scale use at this site. The discharge of effluent from the community septic tank of the Brukunga township is an additional source of pollution to Dawesly Creek. Therefore, a cheap, effective “clean material” would be a more acceptable capping.

Though the study area is located in South Australia, this experiment is applicable to several sites in the Caribbean. This is because sulfidic mine waste dumps in the Caribbean exhibit similar pH values whilst at least doubling the rainfall totals (FAO 2006) of the research area in Australia, and AMD is exacerbated by increased precipitation (Aubertin and Bussiere 2001). The climate of the Dominican Republic is tropical with a temperature range between 18 and 32 °C with generally high humidity. The heaviest rainfall period is between May and November with an accumulation of, more or less, 3 m of water (Nelson 2000).

1.12 Pyritic Mines: A Caribbean Perspective

At Pueblo Viejo Gold Mine in the Dominican Republic (Fig. 11), Trade Wind effects produce higher rainfall intensities than for South Australia tailings (Figs. 1, 9 and 12).

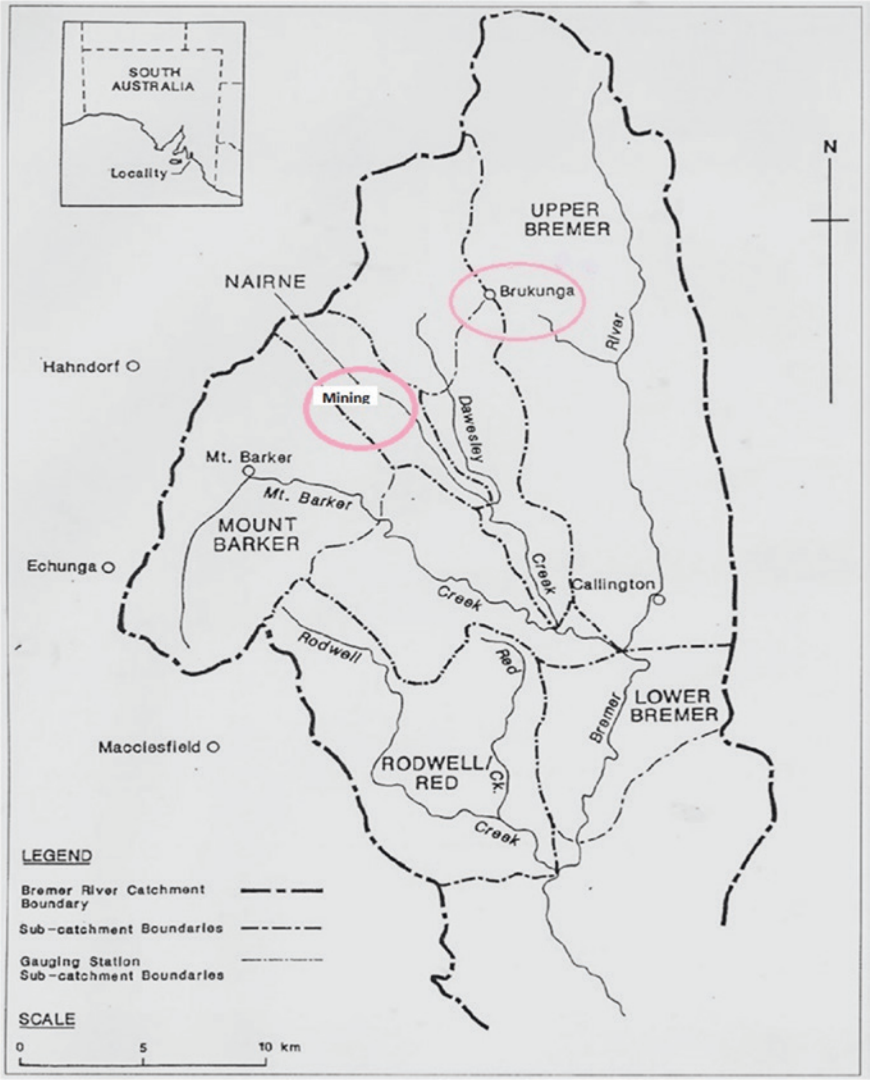


Fig. 9 Location of the Brukunga Mines of South Australia

The "high sulfur" central Cuban provinces of Las Tunas and Ciego De Avila and the inactive Zn–Pb mine of Santa Lucia in western Cuba (Romero et al. 2010) also contain areas of acidic mine drainage. Nevertheless, Alfaro et al. (2015) note that studies assessing the environmental quality of soils in Cuba are very scarce, especially involving various metals on a nationwide scale. Most studies, they report, on Cuban soils, focus on a small number of metals under specific situations (Romero et al. 2010). Nevertheless, as is the case for Pueblo Viejo, capping such mines is imperative to reduce the rate of environmental degradation (Figs. 13 and 14).

Fig. 10 Brukunga Mine, South Australia. Waste rock heaped along a creek bank remains unvegetated. Rainfall maximum here is unimodal (winter only). Comparing this result with that of the more intense bimodal rainfall regime of a similar pyrites mine in the mountainous Trade Wind region of Dominican Republic could reveal greater environmental impacts. *Source* South Australia Government Documents at: www.minerals.dmitre.sa.gov.au

Fig. 11 Pueblo Viejo gold mine, Dominican Republic. Note staining at right by leachate from atmospheric exposure of pyritic waste rocks. Heavy, frequent cumulonimbus clouds seen at top of photo signify a more humid climate compared to that of South Australia (see Fig. 9), indicating more moisture for sulfuric acid generation in the ground. *Source* Barrick Gold Corporation

Fig. 12 Climatic conditions for the Dominican Republic exacerbate the dissolution of exposed pyrites waste rock

Fig. 13 Effects of phyto-organics, and management history on hydraulic conductivity of an Alfisol incubated at 80 % field capacity (water content)

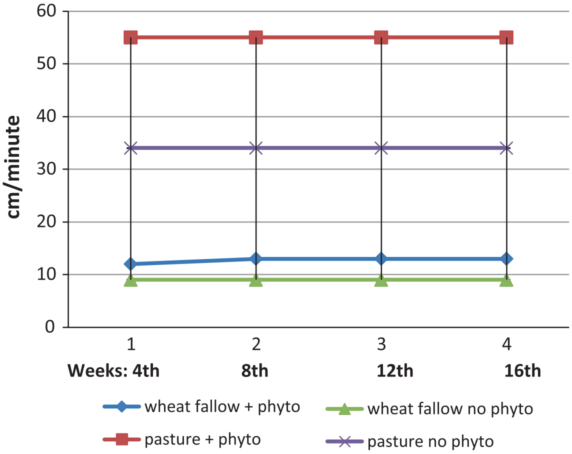
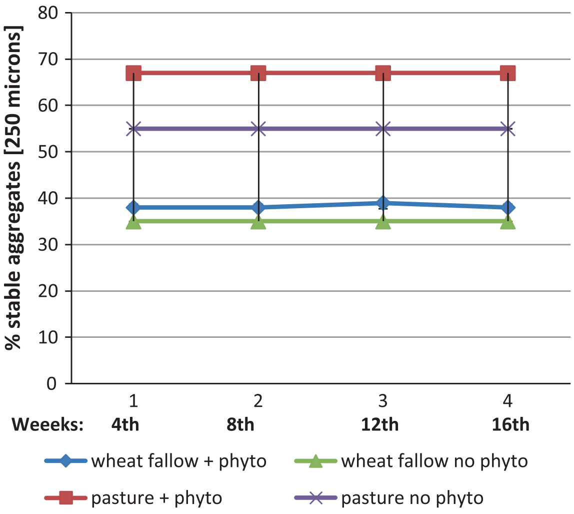


Fig. 14 Effects of storage period, phyto-organics, and management history, on stability of soil aggregates



2 Materials and Methods

2.1 Soil Preparation

Near the foothills of the Adelaide Hills, 30 km south-east of the Brukunga Mine is the Long-term Land-use Rotation Experiment of Adelaide University, South Australia, on an Alfisol (Table 1). Samples of the Alfisol were collected with a scraper to a depth of 15 cm on a random basis, in turn, from the wheat/fallow, continuous wheat, and permanent pasture plots. Each of the above management histories had been in progress for the previous 30 years. After air-drying, the soil clods were broken and passed through a 2-mm sieve and thereafter stored in air- tight

Table 1 Properties of the South Australian Alfisol (0–15 cm)

Sub-soil property	Value
Soil pH	6.8
Organic carbon (%)	1.5
Sand	60[a]
Silt	25[a]
Illite	40[b]
Kaolinite	40[b]
Iron oxide	20[b]

[a] Particle size distribution (%)

[b] Clay mineralogy (% of clay fraction)

containers for 6 weeks. The leguminous plant, *Vicia sativa*, having the capacity to grow well on impoverished soils (Pieters 1927), was grown in a glasshouse in beds containing soil from the wheat/fallow, continuous wheat, and permanent pasture management plots. All seedlings were inoculated during germination, grown for 5 weeks and harvested prior to flowering. Twenty plants were grown in each bed. After the harvesting of all shoots on the same day, the plant parts were cut into small pieces (3-cm lengths) to increase the area of contact with soil particles. As it was anticipated that the incorporation process of the plant parts would entail a time period of at least one week, immediately after harvest the needed aliquots (of 80 g for each 1 kg of soil) were placed into plastic bags and tightly sealed against desiccation until the time of incorporation a few hours later. The following treatment particulars were adopted:

1. Plant parts incubated: young shoots only, as Amato et al. (1983) found that in soils, shoots decomposed faster than root or stem material.
2. Soils selected on the basis of their management history: wheat fallow, continuous wheat, and permanent pasture.
3. Water regimes used in soils: (a) 80 % of field capacity, as Linn and Doran (1984) found that moisture levels below 60 % of, at, or in excess of field capacity of soils, significantly retarded decomposition of buried plant materials, (b) alternate wet/dry water cycles (i.e. weekly alternations of watering to 80 % field capacity followed with one week of drying, thereby more realistically simulating water regimes under field conditions. Incorporation was achieved by spreading thin layers of soil between alternate thin bands of fresh plant parts. Equal weights of young stems and leaves were applied. After incorporation, the surface of the soil was firmly pressed down, in an effort to simulate the action of a roller, under field conditions, to facilitate better contact between soil particles and the potentially decomposing substrate.

The study maintained a temperature of 25 °C in a controlled growth chamber consisting of a sealed walk-in cabinet. Three replicates of each treatment were randomly arranged on tables for the duration of 4, 8, and the 12-week incubation storage, which simulated soils under storage conditions. A timed, calibrated dripper system was used once per week. To reduce the impact from the dripper, and reduce evaporation, the soil was covered with an inert plastic mulch separated from the soil surface by a nylon cloth. As an added precaution against water loss, and to ensure complete equilibration, the pots were tightly covered with plastic sheeting over the next two days. Three techniques were used to assess the soil structural stability and hence, changes to its capping suitability resulting from the various treatments: water stable macro-aggregation, water retention, and hydraulic conductivity.

2.2 Macro-Aggregation

For water stable macro-aggregation, the method of Kemper and Rosenau (1986) was adapted as follows: All samples were exposed after incubation storage until air-dry. The soils were gently crushed with a wooden mallet and passed through a 5-mm sieve. Three subsamples of 25 g were taken from each replicate. The samples were then placed on a nest of sieves of the following mesh diameters: 1000-, 500-, 250- and 125 µm. Samples were slowly lowered into a cylinder of distilled water until the water made contact with the bottom of the soil layer and then immersed in the cylinder and oscillated vertically at a stroke length of 2 cm with a frequency of 30 strokes per minute for 5 min. The material was carefully washed from each sieve into containers, oven dried at 105 °C for 48 h and each re-weighed. Water-stable macro-aggregation (WSMA) was calculated as the amount of material left on the 250 µm sieve plus the amount left on all sieves above this size; this was then corrected for the weight of sand >250 µm and expressed as a percentage of the original weight of aggregates.

2.3 Hydraulic Conductivity

Rate of water movement in soils was to be measured because a low infiltration rate results in a correspondingly high rate of runoff, with high volumes of runoff causing severe erosion in a short space of time, especially on the sloping reshaped mounds characteristic of open pit extraction sites. According to Hannan (1978), replaced top-soil in such situations is the first material to be lost. For the determination of the rate of water movement through the soil, the saturated hydraulic conductivity (K_{sat}) was determined for each treatment utilizing a constant hydraulic head in the following manner: 50 g of loose oven dried aggregate were placed in a “Perspex” cylinder. The soil surface was protected from the direct impact of the hydraulic head by using a filter paper. A constant head of 15 cm of water was maintained on each replicate, over a 2-h period during which four measurements were taken every 30 min of the amount of water conducted (q, cm^3) in that time period (t, h) period. The K_{sat} ($cm\,h^{-1}$) of three replicates for each treatment was calculated as:

$$K_{sat} = q(L)/H(At) \tag{1}$$

where q was the volume of water (cm^3) collected per unit time, t(h), A(cm^2) was the cross-sectional area of the cylinder, L was the length of the sample, and H (hydraulic head) was (L + 15 cm).

2.4 Water Retention

The importance of moisture retention in stored top-soils has already been stated. Air-dried aggregates were equilibrated and measured, based on the method of Klute (1986). The amount of water retained in soils as a result of each soil treatment was determined by the pressure plate apparatus and sintered funnel assemblies with a range of suctions applied to the soils at: 0.1, 1, 10, 100 kPa suction, respectively.

3 Results and Discussion

3.1 Saturated Hydraulic Conductivity

Green manure caused significant increases in K_{sat} of all stored top-soils, particularly for the permanent pasture (PP) soils, where the increases were more than three times those of either continuous wheat (CW) or wheat/fallow (WF) soils (Fig. 2). Even without green manure, the K_{sat} of the untreated PP samples was 3-fold that of the untreated WF and CW samples, indicating the inherent superiority in water transmissivity of the PP as mine-capping material, compared to those of the same soil under different management histories (Fig. 2). A high proportion of un-decomposed stems was observed for the treatments having a regime of 80 % field capacity. Thus, the succulent shoot material decomposed quickly in those samples, in the process releasing a greater quantity of binding agents, thereby causing greater porosity. This indicates that decomposition and formation of organic binding agents and thus some stabilization of structure had taken place in all soils in the presence of green manure and adequate moisture and air. Schwendenmann and Pendall (2006) point out that the ‘active’, ‘labile’ or ‘fast’ pool is assumed to be composed of microbial biomass and easily decomposable compounds (e.g., proteins and polysaccharides) from leaf litter and root-derived material with short MRT (from days to years), while the ‘slow’ or ‘intermediate’ pool is understood to consist of refractory components of litter, weakly held carbon, and MRT from 10 to more than 100 years. The increases in K_{sat} were maintained throughout the 12 weeks of incubation, with highest increases beginning at 4 weeks.

This trend seems to tie in with the observations of Mason (1977), who found that differences in N mineralization rates of incubated green plant material were relatively small up to the third week of incubation, after the largest increases in the first week.

It is of interest that K_{sat} increases under a wet/dry water regime were not found for any of the samples. This suggests a minimal amount of microbial degradation of the newly added decomposable organic matter in those samples during storage. Microbial life was not therefore as active under the wet-dry conditions of storage, after the end of four months of storage. This could have been an indication of low microbial populations. As such water regimes of alternate wetting and drying often prevail in field locations, these results seem to corroborate the findings of Hannan (1978), who reported depletions in microbial counts (possibly due to low water retention) leading to sterile conditions for soils stored in excess of six months.

3.2 Macro-Aggregate Stability

Large increases of approximately 25 % above the controls for the permanent pasture system occurred (Fig. 3). There were no substantial increases in WSMA among either of the previously cultivated systems, and the only significant change occurred when the WF and CW were subjected to green manure at a water regime of 80 % of soil field capacity (Fig. 3). The wet/dry regime was therefore ineffective. Utomo and Dexter (1981) found that providing there is an extra energy source for microbial activity, wetting and drying first increases the proportion of water stable aggregates >0.5 mm to a maximum value; however, when there is no extra energy source, wetting and drying steadily decreases water-stability. As the samples in this study were not inoculated, and were held at air-dry for 6 weeks in the first stage of storage with no external energy source, such a process could have severely depleted the already low levels of viable but dormant organisms in the CW and WF samples. Conversely, the microorganisms in the PP samples would have been more abundant, and therefore more of them would have been expected to have survived this air-dry stage.

An additional possible explanation for the meagre significance of the WSMA results for the CW and WF systems is that the method of determining WSMA might have been too severe. It is known that macro-aggregates are more susceptible than micro-aggregates to breakdown under prolonged physical stresses, particularly for the more recently formed aggregates (Tisdall and Oades 1982; Varadachari and Ghosh 1983). Thus, some aggregates formed as a result of the treatments in this study, could have been destroyed via the impact of the wet sieving process. This could have partially masked significant improvements, however slight, in WSMA for the CW and WF management samples. On the other hand, the process of measuring saturated hydraulic conductivity of samples involved a much lower expenditure of kinetic energy than that of wet sieving. Under this process, more effective preservation of weaker aggregates and thus a greater response for hydraulic conductivity from the cultivated soils would have resulted. Thus, the changes contributing to the increase in K_{sat} for those samples were likely to have been of increased micro-aggregation and porosity. K_{sat} therefore seems to be a more precise parameter and a more sensitive instrument compared to WSMA for determining minute changes in structure of such disturbed samples.

Due to the extensive root systems of pasture plants, the upper soil horizon in old pastures is almost all rhizosphere (Connell and Hadfield 1961). Among the three original soils used in this study, the microflora population would therefore have been highest in the permanent pasture soils. Conversely, the cultivated soils inherently would have contained low levels of organic matter, owing to the dried out and resistant nature (more lignaceous) of the organic fraction in those soils; Golchin and others (1994), and Grierson et al. (1972), found that decreases in water-stability of aggregates have been associated with reductions in total amount of carbon in the soil in semi-arid areas of South Australia. Swift (1992) found that pasture soils contained dormant microorganisms in far greater numbers than those of cultivated soils. In such a favourable environment, the addition of green manure, by providing an abundant nutrient source for microorganisms, would have triggered a "priming" effect for dormant microorganisms in the pasture soils of this study. This in turn could have released a greater amount of binding agents, compared to the CW and WF soils. A higher level of biological activity therefore, compared to cultivated soils, improved the soil structure. However, whereas the increases recorded by Swift (1992) were short-lived and reduced after 4 weeks, in the present study, increases in WSMA and K_{sat} for the PP soils were maintained for up to 12 weeks during storage. This is likely to be a result of the complexity and far greater size of the substrate molecules in this study, compared to those of glucose, and hence a longer lasting effect by green manure which is not as quickly consumed.

3.3 Water Retention

Green manure did not significantly increase water retention in any of the samples. The only statistically significant trend seen in this study is that of the higher rate of water retention as it relates to prior soil management, and that without the need for any green manure. This is not surprising for the cultivated soils, as little decomposition was evident in their samples. For the PP samples, this lack of response, in spite of substantial decomposition is not surprising, as the green manure changed its macro- and micro-aggregation that largely influences water-holding characteristics of a soil. Nevertheless, an increase in density of organic matter would have increased its water-holding capacity, but the green manure organic matter added did not necessarily cause an increase in density of the pre-existing organic fraction in the PP. Only if the density of the organic matter in the treated samples increased, would the water retention of the PP samples also increase. It is possible that the organic matter added to the PP samples by the green manure, being recently degraded, was not as dense, and therefore no more water retentive than the typical rhizosphere-rich inherent organic matter typical of soils with a management history of permanent pasture, as found by Connell and Hadfield (1961).

4 Conclusions

Alfisols previously under a management system of permanent pasture are inherently superior, and show much more significant improvements in physical characteristics when organically amended, compared to cultivated Alfisols. During short-term removal and storage for up to three months, permanent pasture soils show no signs of sterility, whereas stored, previously cultivated soils are largely unresponsive to green manure treatments. Therefore, soils left in the field under grazing for prolonged periods prior to removal for capping may be more suitable and responsive as a growth medium than soils previously cultivated.

Based on large value differentials between K_{sat} and macro-aggregate stability after green manure treatment for cultivated soils in this study, recently formed aggregates of cultivated soils are weaker than those recently formed in permanent pasture soils. Therefore, to preserve physical integrity, added care may be required when removing and transporting capping material from soils with a prior history of cultivation, after application of organic amendments. If un-pastured overburden is to be removed and placed under storage, its effectiveness is increased if first placed under a management system of permanent pasture.

5 Geobiotechnological Applications

5.1 Choose Tyre-Mounted Machines

A tyre mounted mining machine (scrapers) rather than crawler mounted (dozers) to dig stored soil and minimize compaction (Sheoran et al. 2010). They observe that transporting soil from the stockpile to the reclamation site on a conveyor belt with trundling action improves soil structure by breaking up massive aggregates. As smaller aggregates continue to tumble, they tend to acquire an agglomerative skin of fine particles, which promotes loose soil structure (Sheoran et al. 2010).

5.2 Choose Grasses

Grasses, particularly C4 ones, can offer superior tolerance to drought, low soil nutrients and other climatic stresses, and hence would satisfy the prior management requirements of mine-capping. Roots of grasses are fibrous that can slow erosion and their soil forming tendencies eventually produce a layer of organic soil, stabilize soil, conserve soil moisture (Sheoran et al. 2010).

Fig. 15 Top-soil should be stored low (<2 m in height) and planted with fibrous rooted (grassed) vegetation as above

5.3 Use Waste Rock

Research data now available from other mine-sites demonstrate that in some areas, waste rock weathers rapidly to form suitable materials for revegetation. Consideration may also need to be given to the re-spreading techniques used, with a view to minimizing soil compaction that can inhibit later revegetation.

5.4 How to Stockpile Soil

In cases where stripped soil cannot be re-spread immediately, it should be stockpiled. Stockpiles should be established as close as practicable to areas to be rehabilitated (SVDPI 2004). They should be low (Fig. 15) (generally less than 2 m in height), gently battered and located away from drainage lines. Importing of soil is not recommended, especially in areas of native vegetation, because of the risk of the imported soil introducing weeds or plant diseases.

Top-soil stripped ahead of mining is applied to the reshaped surface in an even layer generally not less than 100 mm. Top-soil is placed using rear dump haul trucks and spread with dozers or graders. Once spread, the top-soil surface is disc or chisel cultivated to create a textured surface which assists in trapping surface runoff, provides seed entrapments and creates microclimates favourable for seed germination (SVDPI 2004). Where bio-solids are used, cultivation also integrates the top-dressing material. Increasingly, the aim of mine residue rehabilitation is moving towards ecosystem reconstruction rather than vegetation establishment.

5.5 Role of Capping Systems

Top-soil is used to cover poor substrate and to provide improved growth conditions for plants. Stockpiling of top-soil in mounds during mineral extraction has been shown to affect the biological, chemical and physical properties of soil (Johnson et al. 1991; Davies et al. 1995). Long term studies have indicated that capping systems deteriorate with time and often do not perform as expected. As a result, costs for managing water makes from mined out areas are likely to be higher than may otherwise have been expected. Future maintenance requirements of capping systems have generally not been seriously addressed (SVDP 2004).

5.6 The Function of Increased Aggregate Stability

Soil structure plays a dominant role in the physical protection of SOM by controlling microbial access to substrates, microbial turnover processes, and food web interactions (van Veen and Kuikman 1990). Relatively labile materials become physically protected from decomposition by incorporation into soil aggregates (Gregorich et al. 1991; Golchin et al. 1994) or by deposition into microbially inaccessible micro-pores.

Decreased soil stability can lead to increase in bulk density because the matrix does not resist slaking, dispersion by water and the forces imparted by wheels, hooves and rainfall. This, in turn, leads to decreased aeration and water infiltration rate and the development of anaerobic conditions. N losses by denitrification may follow under such an environment.

5.7 Ideal Compaction Levels

The surface four feet of mine soil material should be easily-weathered overburden, meaning that most rocks and boulders break apart and decompose quickly to fine soil materials. The soil texture of the fine-earth fraction should be loamy to sandy, and the mine soil should be low in total salts; mine soils should be moderately acid (pH 5.5–6.5) when native hardwoods are being planted. Most importantly, the mine soil must also be left uncompacted to a depth of four feet (Daniels 1999).

Loosely constructed, or “fritted”, subsoil is very important to plant root systems. The extent of the root system determines a plant’s ability to maximize its surface area and access a greater volume of water and soil nutrients. Plants grown in fritted subsoil have root patterns with extensive vertical and lateral penetration (Sheoran et al. 2010). Soil storage is for very short periods, periodically opening up and aerating the soil while stockpiled or permanently aerating, allowing drainage with a network of pipes and use of nitrification inhibitors after restoration are the operations that may in part ameliorate the problem (Davies et al. 1995).

5.8 What Is the Objective?

The top-soil is severely damaged if it is not mined out separately in the beginning with a view to replace it on the filled void surface area for reclamation in order to protect the primary root medium from contamination and erosion and hence its productivity (Kundu and Ghose 1997). Sendlein et al. (1983), however, indicate that systematic handling and storage practice can protect the physical and chemical characteristics of top-soil while in storage and also after it has been redistributed into the regarded area.

The three major macronutrients, namely nitrogen, phosphorus and potassium are generally found to be deficient in overburden dumps (Sheoran et al. 2008). Adequate top-soil management was considered the most important factor in successful rehabilitation of the project since the objective is to restore the native ecosystem of the project area. The top-soil from all areas being cleared would be retained for subsequent rehabilitation.

5.9 Soil Organic Carbon (SOC)

Organic matter is the major source of nutrients such as nitrogen, and available P and K in unfertilized soils (Donahue et al. 1990). A level of organic carbon greater than 0.75 % indicates good fertility (Ghosh et al. 1983). The level of organic carbon in overburden was found to be 0.35–0.85 %. Organic carbon is positively correlated with available N and K and negatively correlated with Fe, Mn, Cu, and Zn (Maiti and Ghose 2005). The potential of SOC sequestration in mine-soils depends on biomass productivity, root development in the subsoil and changes in mine-soil properties resulting from overburden weathering (Haering et al. 1993).

5.10 Increase Microbe Population

Microbial activity decreases with depth and time as top-soil continues to be stored during mining operations (Harris et al. 1989). Microbial activity, measured in ATP (adenosine tri phosphatase) concentrations, plummets to very low levels within a few months. Response to glucose is slower by microbes at all depths, suggesting that metabolic rates decrease with time (Visser et al. 1984). Once the soil is removed from the stockpile and reinstated, aerobic microbial population rapidly reestablishes, usually higher than the normal level (Williamson and Johnson 1991) and nitrification restarts at higher than the normal rates.

Microbial activity declines when soil layers are disrupted and is slow to resume independently (Williamson and Johnson 1991). Soil microbes include several bacterial species active in decomposition of plant material as well as fungal species whose symbiotic relationship with many plants facilitates uptake of nitrogen and phosphorus in exchange of carbon. They produce polysaccharides that improve soil aggregation and positively affect plant growth (Williamson and Johnson 1991). Sites with an active soil microbe community exhibit stable soil aggregation, whereas sites with decreased microbial activity have compacted soil and poor aggregation (Edgerton et al. 1995).

Soil enzymes activities have been used as sensitive indicators for reflecting the degree of quality reached by a soil in the reclamation process. Ceccanti et al. (1994) note that a direct measurement of the microbial population is the dehydrogenase activity. Dehydrogenase is an oxidoreductase, which is only present in viable cells. This enzyme has been considered as a sensitive indicator of soil quality in degraded soils and it has been proposed as a valid biomarker to indicate the changes in soil management under different agronomic practices and climates. Measurement of soil hydrolases provides an early indication of changes in soil

Fig. 16 In uneven topography, nutrients are readily leached from stored top-soils. After opencast mining, newly exposed mine-soils require substantial inputs of fertilizers to maintain a new plant community

fertility since they are related to the mineralization of such important nutrient elements as N, P and organic carbon (Ceccanti et al. 1994).

When soil layers are removed and stockpiled, the bacteria inhabiting the original upper layers end up on the bottom of the pile under compacted soil (Williamson and Johnson 1991). A flush of activity occurs in the new upper layer during the first year as bacteria are exposed to atmospheric oxygen. After two years of storage there is little change in the bacterial numbers at the surface, but less than one half the initial populations persist at depths below 50 cm (Williamson and Johnson 1991).

There is a little decrease in viable mycorrhizal inoculum potential during the first two years of storage (Miller et al. 1985). Viability of mycorrhizas in stored soils decreases considerably and possibly to the levels 1/10 those of the undisturbed soil (Rives et al. 1980). Miller et al. (1985) observes this as an indication that soil water potential is a significant factor affecting mycorrhizal viability. When soil water potential is less than −2 MPa (drier soil), mycorrhizal propagules can survive for greater lengths of storage time; when soil water potential is greater than −2 MPa, length of storage time becomes more important. In drier climates, deep stockpiles may not threaten mycorrhizal propagule survival. In wetter climates, shallow stockpiles are more important to maximize surface-to-volume ratios with regard to moisture evaporation.

5.11 Role of Fertilizers

All newly created mine soils, and many older ones, will require significant fertilizer applications for the establishment and maintenance of any plant community (Fig. 16).

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