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Recent Developments in the Reclamation of Surface Mined Lands

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Abstract: A broad review of mine land reclamation problems and challenges in arid lands is presented with special emphasis on work recently completed in India. The economics of mining in the Indian Desert is second only to agriculture in importance. Lands disturbed by mining, however, have only recently been the focus of reclamation attempts. Studies were made and results compiled of problems associated with germplasm selection, soil, plant and overburden characterization and manipulation, plant establishment methods utilized, soil amendment needs, use and conservation of available water and the evaluation of ecosystem sustainability. Emphasis is made of the need for multi-disciplinary approaches to mine land reclamation research and for the long-term monitoring of reclamation success.

Key words: Land reclamation, mined lands, overburden, revegetation, gypsum, limestone, lignite, wastelands, dryland silviculture.

Successful wasteland reclamation can be evaluated using two main criteria-stabilization of surface materials through appropriate geomorphic landscape reconstruction and the establishment of long-term sustainable vegetation communities. These criteria present unique challenges in arid environments not only because of low precipitation, high winds, and high evapotranspiration rates, but because lands being reclaimed in the Thar Desert region of India also must be returned to agricultural use. The latter usually means being subjected to intense grazing pressures. Therefore, not only must appropriate soils be found from available overburden, but soil amendments must be evaluated, rainwater harvesting techniques must be utilized, and plant germplasm must be screened and tested for their vigor, utility, and sustainability.

Reclamation studies in the Indian desert began with sand dune stabilization efforts and saline soil rehabilitation (Anon., 1986). It has only been within the last decade that attention has been given to the importance of reclaiming land disturbed by mining. For example, it is estimated that 12,525 ha of productive land has been abandoned following mining over the last 40 years in western Rajashtan alone (Balak Ram, Personal Communication). These lands, if left unattended, would remain unusable for centuries. Research in the U.S.A. and other countries began about 50 years ago and has focused on the selection, placement, and general management of coal overburden (Gough and Severson, 1995). Studies that examined the unique aspects of the reclamation of acidic, metal laden mine tailings have only recently received attention. It should be emphasized that hundreds of hectares of land presently used for agriculture will be "turned upside down" in Rajasthan within the next few years by new lignite surface mining efforts. If these lands are to be reclaimed in the future, pre-mining plans that involve topsoil evaluation and overburden characterization and selective placement must begin soon.

We report the results of four years of work in western Rajasthan at a gypsum and a limestone mine. These studies emphasize the importance of conducting post-mining soil and spoil inventories that both anticipate potential reclamation problems and help define possible long-term ecosystem stability. Particular emphasis is placed on understanding the characteristics of successful germplasm selection, in characterizing the physical and chemical properties of soil and overburden, in conserving and utilizing available moisture through rainwater harvesting, and in evaluating plant community sustainability.

Cover Soil and Overburden Concerns

Special considerations in arid environments

The successful reclamation of disturbed lands (including mined areas) in arid regions involves the application of principles from disciplines such as: range management, watershed management, the identification of constraints found in the harsh, arid climate of the tracts (i.e., infertile, shallow soils that directly affect the productivity of established vegetation), and the selection of suitable plant germplasm. Indian arid soils can be deep but are generally shallow with minimal profile development. Soil salinity is ever present and may range from only slight to severe.

Overburden excavation, characterization and placement

A limited resource for reclamation of mined lands is topsoil. Often the average soil depth is less than 15 cm on the upland areas. In the valley bottoms, the alluvium is relatively deep but only the surface few centimeters is biologically active. Topsoil may not be sufficient or readily available in a timely period for the capping of overburden to the necessary depth (McKell, 1978). Stockpiling topsoil is used, but this practice could have undesirable effects on soil biological activities. In addition, costs of stockpiling and massive topsoiling are also important considerations that must be carefully examined. Any cost-reducing methods in the use of topsoil will be valuable in overall cost projections. The research in progress involves mixing mine overburden materials to achieve a mixture of sand, silt and clay that resembles the desirable soil. The soil that results from this spoil mixture (cover soil) is being used for the re-establishment of trees, shrubs and various grass mixtures (Sharma *et al.*, 1996).

Pre-mining overburden characterization is required by all states in the arid and semi-arid western U.S.A. The objectives for overburden evaluations are to determine the chemical and physical characteristics of the materials, to estimate the vertical and lateral extent of unsuitable materials, and to develop appropriate mining and reclamation plans which will insure reclamation success of the post-mining root zone and aquifers. Critical to post-mining reclamation sustainability are the impacts on the quality of surface and groundwater resources and the quality of materials within the post-mining root zone (Boon *et al.*, 1987). In addition, trace elements can affect reclamation success. The elements of particular environmental concern in arid regions being mined include B, Mo, S, and Se (Gough and Severson, 1995).

Although the characteristics of soil and overburden are site specific, varying from mine to mine or within a mine, most overburden and spoils in the region of the coal mines in the Northern Great Plains (western U.S.A.) have certain common characteristics. For example, they are typically neutral or alkaline, contain appreciable $CaCO_3$, and contain variable quantities of soluble salts (Power *et al.*, 1978). They are almost universally deficient in plant available P and biologically active forms of organic N, but may contain appreciable amounts of inorganic N (Power *et al.*, 1974). Texture varies widely from location to location, ranging from clays to sands. Generally, bulk density of spoils is 10-30% lower than that of the original overburden. However, the pyritic sandstone, associated with uranium roll-front deposits, and reduced carbonaceous materials associated with coal deposits (such as is found in the Gas Hills region of Wyoming, U.S.A.), have the potential for producing toxic metal and/or acid conditions. These materials can potentially contribute water soluble toxic elements to the reclaimed ecosystem.

In reclamation planning at rock phosphate mines near Dehradun, India, Soni and Vasistha (1987) found overburden with the following characteristics: pH (7.0-7.3), P (P_2O_5: 0.5-3.8%) acid-base balance (14.2-76.0%) and heavy metals like Fe (Fe_2O_3: 1.6-2.8%) and Al (Al_2O_3: 2.5-3.8%). The overburden consisted of shale, limestone, chert and a fraction of topsoil (8-10%). The limestone mine spoil/debris in the Mussoorie Hills, India, was found to be a sandy loam, rich in Ca, alkaline in reaction, high in bulk density and low in water holding capacity and organic matter (Dadhwal *et al.*, 1989). The infiltration rates of mine spoils were found to be 1.5- to 2.1-times greater as compared to normal soil in an adjoining area.

Many of the problems encountered in reclamation can be solved by covering undesirable spoils with good soil material. Sandoval *et al.* (1973) found that a cover of as little as 5 cm of topsoil over spoils increases the infiltration rate several fold, absorbs raindrop impact, reduces surface sealing and runoff, decreases sediment production, increases the availability of beneficial micro-organisms and improves plant survival and growth. However, a minimum non-compacted thickness of 1 m is desirable to ensure long-term mine soil productivity for a variety of post-mining land uses (Sharma *et al.*, 1996). Shrub establishment increased substantially from the older graded spoils with no topsoil to the newer direct haul topsoiled areas (Pfannenstiel and Wendt, 1985). Natural shrub establishment is maximized when the topsoil resources are either direct hauled or stockpiled for less than one year, replaced by lifts, and hauled during moist soil conditions. Management practices such as minimized seedbed preparation and vegetation shredding prior to topsoil removal also promote higher shrub densities. Topsoiling also induces tree succession in reclaimed bauxite mine lands (Hussain, 1988). In recognition of the benefits of covering mine spoils with suitable soil material, legislation has been enacted in major mining countries requiring that suitable soil materials be saved and respread over graded spoils (Boon *et al.*, 1987).

Placement of topsoil in a narrow trench at the site of planting constitutes an effective but limited use of topsoil (McKell, 1978). As a necessary growing medium to receive the plants, the topsoil would provide an inoculum of soil micro-organisms, a partial source of native plant seeds and a buffer against high salt concentrations that might develop from below. The percolation of rainwater through the topsoil in the trench would keep the salinity levels around the root zone within the tolerance of the transplanted species.

Amendment use and engineering practices

Various types of mulching materials are used on replaced mine soils to help control erosion until plant growth is established. Many woody residues are the source of water soluble organic materials that percolate into the planting media and are readily utilized by soil micro-organisms. Cosz *et al.* (1978) mixed naturally occurring humus in mine spoils and thus increased the moisture-holding capacity and decreased the alkalinity so as to enhance the success of revegetation in New Mexico (U.S.A.) uranium mines. Sopper (1992) used municipal sludge for the reclamation of coal mine spoils which are acidic, droughty, and devoid of organic matter. Sludge has been shown to improve soil structure, water holding capacity, and bulk density in addition to adding N, P, K and other plant nutrients. The use of sludge as a spoil amendment eliminated the initial lag period that characterizes conventionally reclaimed sites, during which plant growth and microbial activity were at a low level. Sludge amendments quickly increased the numbers and activity of micro-organisms, whose activities enhanced the development of a soil environment conducive to continued plant growth. As in the U.S.A., fly ash, when used as a topsoil substitute, may provide a desirable alternative to conventional methods in the reclamation of abandoned mineland and coal refuse in India. Reclamation of minelands that contain acid spoil materials could be achieved by applying dry flue gas desulfurization (FGD) by-products from thermal power plants as an alkaline amendments (Stehouwer *et al.*, 1995). These by-products were effective in raising the pH of the spoil materials. Leachate pH, electrical conductivity, dissolved organic C, Ca, Mg and S tended to increase with increased FGD amendment, while Al, Fe, Mn and Zn decreased. Overall, with FGD amendments of 120 g kg^{-1} or less, leachate concentrations of most elements of environmental concern were less than drinking water standards. Moore et al. (1991) used gypsum and wood residue amendments to facilitate maximum plant growth through amelioration of non-topsoiled bentonite mine spoil sodicity. This was particularly effective for the growth of dominant seeded perennial grasses.

Mine Tailings and Drainage

Characterization

Mine tailings, defined here as any material being dumped that has been processed in some way by the mining operation, are almost universally deficient in N and P and are commonly deficient in K. In addition, secondary or micronutrient elements are sometimes deficient. Successful plant establishment is difficult to achieve because tailings are usually fine textured and easily eroded. In the western U.S.A., mine tailings are commonly pyritic and extremely acidic (pH 3.0). Without the mechanical regrading of steep tailings slopes, erosion progresses rapidly and results in the movement of acidic materials over nearby native, productive soils.

Mine drainage

Waters containing the highest metal concentrations have been collected from the base of tailings piles of Alaskan (U.S.A.) sulphide deposits (Gray and Sanzolone, 1996). These waters contain as much as 3600 ppb Cu, 3300 ppb Zn, 21000 ppb Fe, 220 ppb Pb, 10 ppb Cd, and 311 ppm sulphate and have pH values as low as 2.6. Mine drainage from a gold mine in Juneau (U.S.A.) that is well buffered by calcareous host rocks has a pH of 8 and concentrations of <0.05 ppb Ag, 0.6-2.7 ppb As, <0.2 ppb Cd, <2 ppb Cu, <100 ppb Fe, <0.2 ppb Pb, ppb Hg, 39 to 52 ppb Zn, and 230 to 340 ppm sulphate. Except for sulphate and Zn, these data are similar to those of background waters collected from unmineralized areas. In the Nuka Bay District (U.S.A.), a maximum concentration of 130 ppb As was measured in water immediately downstream from a tailings pile. The Alaska State drinking water quality standard for As is 50 ppb. Mine drainage from certain ore deposit types (e.g., chromite deposits in Alaska), however, can contain heavy metal concentrations well below drinking water standards.

Germplasm Selection-Principles for the Arid Regions

Germplasm selection is guided by the post-mining environmental setting. In general, arid soils have poorly structured profiles. Wetter regions in arid areas, and desert fringes, show some profile development. However, mining entails removal of this soil and quite often these soils are not stockpiled. Consequently, overburden material is often used as soil material. Loss of the true soil results in extreme impoverishment of microflora, alteration in bulk density, moisture holding capacity, infiltration rate, capillary fringe, as well as changes in pH, EC and micro-, macronutrient status. There is also a loss of the soil seed bank, both persistent and permanent plant types, thus making natural regeneration difficult to start and slow to progress. Further, this newly created substratum can become colonized by aggressive weeds whose propagules from adjoining areas can invade quickly. Since a large proportion of land in arid areas is perpetually degraded, overstocked and over utilized, these support communities are often dominated by hardy, aggressive annual and perennial weeds. Post mining areas face a dual risk of being both floristically depauperate as well as having normal succession severely impacted. The following are factors that affect revegetation success imposed by mining-induced alteration of the surface:

- Irregular configuration of the soil surface.
- Soil depth limitation-either too loose or too shallow.

- Soil textural limitations-loose gravelly with less loam and/or clay.
- Soil bulk density affecting aeration, compactness or looseness.
- Soil moisture holding capacity-often too low.
- Soil microflora-almost absent.
- Soil nutrients-both micro- and macronutrients are either limiting or in non-available forms.
- Soil seed bank-practically absent.
- Risk of unwanted invader species.
- Biotic disturbance in post rehabilitation regime is more often a rule than exception because of both domestic and wild animal grazing.

In view of the above limitations, the germplasm for reclamation of mine spoils should be such as to either adjust and adapt or overcome these conditions and limitations. Further, these species should also be able to adapt to the following natural climatic vagaries of arid areas:

- Erratic, irregular, and inadequate rainfall.
- Extremes of temperatures-up to 45-50°C in summer and 0°C in winter.
- High rates of moisture loss and consequently high evapotranspiration rates.
- High wind velocity.
- Droughts of varying intensity and periods.
- Frosts of varying intensity and periods.

According to McKell (1978), the ideal characteristics of germplasm for successful mine spoil reclamation should:

- Have a desired rooting habit (configuration).
- Serve as feed for livestock and/or wildlife.
- Be tolerant to utilization.
- Propagate easily.
- Establish successfully.
- Be compatible with other species.
- Should be able to provide quick vegetative cover using pioneer species.
- Should be able to promote the revival and growth of other desirable species (nurse species).
- Should be a succession facilitator species.
- Should possess strategic adaptations in its phenological cycle and morphology so as to be able to evade/adapt to critical periods of extremes of temperatures, drought and salinity.
- Should have a competitive edge over invaders.
- Should be reasonably resistant to pest and microbial infections.
- Should have minimum or no requirements for externally added fertilizers.
- Should have rapid seedling growth and seedling drought/frost tolerance.
- Should have an overall wide ecological amplitude in its lifecycle strategy.

In the light of the above limitations, and the requirement of plants for successful reclamation, plant germplasm should include both the indigenous and exotic species. The indigenous species that have evolved over millennia in these conditions are expected to have many, if not all, of the desired characteristics listed above. However, the Vavilovian principle (which states that sometimes species perform better in their secondary centre of diversity following introduction from a primary center of diversity) may mean that exotic species from similar edapho-climatic regions of the world could also be suitable reclamation material. These may include species introduced into an area long ago and which have become naturalized over the years. The other group of species may be newly introduced.

Establishment requirement

Plant establishment involves the following six phases:

Species selection: A judicious mix of native and exotic species is recommended for use in mine land rehabilitation. Exotic species have their problems, however, and may in time adversely affect community sustainability. Important criteria for selection of species should include their ready availability, water-use efficiency, utility as feed/fodder, and sustainability over time.

Procurement of seeds/propagules: It is desirable to collect the seeds of species to be used for rehabilitation from environments which are similar to that of the rehabilitation site. This facilitates better survival and growth and provides a competitive advantage over those seeds which come from an alien environment.

Raising of saplings/seedlings in the nursery: The direct sowing of seeds on the rehabilitation sites in dry areas should be avoided so as to minimise the mortality of seedlings. The germination phase is the most sensitive period in the entire rehabilitation scheme. In view of this, it is appropriate to raise saplings in the nursery and then transplant them at the site during the rainy season. Seed germination in the nursery requires knowledge of specific germination requirements. For example, many leguminous species require seed coat scarification involving boiling in water or treatment with sulfuric acid for varying durations. Stem cuttings also greatly benefit from treatments with rooting hormones.

Transportation to the site of planting: Though seemingly trivial, proper transportation of planting materials is important so as to reduce sapling mortality. Sufficiently mature saplings are required which can better withstand the shock of transport. Further, saplings need to be acclimatized in the new environment. Hence, the major pre-requisites for transportation are:

- Sufficiently mature saplings.
- Minimum transport time.
- Suitable period of time for on-site hardening.
- Upright arrangement of polypacks (plastic sapling sleeves within which they are grown).
- Immediate watering of saplings upon arrival at the site.
- Relatively dry soil in the polypacks at the time of transport.

Planting of saplings/seedlings: Our studies utilize the application of water at the time of planting. The planting schedule is adjusted to coincide with the monsoon rains; however, it is sometimes necessary to continue the application of water for certain drought-sensitive species, particularly if the monsoon rains are late or brief.

Chemical fertilizers are not used. Farm yard manure is commonly mixed with other soil amendments and it greatly enhances the seedling establishment success rate.

Post plantation operations: After plantation the saplings should be watered, at intervals, for a length of time necessary for the establishment. We have found that hoeing of the soil in the planting pits is also necessary in the first three months.

Measures of Success and Long-term Sustainability

Socio-economic

Efforts to revegetate disturbed areas and disposal sites in arid regions have generally met with failure because of the harsh environmental conditions and the lack of suitable technology. Nevertheless, present societal attitudes and legislation require that lands disturbed in the process of development be rehabilitated. In arid regions, harsh sites with limited precipitation present a challenge to revegetation. The philosophy expressed in the US National Environmental Policy Act (1969) declares a national commitment to the quality of the environment to be an objective concurrent with the regular mission of all federal agencies. The affected lands must be returned to usable and productive condition, which is compatible with existing adjacent undisturbed natural areas and which support biota of the same kind and in the same numbers as those existing at the time the baseline data were obtained. The National Academy of Science Study Committee (1975) on the rehabilitation potential of US western coal lands states:

> "... any decision to surface mine for coal in a particular area must include a strong commitment to rehabilitate the land concurrently ..."

Legislation should be enacted that will provide more flexibility in managing surface mined lands and other disturbed ecosystems (Cairns, 1983). This flexibility can only be justified if more systematic management options for coping with the ecological problems caused by mining activities are developed and supported by a broad scientific base. The four basic management options for surface mined land are: (a) restoration to original condition, (b) rehabilitation of some desirable characteristics, (c) development of alternative ecosystems that may be quite unlike the original but may be desirable for a variety of reasons, and (d) neglect (or natural, unaided reclamation) when evidence suggests that unaided natural processes will produce better results than human interventions. Creative use of research opportunities provided by the management options are of considerable academic benefit and ultimately of social and economic benefits.

Nutrient/energy flow

Surface mine spoils exhibit considerable variation due to a wide range of factors including geological formations, previous land use, reclamation procedures and plant species used to reclaim these areas. Soni *et al.* (1989) showed that in slightly acidic spoil material, vegetation helped increase soil pH and electrical conductivity. This in turn favours the release of nutrients and enhances microbial occurrence and abundance. K concentrations were found to decrease from 15%, in unreclaimed sites, to 12% in reclaimed sites in a period of five years. However, no significant change was observed in the Ca and Na ions. Alexander (1992) studied the effect of twenty years of *Eucalyptus camaldulensis* growth on tin-mine spoils in Nigeria. It was observed that as a result of additional input of organic matter from leaf fall, etc., the reclaimed topsoil had a significantly higher content of organic C, N and cation exchange capacity. Of most interest and concern was the decrease in base saturation from 39 to 22%. Similarly by planting *Faidherbia albida*, significant increases in organic C, N, Ca, Mg and base saturation were observed.

Community heterogeneity

In a rock phosphate mined reclamation site the floristic composition (plant diversity) increased significantly from the initial baseline level over a period of five years (Soni *et al.*, 1989). The number of plant species increased from 20 to 31, which is nearly equal to the adjoining undisturbed forest. During the same period the amount of litter also increased from 433 to 1025 kg ha^{-1} resulting in an increase of 21 % in soil nitrogen levels.

Soil development

In recent years, as reasons for observed reclamation successes or failures have been investigated, a greater number of studies have addressed the question of minesoil development, particularly management of the early developmental processes. Typically, soil development is a gradual process taking hundreds of years. While this is true for mature soils, relatively rapid chemical changes may be expected for unweathered overburden with little or no replaced topsoil or subsoil. In the arid western U.S.A. expected chemical changes can range from sodium accumulation in the rooting zone, to rapid development of acidity from oxidation of sulphide minerals (Gough and Severson, 1995). Although mine spoils can eventually recover 'soil' characteristics through intensive reclamation and management techniques, annual fertilizer additions are usually required for several years. Chichester and Hauser (1991) examined changes in the chemical properties of lignite minespoils developed under forage grass in Texas and found these changes to be strongly influenced by weathering processes. Incorporation of fertilized crop residues increased total C, N and P in the near-surface layers. Both pH and residual C increased in minespoils. Electrical conductivity increased with depth as salts leach from the surface soil. A detailed examination of both reclaimed and unreclaimed mine lands by Alexander (1992) demonstrated that successful agricultural activities could be established on tin mine spoil using inputs of both standard chemical fertilizers and a range of locally available organic manures including urban refuse. Thus, 'waste' tin mine land and 'waste' urban refuse have been brought together with animal 'waste' to produce agriculturally fertile soils.

Rehabilitation of Mined Wasteland in the Indian Desert - A Case Study

Surface mining is second only to agriculture in economic importance in India and is spread over about 700,000 ha (Soni and Vasistha, 1986). The direct effects of surface mining on the site include removal of vegetation, disturbance of the soil profile, and compaction. These effects may cause increased surface erosion and sedimentation, changes in surface water and groundwater chemistry, development of unusable wastelands, and reduced aesthetics at the site (Sidle and Brown, 1992). Additionally, mass wasting (landslide) hazards may exist on steeper slopes.

Surface mining of gypsum and limestone plays an important role in the economy of the Indian desert. Out of the estimated reserve of 1.08×10^9 t of gypsum in India, 970×10^6 t occurs in the desert; the annual production are 18.781×10^6 t. Gypsum is used in the manufacture of cement, fertiliser, plaster of Paris, pottery, sulphuric acid, building plaster, and in the reclamation of alkaline soils. The estimated limestone reserves in the country are 76.446×10^9 t and the annual production is 120.5×10^6 t. Limestone is used as a flux in iron-ore smelting, cement manufacturing, mortar and lime production, and for paving roads. However, the broad-scale open-cast mining of gypsum and limestone and the absence of environmental protection practices, have caused the destruction of land resources. Rehabilitation of such degraded sites is a challenging task in the arid regions due to the harsh environmental conditions and the lack of suitable technology.

The objective of this study is to produce an ecologically stable rehabilitated site. Stability is defined in terms of a diverse vegetative cover and an enhanced or favourable soil environment but without continued inputs of resources (such as water and fertilizer) and without the requirement of complete protection from animal use. This has been achieved through an optimum combination of rainwater harvesting, soil profile modification and the application of appropriate plant species. A silvipastoral system has been designed for rehabilitation of these mined wastelands. This system complements the needs of the local population which, prior to mining, was used largely as grazing land.

The gypsum mine is located at Kavas (25.5°N, 71.4°E) in northwest, arid India. The average annual rainfall is 265 mm; about 90% of which occurs as summer monsoon rainfall between June and September. The site has a mean daily maximum temperature of 35°C (the highest being 48.6°C) and a minimum temperature of 18°C. The gypsum is a sedimentary deposit which occurs in the area as a seam or bands intercalated with sand and silty materials and is of recent to sub-recent origin. The gypsum bed, overlain by thin sand cover, is generally flat and occurs at a relatively lower elevation compared to the surrounding area The limestone mine is located at Bilara (26.2°N, 73.5°E), also in the northwest, arid India. The average annual rainfall is 424 mm, generally occurring as summer monsoon rainfall. The study area has a mean daily maximum temperature of 33°C and a minimum temperature of 20°C. The limestone outcrops are of sedimentary origin and of Cambrian age.

A mine area rehabilitation plan makes logical and effective use of natural resources available in each area such as locally adapted plant species, precipitation, topsoil and topography. In addition, the revegetation system should be as cost-effective as possible (McKell, 1978; Sharma *et al.*, 1996). Following compaction (employed to stabilize the mine spoil and to reduce its permeability) the surface of the gypsum and limestone spoil material was shaped into terraces and

Table 1. Plant species used in the rehabilitation of mined wastelands, India

Life form	Indigenous		Naturalized	Exotic
	Leguminous	Non-leguminous	leguminous	leguminous
		Kavas (Gypsum)		
Tree	*Prosopis cineraria*	*Tamarix aphylla*	*Pithecelobium dulce*	
		Salvadora oleoides	*Acacia tortilis*	
		Salvadora persica	*Acacia famesiana*	
		Azadirachta indica	*Acacia senegal*	
		Tecomella undulata	*Parkinsonia aculiata*	
		Holoptelia integrifolia		
Shrub	*Mimosa hamata*	*Ziziphus nummularia*	*Prosopis juliflora*	*Acacia nubica*
		Capparis decidus	*Dichrostachys mutan*	*Cercidium floridum*
			Ceasalpinnia coraria	*Cassia strutii*
Grass		*Cenchrus ciliaris*		*Colophospermum mopane*
		Cymbopogon jwarancusa		
		Bilara (Limestone)		
Tree	*Acacia catechu*	*Azadirachta indica*	*Bauhinia racemosa*	
	Acacia planifrons	*Salvadora oleoides*	*Pithecellobium dulce*	
		Holoptelia integrifolia	*Acacia senegal*	
			Acacia tortilis	
			Albizia amara	
Shrub		*Maytenus emarginata*	*Maytenus emarginata*	*Cercidium floridum*
		Commiphora wightii		*Dichrostachys mutan*
		Ziziphus nummularia		
		Grewia tenax		
Grass		*Cenchrus ciliaris*		
		Cymbopogon jwarancusa		

slopes providing a catchment for harvesting precipitation and a terrace for receiving transplanted seedlings. The rainwater harvesting techniques were designated as micro-catchment, ridge and furrow, half-moon terraces and inward sloping bench terraces. These were replicated four times in a randomised block design.

In addition to water, another limiting resource of these mined wastelands is topsoil. The soil survey of tracts indicates that the average soil depth is less than 15 cm. Because of cost and low success in recoverability, topsoil stockpiling was not used. Transplanting of container-grown native plants directly into favorable spoil material was done in auger holes that were 15 cm in diameter and 1 m in depth (Table 1). The container-grown plants gave better results than either direct seeding or bare-root seedling transplants. Necessary soil amendments were added to the auger holes and consisted of a mixture of fine sand, topsoil, farm-yard manure and bentonitic clay. It was expected that the percolation of harvested rainwater from the catchment slopes into the auger holes would keep the root zone moisture to an optimum level for growth of the transplanted native species. Monthly supplemental irrigation was applied as an added safeguard during extended drought periods in the early two years of the study. The study was initiated during 1992 in 16 ha area of gypsum mined wasteland and in 10 ha area of limestone mined wasteland. The study area was fenced with a live *Prosopis juliflora* hedge.

During the study period (1992-1995), the annual rainfall at Kavas varied between 300 and 481 mm in 12 to 46 rainy days as compared to 283 to 583 mm in 25 to 39 rainy days at Bilara; 81 to 98% of precipitation was received as summer monsoon rainfall during June-September. Typical of the desert climate, the rainfall occurred with relatively high intensity and extreme variability both from year to year and within each rainy season.

Striking differences were found at Kavas between topsoil and gypsum mine spoil: pH varied only from 7.8 to 7.9; however, electrical conductivity of mine spoil was 1.79-2.21 dS m^{-1} as compared to 0.20 dS m^{-1} of topsoil. Higher water holding capacity (28.0-32.5%), moisture equivalent (6.1-9.8%) and silt plus clay content (12.1%) was found for mine spoil as compared to topsoil (25.0-28.0%, 3.1-4.0% and 6.6%, respectively). The mine spoils were extremely low in organic carbon (0.09-0.14%).

The chemical analysis of mine spoil and topsoil at both the sites indicated an adequate total concentration of a number of elements such as Na, K, Ca, Mg, Fe, Mn and B (Table 2). Calcium is dominant over Mg in all the samples. Limestone mine spoil and topsoil of gypsum mines contained the highest amount of total Ca. Gypsum mine spoil and topsoil of limestone mines showed the greatest Mn levels. In general, the gypsum and limestone mine spoils are deficient in P (0.01-0.06%), Mo (<2.00 ppm) and Se (0.10-0.17 ppm). These sites are not deficient in Cu, Zn and Co. The topsoil and mine spoils show exceptionally high B content, and a potential for phytotoxicity in the growing medium exists.

Soil moisture storage was recorded every month, using a neutron moisture probe, at both the study areas, up to 1 m in depth at 20 cm increments. In the gypsum mined area, among various rainwater harvesting treatments, on an average the micro-catchment recorded the highest soil moisture storage (4.6%) followed by the half-moon terraces (4.4 %), ridge and furrow (4.2%) and planted control (4.2%). This is in contrast to 2.9% moisture recorded in the unmined area. However, throughout the year, the highest soil moisture storage occurred in the unplanted control sites (6.5%) as there were no plants to utilize this moisture. Among the rainwater harvesting treatments, no significant difference was observed in the soil moisture values. In the unsaturated phase the moisture move-

Table 2. A comparison of mine spoil and topsoil chemical parameters

Element	Gypsum mine		Limestone mine	
	Mine spoil	Topsoil	Mine spoil	Topsoil
Na (%)	1.40	0.58	0.21	0.69
K (%)	1.16	0.59	0.38	1.19
Ca (%)	6.5	16.2	23.0	7.8
Mg (%)	0.86	1.73	5.00	0.79
P (%)	0.05	0.04	0.01	0.03
Al (%)	4.57	2.32	1.50	4.30
Fe (%)	1.72	0.96	0.74	1.90
Mn (ppm)	437	350	130	433
Zn (ppm)	22.4	18.0	10.0	30.0
Cu (ppm)	7.33	7.75	4.00	13.0
Mo (ppm)	<2.00	<2.00	<2.00	<2.00
Co (ppm)	7.11	5.75	5.00	8.70
B (ppm)	53	51	20	53
Li (ppm)	15.7	30.8	10.0	18.7
Cd (ppm)	<2.00	<2.00	<2.00	<2.00
Cr (ppm)	39	26	21	62
Se (ppm)	<0.10	<0.10	0.10	0.17

ment in mine spoils was slow (0.02% day^{-1}) due to an extremely dense and impeded soil profile.

Throughout the year in the limestone mined area, the middle of the mine spoil mound recorded significantly higher soil moisture storage (8.1%) than the top (4.9%) and base (4.2 %) of the mound. On an average the 'tear-drop' rainwater harvesting configuration recorded 4.4% moisture. The higher soil moisture at the middle of mound resulted in significantly better plant growth at that site as compared to any other location (Table 3). However, limestone outcrops showed a higher soil moisture storage (6.4%).

Over a period of three year's time, a slight increase in the electrical conductivity

Table 3. Growth of Acacia senegal in relation to soil moisture storage (1995)

	Top of spoil mound	Middle of spoil mound
Mean soil moisture storage (% volume)	4.9	8.1
Plant character (mean)		
Cover (m^2)	8.9	10.0
Height (m)	2.4	2.7
Branch length (m)	22.8	23.4
Collar girth (cm)	5.3	7.5

of mine spoil was observed (a range of 2.1-2.5 dS m^{-1} from 0.8-1.87 dS m^{-1}). However, no significant difference in pH was found-values fluctuated around 7.8. Organic C showed a steady increase from 0.02-0.05% to 0.06-0.18% due to decomposition of farmyard manure. This increase was greater under the micro-catchment and half-moon terraces (0.15-0.18%) than under the ridge and furrow system (0.06-0.08%). Similarly, the available P in mine spoils increased from 5-8 kg ha^{-1} to 7-11 kg ha^{-1}, over a period of three years.

Based on the growth performance recorded in terms of plant cover, plant height, number of branches, branch length and collar girth, the four best performing plant species were identified at each site. In the gypsum mined area *Cercidium floridum, Tamarix aphylla, Salvadora persica,* and *Pithecellobium dulce* were superior in terms of mean annual incremental height, branch spread, relative number of branches, and collar girth. Micro-catchment and half-moon rainwater harvesting techniques performed equally well, in terms of plant growth, as compared to the control.

In the limestone mined area, *Acacia planifrons, Acacia senegal, Cercidium floridum,* and *Dichrostachys nutans* performed better in terms of the growth parameters. *Acacia senegal* gained a maximum height of 1.51 m in a period of three years. *Cercidium floridum* exhibited the highest relative growth (24.3%) followed by the *Acacia senegal* (18.3%).

Rehabilitation of mined wastelands in dry areas is a difficult and time consuming exercise. It involves the development of technology, field testing of methods, and a reliance on good pilot studies. Since the growth of plant species is slow in arid zones due to adverse climatic and edaphic factors and competition for water and nutrients it takes five to six years to develop a reasonable plant canopy. Therefore, at this time, no significant difference could be observed in plant growth among various rainwater harvesting techniques. This study has not only developed methods of mined wasteland rehabilitation but also has helped in the understanding of the processes that affect that rehabilitation. The results achieved so far are promising for the successful rehabilitation of degraded lands and the establishment of sustainable plant communities.

Future Challenges and Research Directions

Detailed elemental analysis of reclaimed vegetation may be appropriate in the future. This is because vegetation, utilized by humans and grazing animals, may reflect the elevated element levels commonly found in active and abandoned uranium, coal, and hard-rock mines. The phenomenon of minespoil weathering results in the release of available forms of trace elements; grasses and forbs can act as accumulator species for these elements. Because of work by such authors as Smith and Boon (1985), who found that plant analyses reflect spoil chemistry (correlations were strong between Se, Mo, B, etc. and specific geological materials), this type of study may be important in our work. In addition, work needs to be done for a broader range of revegetation species in developing standard plant washing techniques, in estimating appropriate sampling times, and in assessing appropriate plant parts to be sampled.

There are major uncertainties with our knowledge of mined land reclamation, especially in arid zones. An interdisciplinary effort is needed to further define the chemistry of overburden, the methodologies necessary for identifying and mapping unsuitable overburden, and the amount of mixing that should be accomplished during normal mining operations. Further, as Boon *et al.* (1987) emphasize, regraded spoil sampling intensities need further study, as well as methodologies for predicting spoil water quality, the most appropriate placement of unsuitable materials in relation to the post-mining groundwater quality.

Ghosh and Ghosh (1990) proposed to utilize the abandoned coal quarries for storing municipal and industrial refuse, which is expected to increase greatly in the near future. However, the risk of contaminating groundwater resources by the liquid effluents needs to be examined in greater details.

Ellsworth (1991) has successfully applied computer video-imaging for pre-disturbance planning and post-disturbance rehabilitation evaluation of mineland reclamation. The technology has great potential for broad-scale application in disturbed land rehabilitation.

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