EFFECTS OF TIME ON THE REVEGETATION OF COPPER MINE WASTES

by

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APPROVAL BY THESIS DIRECTOR

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ABSTRACT

Research was conducted at Cyprus Pima Mining Company, Tucson, Arizona, to evaluate revegetation work begun on mining waste sites in 1970.

Slope exposure was a major factor in shrub survival. Four shrubs—fourwing saltbush (*Atriplex canescens* [Pursh.] Nutt.), desert broom (*Baccharis sarothroides* Gray), creosote (*Larrea tridentata* [DC.] Cov.), and Arizona rosewood (*Vaquelinta californica* [Torr.] Sarg.) grew on the north slope but did not survive on the east slope. Differences between tailing and overburden on the north slope did not affect plant survival and growth.

Four tree species—palo verde (*Cercidium microphyllum* [Torr.] Rose & Johnston), tiny capsule eucalyptus (*Eucalyptus microtheca* Muell.), red gum eucalyptus (*Eucalyptus rostrata* Schléchtend.), and velvet mesquite (*Prosopis juliflora* [Swartz.] DC.) grew on the north and east slopes. White thorn acacia (*Acacia constricta* Benth.), silver dollar eucalyptus (*Eucalyptus polyanthemos* Schauer), and desert tobacco (*Nicotiana glauca* Grah.) grew only on the north exposure. Slope exposure did not affect tree size, except for tiny capsule eucalyptus which grew larger on the north slope.

Plant survival and growth were influenced by slope exposure; however, when adequate water and fertilizer were provided, plants were equally successful in both tailing and in overburden soil material.
INTRODUCTION

Open pit mining generates a tremendous amount of waste material which poses air, water, and environmental pollution problems. Pollution control has become an important consideration for mining companies in the United States. Revegetation of mining wastes controls pollution by stabilizing the waste material. Revegetation also improves the appearance of an area containing mining wastes and increases the land value. It is difficult to measure the value of improving the appearance of a disturbed area; however, such improvements have definite social and economic values.

Establishing plant growth quickly on mining wastes is rewarding to the mining company and pleases the general public. The revegetation project at Cyprus Pima Mining Company was far-sighted because it included opportunities for both immediate and long-term success. The endeavor required time, careful planning, and initially, considerable monetary investment. The goal of this revegetation project was to stabilize the mining waste material and establish permanent and self-sustaining plant growth on all disturbed land areas.
LITERATURE REVIEW

Surface mining disturbs the land surface and replaces soil that took thousands of years to develop, with barren and often toxic substitutes. Air and water pollution, loss of wildlife habitats, and impairment of natural beauty are problems caused by waste material produced during surface mining (Cave, 1978). Whitt (1970) stated that much of the 3.6 million hectares of land in the United States that have been disturbed by mining could be stabilized and restored to productive areas such as range and pasture land, cropland, recreational areas, and industrial developments. The U. S. Soil Conservation Service estimated that only one-third of the total acreage disturbed by surface mining has been adequately reclaimed either by natural forces or by man's own efforts (Banfield, 1973).

According to Bennett (1977), mineral recovery is higher from surface mining than from underground mining. In addition, output per workday is greater, operating costs are often lower, and miner safety is greater than for underground mining. The copper industry is the largest generator of solid waste products, which average 375 tons of waste per ton of copper produced (Banfield, 1973).

The initial objective of a reclamation project is to stabilize the land to prevent erosion (Powell and Barnhisel, 1977). The ultimate objective of a reclamation project, according to Ralston and Wiram (1978), is to return the disturbed area to a level of productivity equal to or greater than that which existed before mining. McCormack
(1977) stated that whenever the opportunity exists to restore the productive capacity of a disturbed area, there is both an economic and a moral obligation to do so. LeRoy and Keller (1972) reported that the purpose of reclamation was to establish a vegetative cover which was permanent, self-sustaining, and maintenance-free. An environment suitable for sustained vegetative growth can be established if land stability, soil fertility, and water supply are considered (Gilley et al., 1976).

New practices that require a change in mining methods or equipment are slow and difficult to implement because surface mining operations are very extensive (Power, Sandoval, and Ries, 1977). Attempts to reduce environmental effects of surface mining result in higher production costs which are sometimes hard to justify because the aesthetic value of a particular landscape is the most difficult parameter to measure in economic terms (Sweeney, 1979). Mining companies are in business to make a profit, however, mining companies have moral obligations to reduce the undesirable effects of surface mining (Cave, 1978).

**Mining Wastes**

Open-pit mining wastes consist of two kinds of material, overburden and tailing. Overburden is the non-ore material located above a mineral deposit that must be removed in order to mine the mineral (Grandt, 1974). Overburden is usually a heterogeneous mixture of rock fragments, rock particles, and soil-sized particles (Cave, 1978). Tailing is the waste material from the mineral ore concentration process which leaves the concentrator as a liquid slurry and is discharged via
tailing pipes into a tailing pond (Ludeke, 1973). Tailing from discharge pipes is fairly homogeneous but is deposited in different areas according to density, porosity, texture, and water content (LeRoy and Keller, 1972). Dry tailing is the texture of fine sand and is sterile, unaesthetic, a source of air and water pollution, and subject to erosion (Day, Ludeke, and Tucker, 1977). Tailing is highly porous and cannot retain water for long periods of time (Gilley et al., 1976). However, according to LeRoy and Keller (1972), with proper conditioning and management, tailing can be transformed into a soil. Mill wastes are usually deficient in plant nutrients, contain excessive salts and heavy metal phytotoxicants, and lack normal microbial populations (Dean, Havens, and Valdez, 1971).

Successful revegetation depends to a large extent on the chemical and physical traits of spoils that occur in the plant rooting zone (Jones, Armiger, and Bennett, 1975). The availability of mineral elements essential to plant growth varies considerably in overburden, since the strata of the overburden becomes randomly mixed during mining and results in areas of varying chemical composition (Grandt, 1978). According to Ludeke (1973), mine waste material contained no organic matter, no microflora, and no nitrogen detectable by chemical analysis. Copper mine tailing required the addition of varying amounts of nitrogen and phosphorus for successful revegetation (Ludeke et al., 1974). Spoil materials are usually lacking in biologically active organic nitrogen materials (Power et al., 1977).

Mine wastes are frequently saline or sodic. Saline soils contain excessive amounts of water-soluble salts and can be treated by
leaching salts out of the spoils, reducing evaporation, applying soil amendments, and revegetating with salt-tolerant plants (Barth, 1976). Soil particles, primarily clays, have negative charges and can attract positively charged ions, such as sodium, calcium, and magnesium. If 15% or more of the ions attracted to a soil particle are sodium, the soil is considered sodic (Barth, 1976). Soils with a pH of 8.5 or greater often contain sodium in large enough concentrations to cause dispersion (Gee and Bauer, 1976). The dispersed nature of sodic soils decreases the rate of water infiltration and creates other conditions detrimental to plant growth. Sodic spoils may be made nonsodic by applying amendments such as calcium which result in the formation of soluble salts that may be leached from the profile (Barth, 1976).

Cundell (1977) stated that soil microorganisms have an important role in the reclamation of mine wastes, especially in the creation of soil organic matter, improvements of soil texture, and the accumulation of nitrogen for plant growth. During the plant succession from bare spoil to climax community, which is reflected in the populations of soil microorganisms present, soil formation occurs simultaneously with increases in soil organic matter and minerals (Cundell, 1977).

**Stabilization**

Mining wastes can be stabilized by physical or chemical means, revegetation, or a combination of these methods (Dean et al., 1971). Dean et al. stated that physical stabilization includes using crushed smelter slag, harrowing straw into the soil, using wind breaks, or a combination of these methods. Chemical stabilization involves applying
a reagent to the waste which causes an air and water resistant crust (Dean et al., 1971).

The establishment of vegetation on newly-graded mine waste slopes is the most economical method of controlling erosion and providing stabilization (Day and Ludeke, 1978). Natural revegetation is a very slow process on a strip-mined area because native vegetation may not be compatible with the environment and the surrounding vegetation may be of the climax type and pioneer species may not be present (Cave, 1978).

**Overburden Placement**

Planned placement of overburden maximizes the stability of mine wastes and minimizes environmental damage (Plass, 1978). Evaluating the physical and chemical characteristics of the overburden prior to mining helps determine the methods of selective placement and equipment needs (Ralston and Wiram, 1978). Properly reconstructed soil can be stabilized quickly with useful vegetation, thus reducing erosion and sediment production and eliminating the need for repeated seedings (McCormack, 1977).

Seedbed preparation by the recontouring of mine wastes is the first step in the revegetation process and is essential because reclaimed soil has no structure and tends to puddle and crust on the surface (Verma and Thames, 1975). Researchers have noted that compaction and grading of coal spoils are factors contributing to poor seedling establishment and growth (Shetron and Carroll, 1977).
Grading of spoils is done to achieve a pleasing appearance and control pollution; however, grading to form long slopes causes erosion and siltation problems (Grandt, 1974). Grading serves as a method of physical weathering by breaking the strata and exposing the soil surfaces to further natural weathering (Grandt, 1978). Smoothly-graded spoils are often impervious to water infiltration and conducive to runoff (Powell and Barnhisel, 1977).

According to Ralston and Wiram (1978), the inevitable compaction of soil materials, particularly clay subsoil, when placed by scrapers, may cause severe internal drainage problems which are undesirable for the plant root zone. Powell and Barnhisel (1977) stated that several steps may be taken to minimize the adverse effects of grading: (1) land should be graded on the contour in a forward direction and not back bladed, (2) final grading should not be performed when the spoils are wet or saturated, (3) final grading should be performed just prior to the seeding operation.

**Capping**

Many of the problems encountered in reclamation can be solved by covering undesirable spoils with good soil material, which increases infiltration rate, reduces runoff, and improves plant survival and growth (Power et al., 1977). Plant growth and yield increased as depth of soil material increased to about 70 cm thickness. Greater depths resulted in no further yield increase (Power, Ries, and Sandoval, 1976).
Plant Selection

In order to select the plant species best adapted for the climatic conditions and the specific soil materials being rehabilitated, many different plant species should be considered (LeRoy and Keller, 1972). Dean et al. (1971) stated that vegetative stabilization should produce a self-perpetuating plant cover or provide material in which native plant seeds can germinate and regenerate a plant community. Species selection is determined by the chemical and physical properties of the mine soil and by the geographic location, elevation, season of seeding, compatibility with woody vegetation, topographic exposure, and land use objectives (Plass, 1978).

According to LeRoy and Keller (1972), a good grass and legume mixture will develop a dense underground netting of roots which will consolidate the tailing and reduce erosion. To obtain stability and protection against erosion by reducing runoff impact, a quick growing ground cover of herbaceous grass species should be established early in the reclamation program (Cave, 1978). Lyle and Evans (1979) reported that perennial grasses and legumes are usually slow to produce an adequate soil cover and should be planted in combination with a quickly establishing annual. dePuit and Coenenburg (1979) found that various vigorous, adapted, introduced plant species tended to competitively inhibit native plant species which were seeded at the same time. Complexities of the previous ecosystem, low seedling vigor of native species, and a lack of seed sources make the establishment of native vegetation that existed before mining difficult to achieve (Barker, Ries, and Nyren, 1977). Tree and shrub species do not protect the
surface initially and should not be planted until herbaceous cover has been established (Shetron and Carroll, 1977). According to Murray and Moffett (1977), a mixture of plant species for revegetation provides some insurance against crop failure due to disease.

**Seeding Method**

Broadcast seeding and drill seeding are two methods of seeding used to revegetate mine wastes. Aldon (1978) reported that drilling, a method which places the seed at the proper depth and controls the seeding rate, is the most common method of planting in revegetation. Powell and Barnhisel (1977) considered drill seeding the most effective and most economical method of planting. Broadcast seeding places seeds at variable depths and allows for more diversity in planting (dePuit and Coenenburg, 1979). Broadcast seeding can be done by hydroseeding, a process in which seed, fertilizer, mulch, and other amendments are added to a large water tank, agitated, and discharged through a nozzle (Plass, 1978). dePuit and Coenenburg (1979) found that larger-seeded species of perennial grasses established better under drill seeding, but smaller-seeded species of perennials had higher germination with broadcast seeding. This relationship suggests that the drill seeding method may be beneficial to large-seeded species which require a deeper seed placement but detrimental to smaller-seeded species which require shallower placement (dePuit and Coenenburg, 1979). dePuit and Coenenburg concluded that if the establishment of a diverse plant community is a major reclamation goal, broadcast seeding with proper seedbed conditioning may be superior to drill seeding.
Mulch

Aldon (1978) found that using straw as a mulch aided in the establishment of perennials by lowering mid-afternoon temperatures in the top 3 cm of soil during the period when seeds germinated and seedlings emerged. Bennett (1977) stated that mulches of pulp, fiber, grain straw, sawdust, or wood chips helped conserve soil moisture during the critical seedling establishment period. The introduction of straw or other forms of organic matter was essential to the establishment of plants on copper mine tailing berms (Ludeke, 1973). Incorporating barley straw into copper mine tailing increased the organic matter content and improved the water holding capacity of the tailing (Ludeke et al., 1974). Surface mulching helped control water erosion in mine waste slopes that are difficult to revegetate due to steepness, low moisture availability, and slope exposure (Shetron and Carroll, 1977). Sinha (1975) stated that the residual effect of straw favored the accumulation of humus, which stimulated rooting, and augmented the availability of phosphates in the soil. According to Wittwer, Graves, and Carpenter (1979), survival and growth of seeded plant species can be significantly improved by using bark mulch. Fast-growing plant species such as small grains or summer annuals served as an initial ground cover, minimized erosion, and could be chemically killed and used as an in situ mulch for the seeding of perennials and legumes (Jones et al., 1975). Day et al. (1977) found that barley could be used effectively to stabilize copper mine wastes and could be incorporated into the soil surface to provide a more suitable medium for the establishment of perennial grass species.
The objectives of the research reported in this report were:
(1) to determine which plant species would survive in mining waste material over a period of years, (2) to determine which plant species would grow best and reproduce most over a period of years, (3) to determine whether tailing or overburden was more suitable for plant survival and growth, and (4) to determine whether a north or east slope exposure was more conducive to plant survival and growth.
MATERIALS AND METHODS

Studies were conducted at Cyprus Pima Mining Company in 1979 and 1980 to study the stabilization of copper mine wastes with grasses, shrubs, and trees. Four revegetated areas: (1) tailings, north exposure; (2) tailings, east exposure; (3) overburden, north exposure; and (4) overburden, east exposure were compared with four unplanted areas of the same waste material and same slope exposure. The unplanted areas were considered the controls. The experimental design was a split plot with slope exposure as main plots and soil materials as sub-plots with four replications. The individual plot size was 30.5 m² (10,000 ft²).

The revegetated areas chosen for this study were located on tailing ponds No. 3 and No. 4. The initial revegetation work was begun on these sites in 1970. Prior to seeding, several steps were taken to prepare the seedbed. First, a road patrol caterpillar was used to blade tailing material over the side of the tailing berm and onto the slope to fill the crevices caused by erosion of the slopes. A spike-tooth chain or "sidewinder" was used to drag the slope surface. The sidewinder removed larger rocks, filled in erosion crevices, and scarified the surface to produce a loose seedbed on the 1.5:1 berm slopes. A caterpillar scraper was then used to cap the tailing with 9 cm (6 in) of top soil. A 9 cm (6 in) soil retaining wall was constructed at the edge of the tailing slope to insure against surface erosion from service roads. This wall also prevented water from leaking irrigation equipment.
from flowing down the face of the tailing slope and causing erosion crevices.

Barley straw was applied to the mine waste slopes at a rate of 11.2 metric t/ha (5 t/acre) using a strawblower. Next, a "sheepfoot roller" was used to incorporate the straw into the top 15-20 cm (6-8 inches) of the tailing pond slopes. A sheepfoot roller is a five-ton highway compactor with many small steel pods attached to the roller drum. The drum is filled with water and applies an equal amount of pressure over the surface of the protruding feet.

The slopes were hydroteeded for the first time in November, 1970. Two annual grasses: (1) 'Arivat' barley (Hordeum vulgare L.) and (2) winter ryegrass (Lolium temulentum [L.] Darnel) were planted at the rate of 112 kg/ha (100 lb/acre) per plant species. The hydroteeding mixture also contained 2,240 kg/ha (2,000 lb/acre) of aspen wood fiber, 1,000 gallons of water, and 168 kg/ha (150 lb/acre) of 16-20-10 fertilizer.

Sprinkler irrigation lines were installed along the service roads at the top of the mine waste slopes. Slopes were irrigated regularly throughout the growing season. The application of fertilizer three or four times throughout the growing season was necessary to develop the desired self-sustaining vegetative ground cover. The initial fertilizer treatment was applied in the hydroteeding mixture. Additional liquid fertilizer was injected into the irrigation lines periodically throughout the growing season.

At the point in the growing season when barley and rye contained the greatest amount of organic matter, they were incorporated into the
soil using a sheepfoot roller. These cultural practices provided organic matter, increased the water-holding capacity of the soil, and decreased erosion. Sudangrass (Sorghum sudanense [Piper] Stapf.) and Milo-maize (Sorghum vulgare Pers.) were hydroseeded in April, 1971, at the rate of 112 kg/ha (100 lb/acre) per plant species. These grasses were also incorporated into the soil when they had reached maximum growth.

The next step in the revegetation process was to plant perennial grasses. Weeping lovegrass (Eragrostis curvula [Schrad.] Nees.), Johnsongrass (Sorghum halapense [L.] Pers.), Buffel grass (Pennisetum ciliare [L.] Link), Lehman's lovegrass (Eragrostis lehmanniana Nees.), giant bermudagrass (Cynodon dactylon [L.] Pers.), and perennial ryegrass (Lolium perenne L.) were perennials that were hydroseeded in 1972.

After perennial grasses were established, seedlings of shrubs were planted randomly on tailing ponds No. 3 and No. 4 at the rate of 15 seedlings per 30.5 m² (10,000 ft²). The following species of shrubs were planted:

1. Hopbush (Dodonea viscosa [L.] Jacq.)
2. Desert broom (Baccharis sarothroides Gray)
3. Fourwing saltbush (Atriplex canescens [Pursh.] Nutt.)
4. Quailbush (Atriplex lentiformis [Torr.] Wats.)
5. Creosote bush (Larrea tridentata [DC.] Cov.)
6. Catclaw (Acacia greggii Gray)
7. Arizona rosewood (Vaquelima californica [Torr.] Sarg.)
Once the shrubs were established, tree seedlings were planted randomly on tailing ponds No. 3 and No. 4 at the rate of 20 seedlings per 30.5 m$^2$ (10,000 ft$^2$). The following tree species were planted:

1. Red gum (*Eucalyptus rostrata* Schlechtend.)
2. Tiny capsule (*Eucalyptus microtheca* Muell.)
3. Silver dollar gum (*Eucalyptus polyanthemos* Schauer)
4. Australian pine (*Pinus australis* Michx. f.)
5. Black walnut (*Juglans nigra* L.)
6. White thorn acacia (*Acacia constricta* Benth.)
7. Velvet mesquite (*Prosopis juliflora* Swartz. DC.)
8. Palo verde (*Cercidium microphyllum* [Torr.] Rose & Johnston)
9. Desert willow (*Chilopsis linearis* [Cav.] Sweet)
10. Desert tobacco (*Nicotiana glauca* Grah.)

An evaluation of the revegetation work at Cyprus Pima Mining Company was begun in 1979. Tailing pond Nos. 1, 3, 4, and 6 were selected as study sites. North and east exposures were studied according to the following treatments.

1. Tailing control, north exposure (pond No. 6)
2. Tailing planted, north exposure (pond No. 4).
3. Tailing control, east exposure (pond No. 6)
4. Tailing planted, east exposure (pond No. 4)
5. Overburden control, north exposure (pond No. 1)
6. Overburden planted, north exposure (pond No. 3)
7. Overburden control, east exposure (pond No. 1)
8. Overburden planted, east exposure (pond No. 4)
The following data were collected for each treatment:

1. Number of plant species
2. Number of each plant species
3. Average height of each plant species
4. Average diameter of cover of each plant species
5. Per cent ground cover

Number of plant species and number of each plant species were obtained by counting the plants in each of the four replications for each treatment and the total for each treatment. Average plant size was determined by measuring height and diameter of foliage of a representative sample of each species and then averaging these measurements. Per cent ground cover was obtained by visual evaluation.

All data were analyzed using the standard analysis of variance and means were compared using the Student-Newman-Keuls' test as described by Little and Hills (1978).
RESULTS AND DISCUSSION

Per Cent Ground Cover

Unplanted tailing soil material for both north and east slope exposures and on the control areas was completely void of plant growth (Figure 1). Unplanted overburden—north—and unplanted overburden—east—had 5 and 15% ground cover, respectively. Only one plant species—burro weed (Haplopappus tenuisectus [Green] Blake)—grew on the overburden control areas. The north slope exposures for planted-tailing and planted-overburden had the greatest amount of ground cover with 85 and 80%, respectively. The planted east slopes had 65% ground cover for tailing and 60% ground cover for overburden (Figures 2 and 3).

Survival

Shrubs grew well on the north slope in both tailing and overburden (Table 1). However, the shrubs did not survive on the east slope, regardless of soil material. As a group, trees grew better on the north slope than on the east slope and were more numerous in tailing than in overburden.

The east slope supported significantly more annuals than the north slope. This difference may probably be attributed more to slope location than to slope exposure. Seeds of desert annuals are dispersed on the mine waste material by wind, water, insects, birds, and other animals. The north slope is adjacent to the mine access road and the
Figure 1. Per cent ground cover for two soil materials on two slope exposures of planted and unplanted mine wastes.
Figure 2. Pure tailing from the milling of copper ore.
Figure 3. Revegetated tailing 10 years after reclamation work was begun.
Table 1. Average number of plants in 244 m² for three plant types, two soil materials, and two slope exposures seven years after planting at Cyprus Pima Mining Company, Tucson, Arizona in 1979.

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⁺Means followed by the same capital letter, for the same plant type and between slope exposures, are not different at the 5% level of significance (Student-Newman-Keuls' Test).

⁺⁺Means followed by the same lower case letter, for the same plant type, within the same slope exposure and between soil materials, are not different at the 5% level of significance (Student-Newman-Keuls' Test).
east slope adjoins the desert floor. The east slope is more available for seed distribution than the north slope.

**Shrub Survival**

Seven species of shrub seedlings were planted in 1972 and two of these had 100% mortality—catclaw and quailbush (Table 2). The high number of desert broom shrubs present indicates that the environment was suitable for prolific reproduction of this species. With the exception of one hopbush growing in tailing, no shrubs grew on the east exposure. All shrubs grew equally well in both tailing and overburden on the north slope.

**Tree Survival**

Tree seedlings were planted in 1972 and 1973 after the mine waste slopes had been stabilized with grasses. Of the 11 tree species planted, three had 100% mortality—desert willow, black walnut, and Australian pine (Table 3). Tiny capsule eucalyptus and velvet mesquite survived on all four planted treatments. The large number of desert tobacco present indicates that the original seedlings developed and scattered seeds which established and grew well.

Palo verde was more numerous on the east slope; however, one survived on the north slope (Table 3). Desert tobacco grew prolificously on the north slope but did not survive on the east slope. Slope exposure did not affect the survival of the other tree species.

On the north exposure, white thorn acacia was more plentiful in overburden than in tailing (Table 3). Also on the north slope, desert tobacco grew better in tailing than in overburden. Tiny capsule
Table 2. Average number of plants in 244 m² for seven species of shrubs, two soil materials, and two slope exposures seven years after planting at Cyprus Pima Mining Company, Tucson, Arizona in 1979.

<table>
<thead>
<tr>
<th>Slope exposure</th>
<th>Soil material</th>
<th>Plant type</th>
<th>Catclaw (no.)</th>
<th>Fourwing saltbush (no.)</th>
<th>Quailbush (no.)</th>
<th>Desert broom (no.)</th>
<th>Hopbush (no.)</th>
<th>Creosote (no.)</th>
<th>Arizona rosewood (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailing</td>
<td></td>
<td></td>
<td>0 A⁺⁺⁺</td>
<td>22 A</td>
<td>0 A</td>
<td>57 A</td>
<td>18 A</td>
<td>30 A</td>
<td>4 A</td>
</tr>
<tr>
<td>Overburden</td>
<td></td>
<td></td>
<td>0 a</td>
<td>16 a</td>
<td>0 a</td>
<td>38 a</td>
<td>18 a</td>
<td>32 a</td>
<td>0 a</td>
</tr>
<tr>
<td>East</td>
<td></td>
<td></td>
<td>0 A</td>
<td>0 B</td>
<td>0 A</td>
<td>0 B</td>
<td>0 B</td>
<td>0 B</td>
<td>0 A</td>
</tr>
<tr>
<td>Tailing</td>
<td></td>
<td></td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>2 a</td>
<td>0 a</td>
<td>0 a</td>
</tr>
<tr>
<td>Overburden</td>
<td></td>
<td></td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
</tr>
</tbody>
</table>

⁺⁺⁺ Means followed by the same capital letter for the same species and between slope exposures, are not different at the 5% level of significance (Student-Newman-Keuls' Test).

⁺⁺ Means followed by the same lower case letter, for the same species, within the same slope exposure and between soil materials, are not different at the 5% level of significance (Student-Newman-Keuls' Test).
Table 3. Average number of plants in $244 \text{ m}^2$ for ten species of trees, two soil materials, and two slope exposures seven years after planting at Cyprus Pima Mining Company, Tucson, Arizona in 1979.

<table>
<thead>
<tr>
<th>Slope exposure</th>
<th>Soil material</th>
<th>Plant type</th>
<th>White thorn acacia</th>
<th>Palo verde</th>
<th>Desert willow</th>
<th>Tiny capsule eucalyptus</th>
<th>Silver dollar eucalyptus</th>
<th>Red gum eucalyptus</th>
<th>Black walnut</th>
<th>Desert tobacco</th>
<th>Australian pine</th>
<th>Velvet mesquite</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td></td>
<td></td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
<td>(no.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>White thorn acacia</td>
<td>9 A$^+$</td>
<td>1 B</td>
<td>0 A</td>
<td>32 A</td>
<td>2 A</td>
<td>3 A</td>
<td>0 A</td>
<td>115 A</td>
<td>0 A</td>
<td>11 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Palo verde</td>
<td>2 A</td>
<td>0 a</td>
<td>52 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>220 a</td>
<td>0 A</td>
<td>12 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Desert willow</td>
<td>12 a</td>
<td>0 a</td>
<td>0 a</td>
<td>12 b</td>
<td>4 a</td>
<td>6 a</td>
<td>0 a</td>
<td>10 b</td>
<td>0 a</td>
<td>10 a</td>
</tr>
<tr>
<td>Tailing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>White thorn acacia</td>
<td>0 A</td>
<td>27 A</td>
<td>0 A</td>
<td>38 A</td>
<td>0 A</td>
<td>19 A</td>
<td>0 A</td>
<td>0 B</td>
<td>0 A</td>
<td>15 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Palo verde</td>
<td>0 a</td>
<td>30 a</td>
<td>0 a</td>
<td>70 a</td>
<td>0 a</td>
<td>36 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>14 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Desert willow</td>
<td>0 a</td>
<td>6 b</td>
<td>0 a</td>
<td>2 a</td>
<td>0 a</td>
<td>2 a</td>
<td>0 a</td>
<td>0 a</td>
<td>0 a</td>
<td>16 a</td>
</tr>
<tr>
<td>Overburden</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^+$Means followed by the same capital letter for the same species and between slope exposures, are not different at the 5% level of significance (Student-Newman-Keuls' Test).

$^{++}$Means followed by the same lower case letter, for the same species, within the same slope exposure, and between soil materials, are not different at the 5% level of significance (Student-Newman-Keuls' Test).
eucalyptus was more numerous in tailing than in overburden on both north and east exposures.

Plant Size

On the north slope, shrub size was not affected by soil material (Table 4). Shrub height and diameter of cover were the same for all shrub species in both tailing and overburden. Tiny capsule eucalyptus grew taller and its diameter of cover was greater on the north slope than on the east slope (Table 5). The size of palo verde, red gum eucalyptus, and velvet mesquite was not affected by slope exposure. On the east slope, red gum eucalyptus grew taller in overburden than in tailing. Differences in soil material, within slope exposures, did not affect the size of the other trees.

Effects of Slope Exposure on Temperature and Moisture

North slopes tend to be colder than other slope exposures; however, in this study, due to the nature of the mine design, the north slope was more sheltered and warmer than the east slope. Seedling establishment and survival for shrubs and trees was better on the sheltered north slope.

Slopes receive varying amounts of radiation depending on the exposure (Haase, 1970). For most of the year, the north slope receives less radiation than the east slope, therefore, less water evaporates from the north slope. The average annual precipitation for Cyprus Pima is 26.7 cm (10.5 in) annually. In the Southwest, where moisture is
Table 4. Average plant height and diameter of cover for five species of shrubs growing on two soil materials of a north slope exposure, seven years after planting at Cyprus Pima Mining Company, Tucson, Arizona in 1979.

<table>
<thead>
<tr>
<th>Species</th>
<th>Soil material</th>
<th>Plant height (m)</th>
<th>Diameter of cover (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourwing saltbush</td>
<td>Tailing</td>
<td>1.4 a⁺</td>
<td>2.6 a</td>
</tr>
<tr>
<td></td>
<td>Overburden</td>
<td>1.5 a</td>
<td>3.1 a</td>
</tr>
<tr>
<td>Desert broom</td>
<td>Tailing</td>
<td>2.3 a</td>
<td>2.2 a</td>
</tr>
<tr>
<td></td>
<td>Overburden</td>
<td>1.7 a</td>
<td>1.7 a</td>
</tr>
<tr>
<td>Hopbush</td>
<td>Tailing</td>
<td>1.8 a</td>
<td>1.5 a</td>
</tr>
<tr>
<td></td>
<td>Overburden</td>
<td>1.5 a</td>
<td>1.4 a</td>
</tr>
<tr>
<td>Creosote</td>
<td>Tailing</td>
<td>2.2 a</td>
<td>1.4 a</td>
</tr>
<tr>
<td></td>
<td>Overburden</td>
<td>1.8 a</td>
<td>1.1 a</td>
</tr>
<tr>
<td>Arizona rosewood</td>
<td>Tailing</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Overburden</td>
<td>1.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

⁺Means followed by the same lower case letter, for the same species and between soil materials, are not different at the 5% level of significance (Student-Newman-Keuls' Test).
Table 5. Average plant height and diameter of cover for seven tree species growing on two soil materials and two slope exposures, seven years after planting at Cyprus Pima Mining Company, Tucson, Arizona in 1979.

<table>
<thead>
<tr>
<th>Plant type</th>
<th>White thorn acacia</th>
<th>Palo verde</th>
<th>Tiny capsule eucalyptus</th>
<th>Silver dollar eucalyptus</th>
<th>Red gum eucalyptus</th>
<th>Desert tobacco</th>
<th>Velvet mesquite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ht* (m)</td>
<td>ht (m)</td>
<td>ht (m)</td>
<td>ht (m)</td>
<td>ht (m)</td>
<td>ht (m)</td>
<td>ht (m)</td>
</tr>
<tr>
<td></td>
<td>d** (m)</td>
<td>d (m)</td>
<td>d (m)</td>
<td>d (m)</td>
<td>d (m)</td>
<td>d (m)</td>
<td>d (m)</td>
</tr>
<tr>
<td>North</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailing</td>
<td>2.7</td>
<td>2.4</td>
<td>2.1 A</td>
<td>1.2 A</td>
<td>8.1 A</td>
<td>3.9 A</td>
<td>2.1</td>
</tr>
<tr>
<td>Overburden</td>
<td>3.4 a</td>
<td>2.8 a</td>
<td>2.1</td>
<td>1.2</td>
<td>8.7 a</td>
<td>4.3 a</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>1.9 a</td>
<td>2.0 a</td>
<td>--</td>
<td>--</td>
<td>7.6 a</td>
<td>3.5 a</td>
<td>2.1</td>
</tr>
<tr>
<td>East</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailing</td>
<td>--</td>
<td>--</td>
<td>1.7 A</td>
<td>1.2 A</td>
<td>5.8 B</td>
<td>2.1 B</td>
<td>--</td>
</tr>
<tr>
<td>Overburden</td>
<td>--</td>
<td>--</td>
<td>2.1 a</td>
<td>1.4 a</td>
<td>5.4 a</td>
<td>2.0 a</td>
<td>--</td>
</tr>
</tbody>
</table>

*ht = plant height.

**d = diameter of cover.

+Means followed by the same capital letter for the same species and between slope exposures, are not different at the 5% level of significance (Student-Newman-Keuls' Test).

++Means followed by the same lower case letter, for the same species, within the same slope exposure and between soil materials, are not different at the 5% level of significance (Student-Newman-Keuls' Test).
limited, soil moisture conservation is essential for plant survival. Plants growing on the north slope had more available water.

Vegetation that is successful on the north and east slopes may not be suitable for south and west exposures. West-facing slopes have the highest air temperature, the greatest evaporation, and the most wind movement. Consequently, west-facing slopes are the driest followed by south, east, and north, in decreasing order. Environmental differences between the north and east slopes, such as temperature and moisture, may account for the success of the shrubs on the north slope and their failure on the east slope.

**Tailing vs. Overburden**

Tiny capsule eucalyptus had a higher survival rate in tailing than in overburden for both slope exposures. This species of eucalyptus is tall and deep-rooted. Tailing material is uniform in texture, very porous, and well-suited for deep root penetration. Root penetration decreases as soil compaction increases. Compaction of loose tailing material to a certain density is advisable to obtain a suitable seedbed and provide improved soil, water, air, and plant relationships. Compaction of overburden material is not advisable. When heavy equipment is operated on overburden, the overburden may become too compacted for normal root growth (Ralston and Wiram, 1978; Shetron and Carroll, 1977; Powell and Barnhisel, 1977). If the overburden is wet, the amount of compaction increases. The heterogeneity of the overburden material, in addition to the compaction, may have prevented the root systems of tiny capsule eucalyptus from elongating as they should for satisfactory growth.
SUMMARY

Research was conducted in 1979 and 1980 at Cyprus Pima Mining Company, Tucson, Arizona, to evaluate the success of the revegetation work begun in 1970. Studies were conducted to determine whether a north or an east slope exposure and whether tailing or overburden soil material was more conducive to plant survival and growth. Research also involved determining which plant species would survive and reproduce in mining wastes over a period of years.

Unplanted tailing soil material on both north and east slope exposures was void of plant growth. Unplanted overburden supported a small number of burro-weeds. North slope exposures of both tailing and overburden had more ground cover than east slope exposures.

Two shrub species—catclaw and quailbush—and three tree species—desert willow, black walnut, and Australian pine—had 100% mortality. Desert broom and desert tobacco were prolific on the north slope exposure. Only one shrub, hopbush, survived on the east slope exposure. Palo verde grew best on the east slope but survival of the other tree species was not affected by slope exposure. Differences in soil material within each slope exposure did not significantly affect plant growth, with the exception of tiny capsule eucalyptus, which grew larger in tailing than in overburden soil material.
CONCLUSIONS

This research was designed to study the survival and growth of plant species in copper mining wastes at Cyprus Pima Mining Company 7 to 10 years after planting. Results obtained from the study suggest the following conclusions:

1. Plant selection is dependent upon the chemical composition of the mine waste material, slope exposure, and the availability of plant material.

2. The application of fertilizer may be necessary three or more times throughout the plant's growing season each year in order to develop the desired self-sustaining vegetative ground cover. If effective fertilization practices are maintained during the first two or three years, eventually the need for supplemental fertilization will be eliminated.

3. Irrigation is necessary for the first two years to adequately supply the moisture needed for the fast growing annual species. Irrigation can be terminated once native plant species are established, usually two to three years after planting.

4. Shrub survival was affected by slope aspect. For most of the year, the east slope receives more solar radiation than the north slope and consequently, it is drier. In semi-arid regions such as southwestern Arizona, even slight differences in available moisture may determine whether the species can survive in the area.
5. When adequate water and fertilizer are provided, plant survival and growth are equally successful in tailing and in overburden soil materials.
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