# Proceedings
# High Altitude Revegetation Workshop No. 11
# March 16-18, 1994

Edited By
Warren R. Keammerer
Wendell G. Hassell

March 1995

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Resources Research Institute

Colorado State University

**Proceedings**

# HIGH ALTITUDE REVEGETATION WORKSHOP

## NO. 11

**Colorado State University**
**Fort Collins, Colorado**
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**Edited by**

**Warren R. Keammerer, Keammerer Ecological Consultants, Boulder, CO**
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# PREFACE

The 11th biannual High Altitude Revegetation Workshop was held at the University Park Holiday Inn, Fort Collins, Colorado on March 16-18, 1994. The Workshop was organized by the High Altitude Revegetation Committee in conjunction with the Colorado State University Agronomy Department. The Workshop was attended by more than 200 people from a broad spectrum of universities, government agencies and private companies. It is always encouraging to have participants from such a wide range of interests and application needs for reclamation information and technology.

Organizing a two-day workshop is a difficult task made relatively easy by the sharing of responsibilities among the members of the HAR Committee.

In 1994, in addition to the papers presented on March 16-17, provisions were made to tour the National Seed Storage Laboratory on the campus of Colorado State University. The tour included a presentation by Steve Eberhart which has been included as part of this proceedings.

This proceedings also includes the third installment of the Index to the Proceedings for Workshops 1 - 10 (1974-1992). This third part includes references to species. The subject and author indices were included in the registration materials at the Workshop.

The most important contributors to the conference were the speakers. These Proceedings are their product, and we express our gratitude to them.

The Editors

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# THE ECOLOGY OF ALPINE PLANTS: THEIR ROLES IN HIGH MOUNTAIN ECOSYSTEMS IN A CHANGING BIOSPHERE

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## ABSTRACT

Above timberline, the cold-adapted low vegetations of alpine meadows and fellfields are open to great changes in biotic structure: environmentally, floristically, vegetationally, metabolically, and faunistically. These once pristine and relatively isolated places are now subject to disturbance due to increasing human population pressure and atmospheric changes. The plants dominating alpine and arctic vegetation differ in one fundamental way from all other plants on earth: they can carry on metabolic and reproductive processes during short growing seasons at temperatures only slightly above or even below freezing. If growing seasons become longer and warmer, how will these species and populations fare? Fortunately, through many millenia, most alpine plant taxa have evolved fitness to natural rapid and cyclic environmental changes. But new biological and physical changes are apparent that can disturb alpine ecosystems. Such disturbances may be the triggers that initiate far-reaching future ecosystemic change. Ecological science in this century has been surprised often by the delayed effects of biospheric "surprises". Examples are the increase of atmospheric $CO_2$, radioactivity, destruction of stratospheric ozone, and biological invasions that have occurred when nobody was aware of the ecosystemic consequences. What environmental surprises await alpine ecosystems in the next century? And what can be done now to avoid surprises?

## INTRODUCTION

The distinguished ecologist William S. Cooper (1926) suggested the analogy that change in vegetation is similar to a braided glacial river flowing through time. The diversions, rejoinings, and new combinations of plant and animal species are almost infinite and filled with unpredictable surprises. The key word in this present essay is "change". It is universal through the "life history" of any biome and, of course, of all alpine ecosystems

One cannot view the biosphere provincially either in space or time. This is true, also, of any regional ecosystem including mountain ecosystems. Within ecosystems and the biosphere itself, trigger factors may initiate far-reaching changes through time requiring biological and physical re-adjustments within the system. Such triggers may be changes in a limiting factor or episodic events in the environment on various time scales.

During recent centuries, much global change has resulted from an increasing series of natural and industrial "surprises" that have triggered a "new" and different earth ecologically, economically, and politically. The recent increase in atmospheric carbon dioxide within this century is but one example. Some of these changes had been predicted, but most had not. And, of course, almost none had been planned for or remedial actions prepared. The result, in both alpine and arctic ecosystems, could lead to local and general extinctions of populations of plant and animal taxa. For example, James Brown's (1971, 1978) "alpine islands" of mammals in the western North American mountains with their already partially depleted alpine biota could be doomed in a warming climate. In alpine ecosystems, such local and general extinctions are a real possibility unless preventive measures are taken in time.

## ALPINE-ARCTIC ENVIRONMENTAL GRADIENTS

Three main environmental gradients interact to govern biological and physical systems on the earth's mountain ranges: latitudinal, elevational, and topographic. Each of these large gradients consists of many interacting factors that vary quantitatively along the gradient. Figure 1 (from Billings, 1979) diagrams, in a qualitative way, relative values of a few of the important factors that govern arctic-alpine environments along American mountains from the Arctic to the equatorial Andes. Only daily mean air temperature is relatively uniform along this gradient of 70 degrees of latitude. At any latitude, the interacting factors create a unique mountain environment. This, in turn, is further complicated by the effects of the elevational topographic gradient and the continually changing altitudinal atmospheric gradients. Superimposed on these complications are the effects of topography as they affect wind and the drifting of snow.

The topographic gradient, in turn, consists of two main subdivisions differing in scale: a larger "mesotopographic" and a smaller "microtopographic" (Billings, 1973). Figure 2 diagrams a typical alpine mesotogtaphic gradient and its effects on water, snow, and vegetation. Within any repeatable mesotopographic unit, microtopographic gradients reflect the effects of boulders, treeline krummholz, and cryopedogenic patterning on soil characteristics and snow depths and time of snowmelt.

## ALPINE FLORAS AND VEGETATIONS

There are two main mountain systems in western North America: the Rocky Mountains on the east and the Sierra Nevada-Cascades axis on the west. At latitude 38 N, the main crests of the two systems are about 800 miles or more than 1300 kilometers apart. Between them lie many other mountain ranges, some as isolated as islands and others connected to each other or to one of the main systems. Almost all these ranges trend north and south. Exceptions are the Uinta Mountains of northeastern Utah and the transverse ranges of southern California that lie in an east-west direction.

On most American mountain ranges, the elevational topographic macrogradients are steep compared to latitudinal gradients. The higher mountains are characterized by an alpine timberline of one or more tree

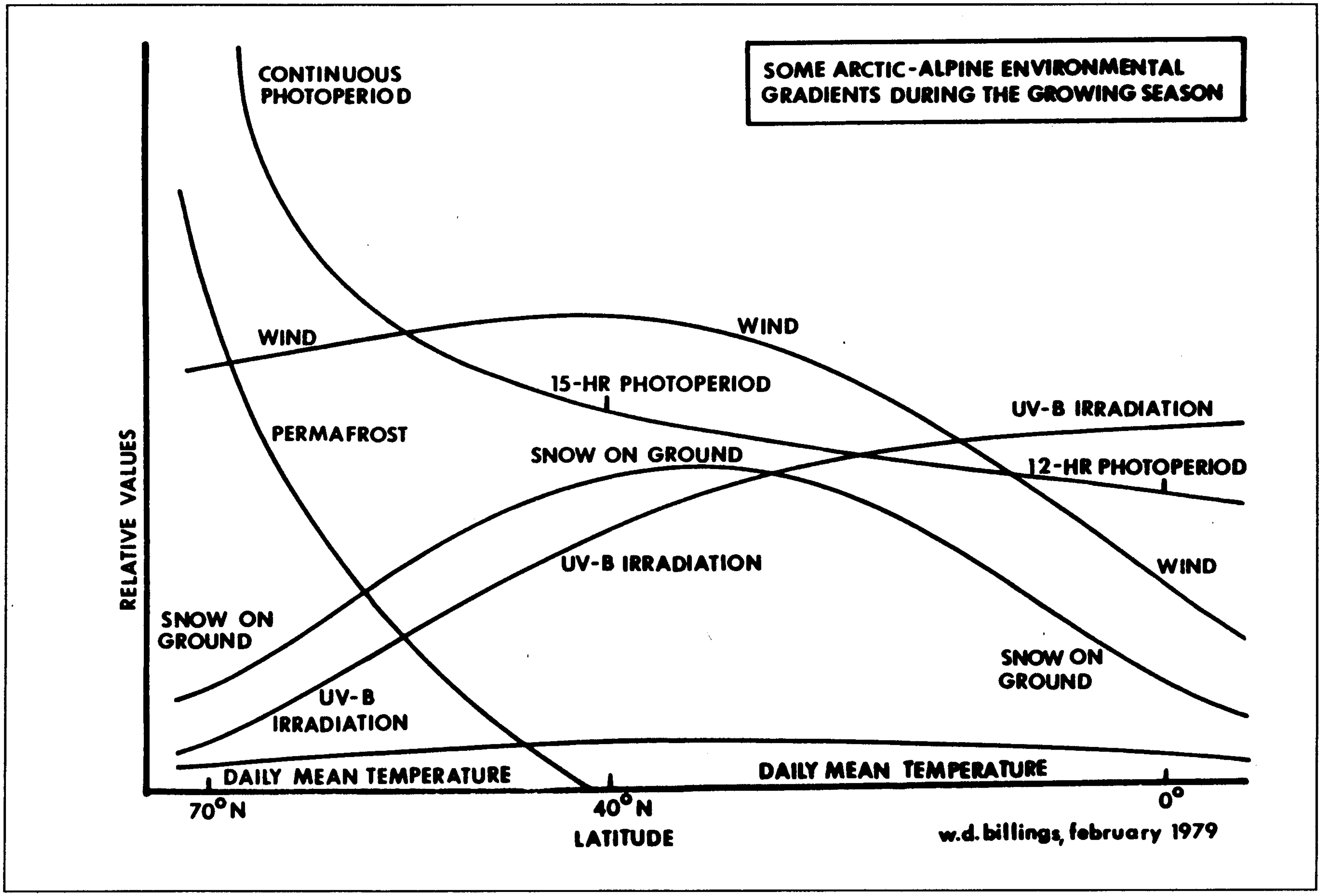


Figure 1. Relative values of six principal environmental factors in alpine and arctic ecosystems along a latitudinal macrogradient from the Arctic to the equatorial mountains in North and South America (from Billings, 1979).

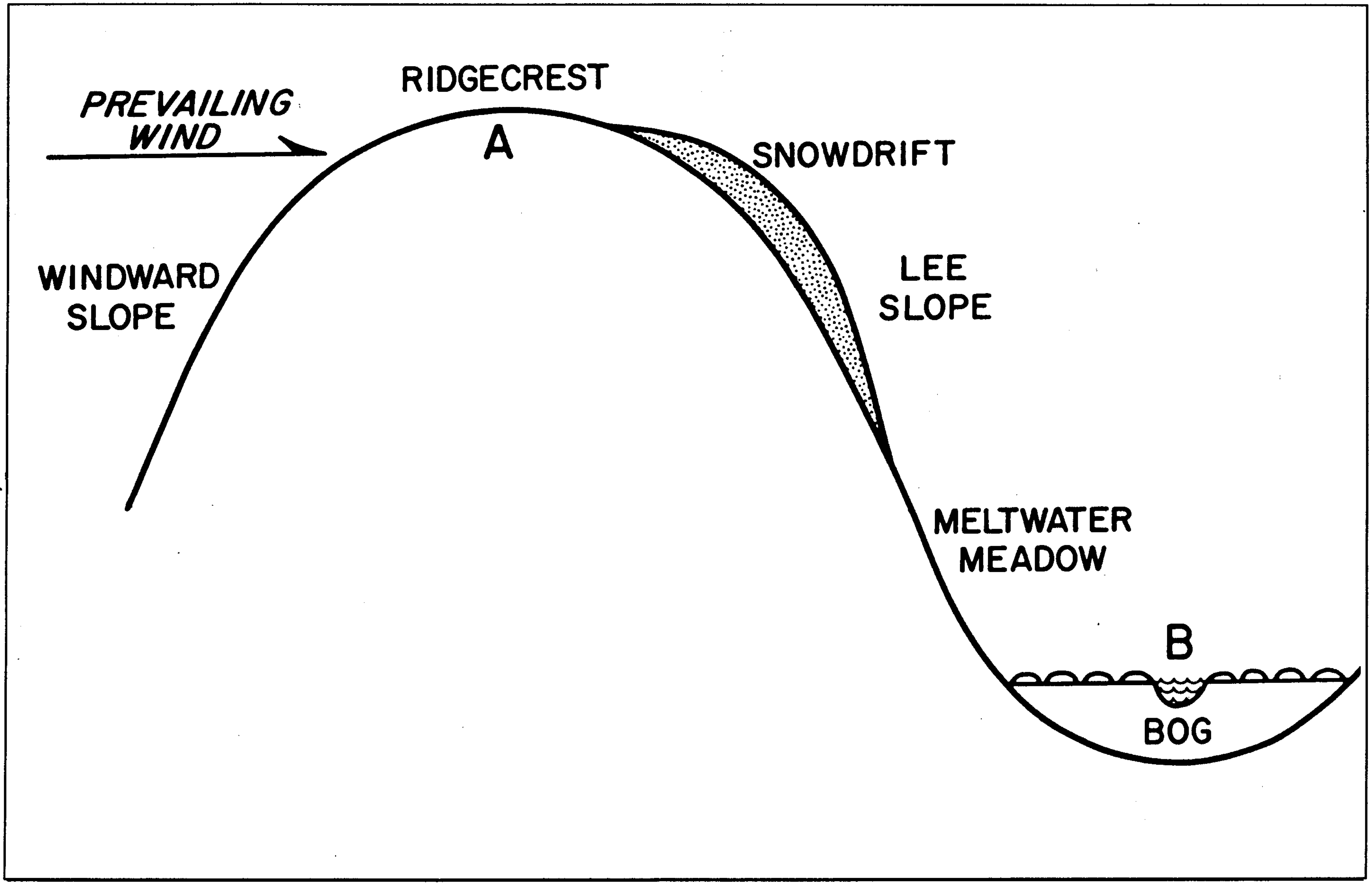


Figure 2. Diagram of a typical alpine mesotopographic gradient unit from the upper windward slope to the lee valley. The vertical scale can vary from about 50 m from ridge to bog to as much as 500 m or more (from Billings, 1973).

species as they reach their tolerance limits to wind, low temperatures, and snowblast. Beyond this forest limit, the truly alpine herbaceous and low shrubby vegetation faces an even more severe environment characterized by blowing and drifting snow of the alpine mesotopographic gradient (Figure 2) and its ridgetop cushion plants, fellfields, and moist meadows.

Alpine vegetations and their floras superficially resemble those of the arctic tundras. Actually, however, they are much different. The local alpine environments are windier, rockier, snowier, with more intense solar radiation (both visible and ultraviolet wavelengths), more scattered and shallower permafrost, and shorter summer daylengths. But beyond these physical environmental factors are the far richer alpine floras with their genetic relationships to the floras and vegetations of the lower mountain slopes (Chabot and Billings, 1972) rather than to those of the Arctic.

In the alpine ecosystems of the middle latitudes of both North America and Eurasia, there are some floristic relationships with the smaller arctic flora. Such relationships are closer on the older mountain ranges with longitudinal ties to the Arctic. The great Cordillera of the Rocky Mountains leads directly to the mountains of the Alaskan Arctic. This cordillera is an ancient and well-travelled migration pathway. For example, 50 per cent of the alpine flora of the Beartooth Mountains is made up of plant species that also occur in the Arctic (Billings, 1978). Conversely, the alpine flora of the southern half of the Sierra Nevada of California from Piute Pass to Olancha Peak has only 10 to 13 percent arctic-alpine taxa. The remainder are Sierran or western North American endemic mountain species (Billings, 1978; Chabot and Billings, 1972; Howell, 1951). But, the Sierra is a young and high mountain range strategically located between the "mediterranean" vegetation of California and the Great Basin desert to the east. It has the largest and richest montane and alpine flora on this continent (Major and Taylor, 1977; Billings, 1988).

Quite similar to the alpine floristic richness of the California Sierra Nevada is that of the Hindu Kush Range of eastern Afghanistan (Breckle, 1974). The floristic relationships of that alpine flora show only weak genetic ties with that of the Arctic (13-17 %) but close relationships with the alpine and montane floras of the high mountains of central Asia. However, at elevations of over 5,000 meters (the nival flora) there are fewer endemics (less than 10%). These nival species are widely distributed on the high mountains of Asia, Europe, and into the Arctic. At elevations of 4,000 meters, the alpine flora of the Hindu Kush is several orders of magnitude richer than that of the European Alps (ca. 350 species of vascular plants as compared to only 15 or 20 species in the eastern Alps at elevations over 4,000 m.). See Figure 3.

## ADAPTATIONS OF PLANTS TO THE ALPINE ENVIRONMENT

Evolution of arctic and alpine plant taxa north of Latitude 30 North requires adaptation to chilling and freezing temperatures during the growing season and to bitterly cold weather and soils during the

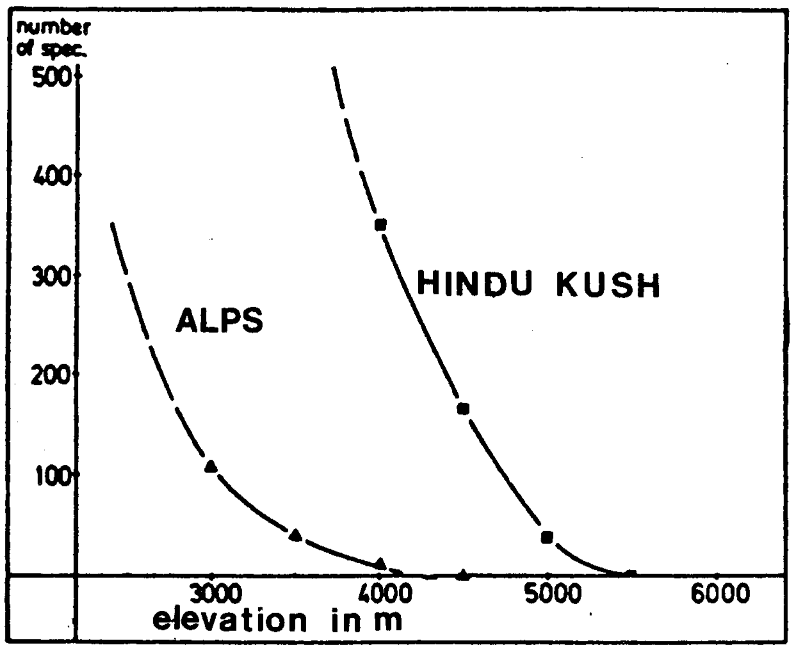


Figure 3. Comparison of the decreasing number of plant species with increasing elevation in the European Alps and the Hindu Kush of Afghanistan (revised and simplified from Breckle, 1974).

winter dormant season. The very low number of vascular plant species and the floristic zonation in the Arctic attest to low growing season temperature as a stressor of first rank.Such plants differ in one fundamental way from all other plants on earth: they can metabolize and reproduce during very short growing seasons at soil and air temperatures near freezing and below. And yet, most of these taxa are so well-adapted to functioning at low temperatures that they are really limited in their local distributions and activity by other factors such as soil nitrogen, phosphorus, permafrost, water table, and soil moisture. (Chapin, 1978, Billings,1987b, Shaver, et al.,1992).

Morphological Characteristics (Life Forms)

A typical alpine vascular plant is a small, even dwarf, angiosperm. Over 95% of these angiosperms are perennial plants that take several years from seed to become established. Once established, however, they break dormancy and grow rapidly during the first half of the alpine growing season at low temperatures after snowmelt. A number of monocot and dicot species also spread into clones through vegetative reproduction from rhizomes or stolons.

The number of life form types, and even leaf shapes is small. The following list indicates those forms that are most common:

- Perennial herbs
  - graminoids
  - rosette plants (acaulescent)
  - cushion plants
  - dicotyledonous "forbs" (not rosettes,graminoids,or cushions)
- Annual herbs (usually rather rare)
- Prostrate shrubs
  - evergreen
  - deciduous
- Caulescent woody rosette plants (tropical mountains)
- Lichens
- Bryophytes
- Macrofungi

Perennial vascular herbs are are the most common both florisically and vegetationally. In most places, they dominate the vegetation. The four main life forms in this class are usually distinct from each other, but not always. There are all sorts of intermediates such as "graminoid rosettes", "rosette cushions", and "forbs with basal rosettes". Graminoids are typefied by almost all grasses, sedges, and rushes. Graminoids are common in almost almost all parts of the mesotopograhic gradient. They tend to be larger and have more coverage, however, in the wetter parts.

Cushion and rosette plants often are pioneers in habitats of low graminoid competition such as ridgetops or snow-blasted windward upper slopes (see Billings, 1988). They also are common on disturbed areas along trails and casual automobile parking pulloffs.

In many alpine regions, prostrate shrubs are next in abundance to perennial herbs. These are long-lived and may be deciduous as are Salix arctica and some other low shrubby willows. Or, they are evergreen such as Salix cascadensis, Cassiope mertensiana, and Phyllodoce empetriformis.

Lichens are almost everywhere in alpine regions. All the principal forms are present. Caloplaca elegans (crustose, nitrophilous), Cetraria islandica (foliose), Cladonia (fruticose), and Thamnolia vermicularis (vermiform) are all ubiquitous. Mosses are also abundant in the wetter places.

Growth and Metabolism

The ability of an alpine plant to adapt to the short, bright alpine growing season lies primarily in being able to operate its metabolism and water balance at low temperatures under a high solar radiation load during a relatively short daylength as compared to that of arctic ecosystems. These physiological adaptations have been described in terms of vascular plant life cycles by Billings and Mooney (1968), Bliss (1971), and Billings (1974). Therefore, they will be summarized only briefly here.

Seedling Ecology:

Seed dormancy in most alpine species is under environmental control. Germination, if other conditions are right occurs soon after snowmelt when there is considerable diurnal temperature fluctuation even though the mean temperature may not be much above freezing. The right combination of fertile seeds and suitable temperature and moisture conditions may not occur every year.

Seedling establishment is only occasional in most alpine species populations. Even so, the availability of viable seed makes such establishment more common in alpine regions than in the Arctic where most species produce seed rarely and vegetative reproduction is the general rule except in certain genera of small dicots. Seedling growth is usually very slow. Much of the first year's photosynthate goes into the development of a root system which is insurance against death of the seedling by late season drought. The root system also serves as a carbohydrate bank for the next season's growth.

Vegetative Growth:

In the second year, and from then on, vegetative regrowth of shoots is rapid from a perennating bud that is usually very close to the ground surface This growth begins very soon after snowmelt when, the soil temperature rises above freezing.

The growth rates of roots and rhizomes in alpine plants is relatively unknown as compared to these rates in arctic plants. There is little reason, however, to believe that it is much different than in those far northern species. Billings, et al. (1973, 1978) found that root growth in three species of tundra graminoids near Barrow, Alaska, can take place at rates of 1 to 2 mm per day at temperatures of 0 C or even slightly below that.

Photosynthesis and Respiration:

The real heart of adaptation in alpine plants to short, cold growing seasons is the ability to carry on photosynthesis rapidly at low temperatures. This ability is genetically determined (the C3 pathway) as coupled, in a strong interaction, with the rapidly changing diurnal and seasonal environment. This allows alpine plants to acclimate in regard to both photosynthetic and respiratory rates. Mooney and Billings (1961) demonstrated that arctic and alpine ecotypes of Oxyria digyna differ from each other in these rates. This was confirmed for many populations of Oxyria experimentally under more controlled conditions by Billings, et al. (1971). This latter research also found that low and high temperature acclimation regimes have very marked effects not only on photosynthesis and respiration as measured by gas exchange (Figure 4) but also on the Hill reaction and mitochondrial activity. They showed that acclimation ecotypes exist, and that alpine ecotypes of Oxyria acclimate metabolically more rapidly and ideally than do arctic ecotypes of the same species. Chabot, et al. (1972) found that this acclimation effect in Oxyria metabolism extends also to the activity levels of the principal carboxylating enzyme, ribulose 1,5 biphosphate carboxylase (Rubisco).

Alpine populations of arctic-alpine species appear to have higher light-saturation values in photosynthesis than do the arctic ecotypes and related lowland plants. This is not surprising in view of the high light intensities at high elevations in most tropical and middle latitude mountains. Light saturation and maximum net photosynthetic rates, however, are closely dependent upon temperature (Scott and Billings, 1964).

One great need to the understanding of photosynthesis and respiration in alpine plants is more measurements under actual field conditions. We made the first ones in 1958 using an infrared gas analyzer at an elevation of 3,300 meters in the Medicine Bow Mountains (Billings, Clebsch, and Mooney, 1966). Among the best of such field measurements are those of Moser (1973) on Ranunculus glacialis, Cerastium uniflorum, and Saxifraga bryoides on the Hoher Nebelkogel at 3,184 meters in the Austrian Tyrol above the village of Solden in the Otztal. The value of these data lies in the detailed measurements for periods of one to several weeks. More than 60% of the measurements were made at temperatures ranging from -5 to +5 C.

Carbohydrate and Lipid Storage:

Characteristic of all alpine plants except the rare annuals is the ability to store carbon compounds that are used in the following season's growth. Most of these compounds are in the form of carbohydrates stored in the roots and rhizomes of herbaceous perennials (Mooney and Billings, 1960). Dwarf evergreen shrubs store a considerable amount as lipids in old leaves (Hadley and Bliss, 1964).

Drought Resistance:

Alpine areas in western North America are prone to late growing season drought. It should be possible to find drought-resistant ecotypes along alpine mesotopographic gradients. In fact, Klikoff

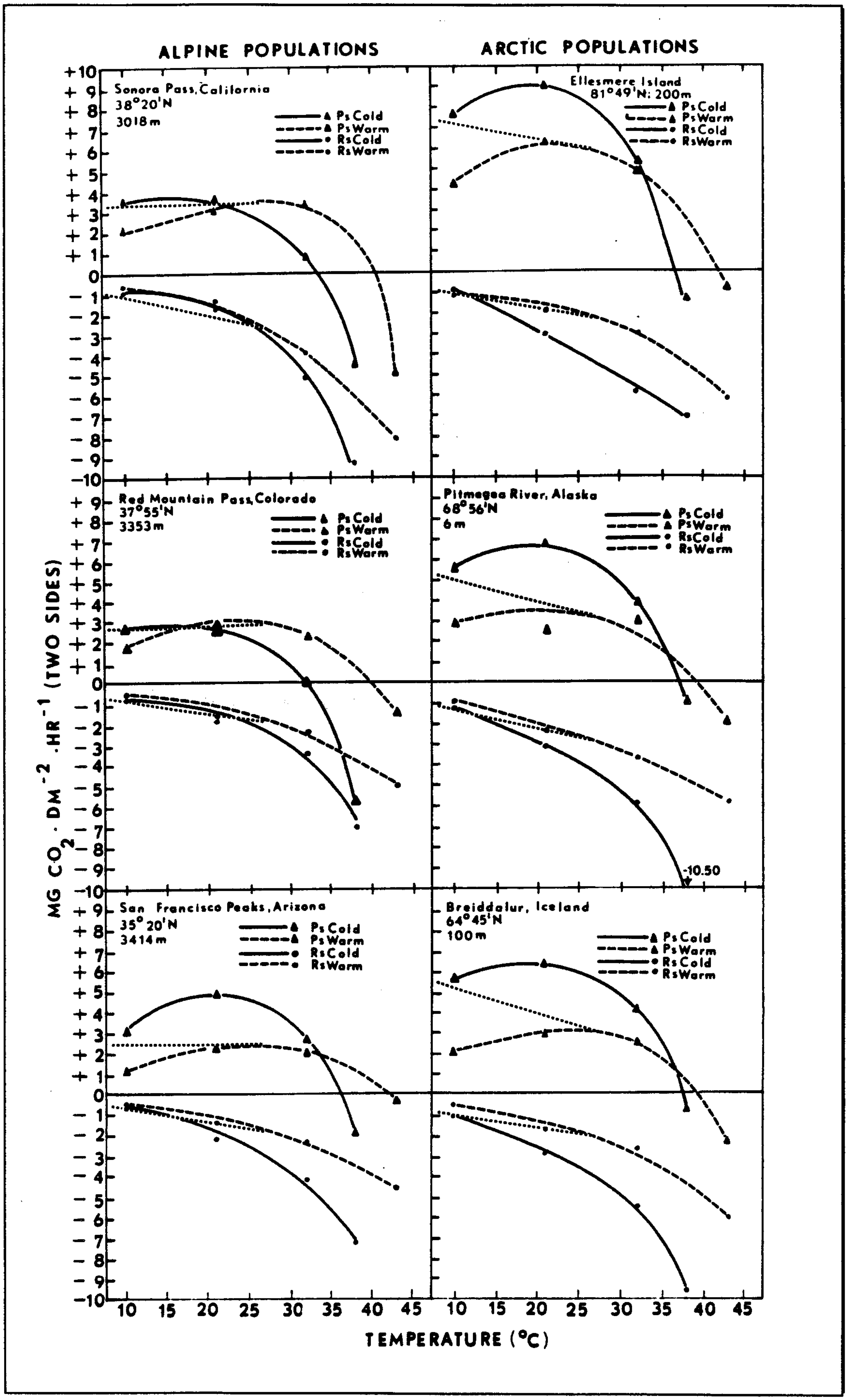


Figure 4. Effects of growth temperature on net photosynthesis (triangles) and dark respiration (dots) of three alpine and three arctic populations of *Oxyria digyna*. The dotted lines connect the mean growth temperatures (cold and warm) with the gas exchange rates at those same temperatures. Level connecting lines indicate that compensation is "ideal" in net photosynthesis of alpine populations; the steep angle of the dotted lines in net photosynthesis of the arctic populations indicates only "partial" compensation. Dark respiration compensates about the same in all populations; it is "partial" but approaches "ideal". (From Billings, et al. 1971).

(1965) found that photosynthesis in Calamagrostis Breweri in a moist alpine site in the Sierra Nevada decreased almost to zero at leaf water potentials below 1 MPa. On the other hand, Carex exserta from drier sites on the same gradient was still photosynthesizing at 25% of maximum at water potentials as low as 2 MPa. Oberbauer and Billings (1981) measured plant water potentials on alpine plants of 29 species at 3,300 meters elevation in the Medicine Bow Mountains of Wyoming for an entire growing season. Leaf water potentials were lowest in ridgetop plants and highest in wet meadow plants. These latter showed leaf death at water potentials below -1.5 MPa But, deep-rooted Trifolium Parryi plants on ridges and high windward slopes had maximum conductance at water potentials as low as 1.7 MPa. We found that in conjunction with leaf characteristics, root system patterns are very important. These rooting differences and the diversity of habitats across topographic gradients, along with summer reainfall, interact to permit the maintenance of a diversity of species and water use patterns.

Onset of Dormancy:

As the summer wanes, plants rather quickly go into vegetative dormancy. In Oxyria, we have found that arctic ecotypes begin to form perennating buds at daylengths as long as 14 to 15 hours. Alpine ecotypes under the same temperature conditions do not do this until the daylength is down to 12 to 13 hours. No matter what the temperature, all Oxyria plants will be dormant when the decreasing daylength reaches about 11 hours. Daylength may be the principal dormancy cue in Oxyria but it is not independent of low temperatures and/or drought. This latter situation may be true of most alpine plant species. Without this dormancy or hardening, alpine plants would not be in condition to withstand the rigors of winter.

Reproductive Characteristics:

Almost all alpine plants produce flower primordia at least the year before flowering and sometimes 2 to 3 years before. These pre-formed flower buds insure that there is no delay in flowering after snowmelt and that there is time for seed-set assuming that all other environmental conditions are met. The pre-formed flower bud is an almost universal arctic-alpine-subantarctic adaptation. Mark (1970) has found them to be almost ubiquitous in the alpine plants of New Zealand; these have evolved from an entirely different mountain flora from those in the Northern Hemisphere.

Flowering in most alpine plants occurs from the pre-formed flower bud within 10 to 20 days after snowmelt; it can be even quicker in those around or beneath late-lying snowbanks. The speed and time of flowering depends greatly on the time of snowmwlt in a given year and the air and soil temperatures that follow. In Oxyria, and perhaps some other species, daylength is also involved in the breaking of dormancy of the flowering bud (Billings, in manuscript). Alpine ecotypes of Oxyria bloom at photoperiods approximating the maximum daylength of the latitude at which the population occurs. Those Oxyrias from the Arctic require continuous light to break floral dormancy.

## PEOPLE AND ALPINE ECOSYSTEMS

People have been living or traveling through the high mountains of the Northern Hemisphere for thousands of years, probably for much of the Holocene, after the continental ice melted in Europe. However, there are relatively few concrete details in time and space on true alpine populations of human beings. Therefore, the discovery of a frozen mummified man, complete with gear, exposed in September, 1991, at an elevation of 3,200 meters, by the peripheral melting of the Similaun Glacier inthe Tyrolean Alps is significant. The discovery site is not far below the 3,525 m peak of the Finailspitze near the head of the Otztal. Thus,the nickname "Otzi" has been applied to him. The discovery is the first solid evidence of the kind of people who lived and hunted in these high mountains more than 5,300 years BP (Eijgenraam and Anderson, 1991; Harrigan, 1992).

In Europe, particularly in the Swiss Alps and the mountains of the Austrian and Italian Tyrol, people have lived for a long time in small village populations as high as timberline. These higher slopes near timberline and above provided transhumance pasturage for their sheep, cattle, and goats during the summers. This latter activity led to cutting of the trees for fuel and timber; such tree-cutting also increased alpine pasturage. The net result is that the actual forest limit today is about 100 to 200 m below potential forest line under the present climate (Walter, 1973). The farmers still harvest the native mountain meadow hay to feed the animals in small, stone-roofed "barns" during the long snowy winters. All of this is done very carefully by these people who live in these mountains and know them very well -- as did their ancestors.

About the middle of the 19th century, two things happened which resulted in some changes in this way of life. The first was the introduction of the American potato which caused a minor population explosion in the villages. The second was the beginning of an influx of tourists during the summers and later during the winters as well: climbing and downhill skiing. Tourism has continued to increase and has brought in enough additional money to make certain lands more valuable for hotels, lifts, and ski runs than for agriculture. Similar situations in regard to tourism have brought financial gains but vegetational damage throughout the Alps.

The village of Obergurgl at 2,000 meters elevation near the head of the Otztal in the Austrian Tyrol is an example of how a changed economy is affecting the life of the people and use of high mountain lands in the Alps. Economic growth, spurred by an increase in tourism after about 1950, has been expressed largely in the form of hotel construction. Such construction not only has impinged upon the surrounding agricultural meadow land but the increased number of tourists is having considerable impact upon the alpine ecosystems. Bunnell, et al. (1974) have produced the "Obergurgl Model" which could be useful as a starting point in understanding how such modified high mountain ecosystems will fare environmentally and economically under the impact of increased numbers of people. It is important to maintain alpine meadows not only for grazing but for the prevention of erosion and mudslides, and also for their aesthetic values. As in other high mountain regions, increased pressure from people and domestic animals and no increase in carrying capacity could lead to decreased vegetational cover, an increase in ersosion, and loss of the native biota. More recently, Moser and Moser (1986) have made a very thorough study of the human and natural ecology of Obergurgl and its alpine ecosystem. Their study could serve as an excellent model for similar research on the places of people in our western mountains in this country.

As contrasted with the Alps, the Rocky Mountains of western North America were almost untouched by modern man until the middle of the 19th century. Except for relatively slight effects by American Indian tribes crossing these mountains during summers, these alpine ecosystems evolved in the absence of man -- but in the presence of natural fires caused by lightning. The small populations of migrating Indians probably did have some influence in reducing populations in a few species of large mammals. But, their major influence was probably within the fabric of the natural ecosystem in regard to increased frquency and extent of forest fires. Revegetation by forest after such fires is a matter of two or three centuries except near timberline where revegetation is very slow because of post-fire changes in snowdrift patterns resulting from exposure to winter alpine winds (Billings, 1969; Earle, 1993).

European man's earliest influences during the first half of the 19th century were relatively slight and involved mostly the trapping of beaver. The mountains remained wild. Mining and timbering activities appeared in the latter half of the century. These were accompanied by establishment of high mountain towns and mining camps. In addition to local destruction of rock and soil, mine tailings, forest cutting, and fires increased markedly. So, also, did hunting of large native herbivores: deer, wapiti, mountain bison, bighorn sheep. Introduction of domestic sheep at this time also subjected the alpine and subalpine meadows to severe grazing pressure and erosion.

Alpine vegetation is very susceptible to trampling by people and hooved animals, both domestic stock and native ungulates. The effects of the many thousands of visitors to the National and State Parks in North America and Europe lead to trail proliferation and eventually to erosion especially in snowdrift areas and in some kinds of wet meadows. Pioneer research on these effects on alpine vegetation in our western National Parks include those of Willard and Marr (1970) in Rocky Mountain National Park, Bell and Bliss (1973) in Olympic National Park, and Hartley (1976, 1980) in Glacier National Park. Hartley's research still continues. In Europe, Grabherr's (1982) pertinent paper describes quantitative results on trampling on Hohe Mut, a mountain ridge at an elevation of 2,550 to 2,650 m accessible by cable car from near Obergurgl in the Tyrolean Alps of Austria. Grabherr foun that the most sensitive plants on Hohe Mut were fruticose lichens. The dominant angiosperms, *Carex curvula* and *Ligusticum mutellina* did not disappear completely even at a tourist frequency of 150 per meter of trail per day.

The most thorough field research on trampling effects on alpine vegetation and trail formation by people is that of Hartley (1976) in the meadows east of Logan Pass in Glacier National Park. His research involves quantitative tourist load sampling, quantitative vegetation mapping, and experimental trampling effects. He started his research there in 1967 and still continues; the latest measurements on damage and recovery were taken in July, 1992. It is truly long-term ecological research.

Hartley's main conclusions as of 1976 and 1980 are:
(1) The local landscape at Logan Pass has changed conspicuously due to building of amenities, educational facilities, and water supplies for tourists.
(2) Animal life has been affected in various ways by the continued closeness of people. This is true of grizzly bears, mountain goats, and mountain sheep. Smaller animals including Columbian ground squirrels and hoary marmots have adjusted to the presence of people, as have a number of bird populations including the white-tailed ptarmigan.
(3) The herbaceous plant cover near Logan Pass has been reduced by human activity, and the floristic composition has been changed by such activity through the years. Aside from permanent structures, paved roads, parking lots, and constructed trails, much of the remaining vegetation has been trampled to some extent. Such damage is particularly severe along trails and close to them. The degree of vegetational damage depends on foot traffic interacting with the kind of vegetation, slope, and wetness of soil. Wet meadows are often damaged severely but may recover more rapidly also. Only a few people walking in single file can create a new trail. If this is followed by other groups, the damage is started. Some plant species are very sensitive and can disappear very soon even under light use.
(4) Hartley constructed a useful model of the effects of trampling on the physiological status of alpine vegetation under the stress of trampling. Billings (1983) modified this model slightly; it appears here as Figure 5. Primarily, it starts through physical damage to the plants and the loss of photosynthetic tissue. Secondarily, then, energy capture by leaves and thence by translocation to carbohydrate storage in roots, rhizomes, and bulbs is severely hampered or stopped. Since these are the perennating organs of the herbaceous plants, lack of re-growth and reproduction can cause the local extinction of susceptible species. These include *Phyllodoce empetriformis*, *Senecio resedifolius*, and to some extent, the bulbiferous *Erythronium grandiflorum*.
(5) The soils of the research area were damaged by trail traffic resulting in compaction and subsequent erosion. Such soil destruction makes vegetational re-establishment very difficult and slow. Depending upon degree of soil damage and loss of plant reproduction potential, revegetation and soil development may take centuries or even tens of thousands of years in alpine ecosystems of the type near Logan Pass.

## ALPINE ECOSYSTEMS OF THE NEXT CENTURY?

What are the problems likely to be? What environmental "surprises" await for these mountain ecosystems either locally or globally? As Rosenberg (1986) entitled his paper, "A Good Crystal Ball is Hard to Find!". Will the global climate of the mid-21st century be warmer than now as the carbon dioxide, methane, and other greenhouse

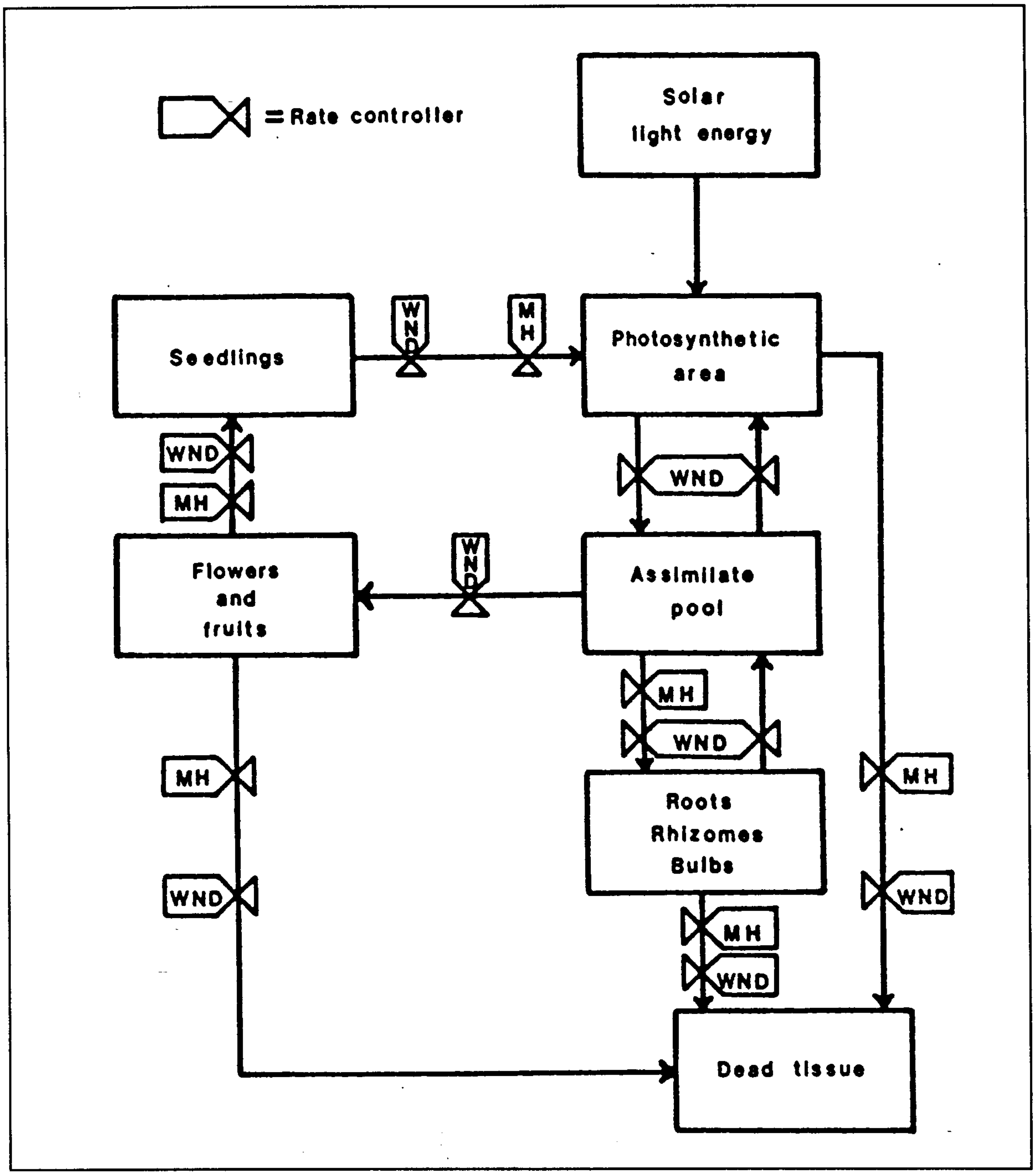


Figure 5. Rate controller model of the impact of trampling by people on photosynthesis and carbohydrate storage in subalpine and alpine vegetation near Logan Pass in Glacier National Park, Montana. Slightly modified and redrawn from Hartley (1976) and published in Billings (1983). W = water status; N = nutrient status; D = disease; H = herbivores; M = people.

gases increase in atmospheric concentration? Or, what are the the uncertainties in this regard? Local mountain environments will certainly vary plus or minus in temperature trends from global means. Some mountain regions possibly will be more cloudy or snowier than now; others may be less cloudy and perhaps drier.

It is difficult enough to predict what the climates of the lowlands will be in the next century with their thousands of first class and long-term weather observing stations. But, as Barry (1992) reminds us, there are relatively few mountain weather stations. These are usually far between, and with records mostly spanning only the last century or less. In the western North American mountains, there are very few observing stations at all, and only two or three sufficiently equipped with first rate instruments and personnel. One of these is the INSTAAR station on Niwot Ridge established by Dr.John Marr in 1952. Switzerland has many more and has had them for a longer time.

Good past records of weather observations at a given site are the foundations upon which climatic predictions for that site can be made from the best models. Therefore, we face a handicap in trying to predict what the alpine weather and climate will be like in our mountains in the middle of the next century.

## Greenhouse Gases and Possible Climatic Change

Within this century, it is apparent that the global mean air temperature is increasing. But, global warming, in spite of much research and modeling efforts, is still rather unpredictable (Jones and Wigley, 1990). True, atmospheric carbon dioxide levels have increased in the last two centuries from ca. 280 ppm by volume to almost 360 ppm now. However, the longest consistent and detailed record in one place (Mauna Loa, Hawaii) began only in 1958 (Keeling, et al., 1982) when the CO2 concentration there was 315 ppm. There are now a number of other global stations continuously monitoring atmospheric CO2 but with far shorter records.

Even though CO2 is the main and most abundant "greenhouse" gas, there are several others of importance. Notable among these are methane (CH4) which has more than doubled in the last several decades to over 1700 ppb (although within the last year its increase seems to have slowed or stopped), nitrous oxide to 310 ppb, and the man-made chlorofluorocarbons that did not even exist during the first half of this century and now are ca. 1 ppb. The CFCs, of course, are also primarily the causes of the breakdown of the stratospheric ozone layer and the ultraviolet-B irradiation problem. (Rowland, 1989). The UV-B problem itself is intensified in alpine regions especially in the tropical high mountains (Caldwell,et al., 1980).

Jones and Wigley, (1990) calculate that the present global air temperature is ca. 0.75 degree C warmer than it was in the early part of this century. However, the yearly means are rtather erratic. All models predict that warming will accelerate in the first half of the 21st century. But, there is considerable uncertainty as to how much of an increase. By the year 2050, global mean air temperature could be somewhere between 2.0 to over 4.0 degrees C warmer than now on a global basis. What does this mean for the high mountains of the earth?

Aside from the effects of global warming on the earth's alpine ecosystems, there are the direct effects of increasing CO2 levels on photosynthesis and growth of mountain plants. Almost all plants at high elevations in the mountains of the middle latitudes have the C3 photosynthetic pathway. Plants with the C4 mode of photosynthesis do not operate well in thse cold summer temperatures, and are therefore absent or extremely rare. Also, the direct effects of increasing atmospheric CO2 on photosynthesis and growth favor C3 plants over those with C4 metabolism (Strain, 1987). Strain also reports that water-use efficiency increases as atmospheric CO2 concentration increases. This leads to stomatal closure causing transpiration to decrease at the same time that photosynthesis is increasing. This improved plant water balance in the C3 vegetation is estimated to increase water yield in some mountain watersheds. This is yet to be proven.

Korner (1992) has studied the effects of climatic warming on alpine vegetation in the Tyrolean Alps with special attention to the interactions between rising CO2 and temperature. He concludes that the extent to which rising CO2 levels will result in increased primary production and consequent changes in alpine vegetational patterns will depend on trends in atmospheric and soil temperatures.

Recently, Korner (Korner and Diemer, 1994) has followed up on the earlier research of Billings, Clebsch, and Mooney (1961) in comparing high and low elevation populations of alpine-arctic plant species in regard to photosynthesis under actual CO2 volumetric concentrations in the atmosphere. Billings, et al. (1961) found that the high elevation alpine populations of Oxyria digyna were more efficient in photosynthetic utilization of low concentrations of CO2 than sealevel populations of the same species. Korner and Diemer, after their experiments comparing high elevation populations of related species in the Alps, conclude that alpine populations, because of their greater photosynthetic efficiency at low CO2 concentrations, may obtain relatively greater carbon gains in the CO2-enriched atmosphere of the next century than comparable and closely related lowland species.

Increase in Ultraviolet-B (UV-B) Irradiation

The high mountains of the middle latitudesand the tropics have always had an environment with strong fluxes of incoming solar ultraviolet radiation. This downward flux is in spite of the screening out of such radiation, especially UV-B, by the stratospheric ozone layer. A key environmental danger is, therefore, severe sunburn or skin cancer of many people who inhabit the mountains or ski and climb in them in the clear, transparent air. Snow cover and ice, by reflection, increase the irradiation of UV-B as received on the skin. Plants also receive this irradiation; some leaves reflect it while others screen it out by compounds such as flavonoids in the epidermis.

While this ultraviolet irradiation hazard has been present as long as there have been high mountains, the UV-B gradient between the polar mountains and those in the tropics increases curvilinearly toward the tropics. The Andes, the Himalayas, the Hawaiian volcanoes, and the equatorial mountains of east Africa are examples of the steepness of this gradient (see Figure 1). This increase toward the Equator is due to a combination of increased mountain elevation, a thinner ozone layer over the tropics as compared to that over the polar regions, and the steeper angle of incidence of solar radiation as received at the earth's surface in the tropics (Caldwell, et al. 1980).

The 20th century has seen drastic increases in UV-B irradiation not only in the mountains but also at sealevel. It is now known, of course, that the stratospheric ozone screen is breaking down, not just over the tropics, but also in the polar regions over Antartica and the Arctic. The cause is the continued accidental release of a product of the mid-20th century, the man-made chlorofluorocarbon gases (CFCs or "Freons"). As Molina and Rowland (1974) and their colleagues discovered, these chlorine compounds escaping from aerosol cans, refrigerators, and air conditioners into the atmosphere, rise to high altitudes where they break down the stratospheric ozone molecules. This is summarized in Rowland (1989). We still know relatively little of the effects of solar and sky UV-B irradiation on the growth and physiological processes of plants. However, Caldwell's (1968) pioneer work has set the stage for what we do know at present. And, his research group and ours has continued to work on these problems with particular reference to alpine and crop plants (Caldwell, et al., 1980, 1982; Billings,1984).

Reflectance of UV-B is generally less than 10% from glabrous leaves. However, some species with glaucous or pubescent leaves reflect a considerable fraction of the UV-B irradiance. In the very high UV-B environment on the alpine summit of Haleakala (3,024 m.) on Maui, the light-colored pubescent leaves of Geranium tridens reflect ca. 20% of the ultraviolet irradiance across the UV spectrum from 290-400 nm.(Robberecht, et al., 1980) Its neighboring species in that barren, open landscape, Argyroxiphium sandwicense (silversword or "ahinahina"), reflects from its silvery appressed pubescence about 40% of the UV across the same spectral gradient. Modification of epidermal transmittance either by reflectance or absorbance resulting in lower UV-B irradiance at the level of the mesophyll may represent one mechanism toward acclimation by plants to UV-B radiation. It appears that plants growing in a naturally high UV-B environment have developed genetic ways that maintain reproductive phenology and carbon uptake in spite of increased UV-B

Caldwell, et al. (1982) found experimentally, with several ecotypic or species pairs from the arctic-alpine zone along the Cordillera, that UV-B radiation inhibits photosynthesis. These taxa included arctic and alpine ecotypes of Oxyria digyna, the arctic Taraxacum lateritium and a Taraxacum sect. Mexicanum from 4,000 m. elevation in the Peruvian Andes,and Lupinus arcticus from northern Alaska vs. L. meridanus from the Venezuelan Andes at 3,000 m. .They found that the arctic ecotypes of Oxyria, the arctic Lupinus, and the arctic Taraxacum were consistently and significantly more sensitive to UV-B iirradiation than their southern Rocky Mountains or Sierran ecotypes (Oxyria) or Andean counterpart species (Taraxacum, Lupinus) in regard to inhibition of photosynthesis.The arctic taxa exhibited short-term fluorescence transients indicating damage to the oxidizing side of Photosystem II in the photosynthetic light reaction. There was no indication of this in the alpine taxa.

Essentially, we can conclude that middle-elevation and tropical alpine plants have evolved in the presence of high UV-B irradiation and reflect or screen it out epidermally. Nevertheless, alpine UV-B is likely to increase in the next decades. We do not know for sure what this will actually mean in regard to the ecophysiology of alpine plants.

Possible Changes in Snowfall and Runoff

Wind, snowdrift patterns, and meltwater runoff govern the local distribution and community structure of most alpine-subalpine herbaceous and woody alpine plants since all can metabolize, grow, and reproduce at low temperatures after thaw. Referring back to Figure 2 on the effects of topography and wind force on snow, one can deduce that the mountain mesotopograhic snow gradient controls alpine community structure and vegetational pattern (Billings, 1973). Meltwater meadows lying below relatively early-melting snowdrifts are the most productive alpine and subalpine ecosystems (Billings and Bliss, 1959).

Precipitation types and regimes of the next century are more difficult to predict than atmospheric $CO_2$ concentrations or changes in temperature.in regard to the earth as a whole. Such predictions are even more difficult in mountains than elsewhere because of the complexity of topographic, geographic, and atmospheric factors involved. Certainly, whether or not precipitation, particularly snowfall, increases or decreases in the western North American mountains, there will be considerable impact on runoff as it affects urban water supplies and agricultural irrigation water in these arid and semi-arid lowland regions. In all such dry regions in the middle latitudes, water supply is largely dependent on mountain snowpacks, and especially so now that subterranean aquifers are being depleted.

Migrations of Species in Response to Warming

The upward movement of timberlines in the western North American Cordillera could eventually result in smaller and less continuous mountain peak and high ridge "islands" that would decrease the opportunities for migration of the alpine biota either north or south. In colder climates of the past, these Cordilleran routes were open and available to many cold-tolerant species of plants, a situation that has already been reduced in the last two or three centuries. Some species will become extinct, locally at least, but others migrating up from below may take their places and change the composition and functioning of the ecosystem.

As an example, Hofer (1992) has tabulated lists of vascular plant species on 14 peaks in the Bernina region of the Swiss Alps between the years 1905 and 1985. On 12 out of the 14 peaks, in the subnival and nival zones, significant immigration of species from below has occurred in that period of 80 years in this century. All the adventive species now present at the end of those 80 years are typically alpine or arctic taxa with seeds mostly distributed by wind. The average number of species per peak has increased from 16 to 28. Hofer attributes this increase to the rise in temperature on these mountains in this century and the retreat of glacial and firn ice. The rise in temperatures between 1911 and 1990 in the higher zones of the Alps is ca. 0.6 to 0.8 degrees C. Rubel (1912) reporting on his 1905 survey that is the initial basis of Hofer's comparison, listed 70 species of vascular plants above timberline on 20 Bernina peaks. Hofer, using only 14 of these 20 peaks, now has found 108 species. Only one peak, Piz Languard at 3,261 m., has fewer species now than found by Rubel in his 1905 census. Apparently, in the Bernina Alps, immigration from below has dominated considerably over extinction during this century.

## MOUNTAIN CLIMATIC CHANGE? THINGS TO DO NOW

1. Establish, census, and maintain permanent plots and transects on LTERs and elsewhere.

2. Remote sensing of larger areas.

3. Continuous ground truth documentation of vegetation, flora, and biotic populations.

4. All of the above, both within ecosystems and across ecotones.

5. Continuous measurements of environmental factors with attention to notable changes in temperature, precipitation, and runoff.

6. Make predictive models using all physical and biotic information from the above data.

## MY GENERAL BIOSPHERIC CONCLUSIONS

In the last two or three centuries, within the span of the Industrial Revolution, there has been a "speed up" of environmental and biospheric change that, in many cases, is almost logarithmic in progression. Much of his acceleration has been caused by well-documented changes in composition and temperature of the atmosphere. Extinction and migration of the biota are also increasing; much of this is due to deforestation. As a result, these latter centuries have been filled with biospheric "surprises" that were not expected, not predicted, and that have changed our world. These surprises also include human population increases and wars.

In the last decade, much attention has been given to the question "Are ecosystems and the biosphere sustainable?" (Clark and Munn, 1986; Lubchenco, et al., 1991).

This is not a trivial question. The future of the earth as a habitable place depends upon the answer. Lubchenco and her committee propose three research priorities: (1) Ecological causes and consequences of global change in all its aspects; (2) Ecological determinants and consequences of biological diversity and the effects of global and regional changes on such diversity; (3) The management of sustainable ecological systems and the interface between ecological processes and human social systems. The implementation of this very important and complex research program on earth ecology is spelled out in detail in Lubchenco' committee report.

The most succinct and to the point approach to the question of the principles of ecosystems sustainability is that of Chapin (1993). He defines "a sustainable ecosystem as one .... that maintains its characteristic diversity of major functional groups, productivity, and rates of biogeochemical cycling in the face of some disturbance". Such a system occurs when negative feedbacks tend to maintain the current characteristics of an ecosystem; positive feedbacks hasten change away from stability and the status quo.

Can future biospheric characteristics and interactions be predicted? At this period in time, estimates of approximate values and fluxes can be attempted by monitoring changes of all kinds on a global basis by experiments both in the field and under controlled conditions using intact or synthetic microcosms of native species and by mathematical modeling. Facts are necessary to all of these approaches. We must conserve all sources of these facts ("information") before they are lost forever: genetic,environmental, populational, communities, ecosystemic, and people, all in the broadest sense. And, we must be ready for surprises.

Beyond all this, cooperation is needed between and among all the sciences including ecology and economics, between the sciences and politics ("governments"), and among nations. The "braided stream" flows on, and ever faster.

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# VEGETATION RESTORATION RESEARCH, ROCKY MOUNTAIN NATIONAL PARK: PATTERNS OF SECONDARY SUCCESSION FOLLOWING ANTHROPIC DISTURBANCES

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## ABSTRACT

Numerous anthropic disturbances have occurred in Rocky Mountain National Park (RMNP). A goal of the National Park Service is to restore these disturbed areas to late-seral conditions. In order to minimize further anthropic influences, the restoration technique of choice is natural secondary succession. We began studies in 1991 to evaluate patterns and rates of secondary succession in RMNP. We located 58 sites where anthropic disturbances such as homesteads, sawmills, and lodges had occurred and selected 18 for sampling. We evaluated recovery by comparing vegetation and soil characteristics on these sites to those on nearby reference areas.

Our results suggest that natural secondary succession is an effective method of vegetation restoration on many sites in RMNP, but that successional dynamics are influenced by intensity and size of disturbance. Our data indicate that unaided secondary succession requires approximately 100 years in grasslands and shrublands and 200-300 years in forests to redevelop appropriate late-seral communities. Sites that have been intensively impacted may require some artifical restoration efforts to redevelop appropriate communities within these time spans.

## INTRODUCTION

Rocky Mountain National Park was established in 1915 to perpetuate the natural ecosystems within the Park in as near pristine conditions as possible. Prior to its establishment, numerous anthropic disturbances occurred on sites now within RMNP. In addition, some settlement and private recreational activities continued after 1915, and some privately-owned properties still remain within Park boundries. It has been the policy of the National Park Service (NPS) since the earliest days of RMNP to acquire these properties whenever possible and to remove most buildings after acquisition.

The anthropic disturbances varied considerably as to type, intensity, and duration of disturbance. Disturbances included mines, homesteads, sawmills, roads, settlements, lodges, cabins, camps, a ski-slope and lift, a golf course, livestock grazing, haying, and an asphalt mixing plant. Some of these activities began in the 1870s. Logging and most mining operations ended around 1920, but ranching operations continued on some homesteads until the mid-1930s. Large-scale removal of settlements, lodges, and cabins began in the 1930s and continued through the 1960s. This process of removal of buildings continues to date as additional sites are acquired by the NPS.

A primary goal of the NPS is to restore disturbed sites to apropriate late-seral conditions with a minimum of additional human impact. To do so, it is necessary to reasonably estimate the rate and degree of recovery via natural secondary succession. If secondary succession on anthropic disturbance sites is progressing at an acceptable rate and in an acceptable direction, natural secondary succession would seem to be the restoration technique of choice because it would not further contribute to human impact. However, if natural secondary succession proceeds too slowly, or if it results in an undesirable plant community occupying the site, artifical restoration efforts, of some degree, are required.

In 1991, RMNP funded a set of research projects to study successional dynamics on anthropic disturbance sites in the Park. In particular, RMNP personnel were interested in developing quantitative estimates of the rates and patterns of secondary succession on as many anthropic disturbance sites as possible in RMNP and determining if abandoned roadways provided unique or especially difficult sites for vegetation restoration via natural secondary succession. In this report, we will present results of a preliminary analysis of data from our study of rates and patterns of secondary succession on anthropic disturbance sites.

## OBJECTIVES

There were three objectives to this project: 1) to locate and mark as many anthropic disturbance sites as possible, 2) to compare vegetation and soil characteristics of these sites with adjacent reference sites, and 3) to estimate successional dynamics and recovery rates from these data.

## METHODS

An inholding file is maintained in the RMNP Library. This file contains historical information on most properties in

RMNP acquired by the NPS after establishment of the Park and information on many of the sites included in RMNP at the time of establishment. We used information contained in these files to determine specific locations of some anthropic disturbances and general locations of a number of others. The files contained information on a total of 166 anthropic disturbances. A list of 85 possible initial sampling sites was compiled from the larger list and consisted of 10 settlements, 7 sawmills, 12 lodges or major homesteads, 19 cabins or minor (short-term) homesteads, 33 shelters or temporary cabins, and 4 roads or major ditches. Discussions with Park personnel were conducted relative to sampling priorities based on these two lists. A short-list was developed from the list of 85 sites and was used to establish sampling priorities.

A total of 58 disturbance sites were located in the field and each site was marked with a steel rebar-stake. One of three criteria were considered necessary to establish a disturbed site location. 1) The inholding files contained photographs of some of the structures, taken while the structures were in use or at the time of removal. If these photographs were available, verification of the site could often be made based on landscape features in the photograph. However, we also required physical evidence at the site (e.g., cans, broken glass, foundation stones) before we considered the site to be verified. 2) Physical evidence of a building (e.g., boards, nails, broken window glass, foundation stones, sheet metal) was considered sufficient to establish a site location. 3) Other types of debris were considered sufficient if they were of a type consistent with the disturbance (e.g., broken tools, saw blades, broken dishes, pieces of furniture). Perhaps the most common types of debris were cans, wire, and broken glass. However, these were not considered sufficient evidence unless in large quantities (suggesting a dump site) or in association with other debris (such as boards or window glass) because cans and bottles could have been transported to the site by water or cast down by campers or hikers.

The 58 sites consisted of 13 homesteads, 5 sawmills, 4 camps, 7 lodges, 23 cabins, 2 mines, and 4 stores. Eight of these sites had not been previously recorded, the precise locations of another 10 had not been previously recorded, and the locations of another 2 had been incorrectly mapped. Time limitations precluded sampling on the west side of RMNP, all but one of the 58 sites being east of Milner Pass.

Eighteen of the 58 sites were selected for sampling. These consisted of 6 grassland, 6 shrubland, and 6 forest sites (Table 1). Selection of these sites was based on ecological and management goals. Effort was made to include as many

Table 1. Descriptions of 18 disturbance study sites, Rocky Mountain National Park, Colorado.

| Site | Ecosystem Type | Elevation (m) | Years Since Disturbance | Type of Disturbance |
|---|---|---|---|---|
| Barnes Homestead | Grassland | 2570 | 59 | Homestead |
| Osborn Homestead | Grassland | 2570 | 59 | Homestead |
| Horseshoe Cabins | Grassland | 2580 | 62 | Cabins |
| Horseshoe Inn | Grassland | 2590 | 60 | Lodge |
| Ashton Homestead | Grassland | 2640 | 46 | Homestead |
| Mill Creek RngSta | Grassland | 2750 | 33 | Ranger Sta |
| Hupp Homestead 1 | Shrubland | 2560 | 59 | Homestead |
| Hupp Homestead 2 | Shrubland | 2560 | 59 | Homestead |
| Hollowell CCC | Shrubland | 2590 | 48 | Camp |
| Mill Creek Sawmill | Shrubland | 2600 | 101 | Sawmill |
| Allens High Drive | Shrubland | 2620 | 60 | Store |
| Lynch Cabin | Shrubland | 2770 | 33 | Cabins |
| Hollowell Cabin | Forest | 2600 | 101 | Cabin |
| Mill Creek Cabin | Forest | 2620 | 84 | Homestead |
| Horseshoe Rng Sta | Forest | 2650 | 64 | Ranger Sta |
| Hidden Valley Swm | Forest | 2690 | 82 | Sawmill |
| Bear Lake Lodge | Forest | 2910 | 29 | Lodge |
| Fern Lake Lodge | Forest | 3000 | 17 | Lodge |

Table 2. Mean canopy cover (%) of lifeforms and mean species richness on reference (Refr) and on disturbed (Dstr) sites in three types of ecosystems in Rocky Mountain National Park. Values are means of 6 sites per column.

| | Grassland | | Shrubland | | Forest | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Refr | Dstr | Refr | Dstr | Refr | Dstr | Refr | Dstr |
| Trees | 3.4 | 6.4 | 5.9 | 4.6 | 59.3 | 29.4 | 24.4 | 13.5 |
| Shrubs | 0.9 | 2.1 | 21.0 | 16.9 | 5.9 | 6.8 | 9.7 | 8.6 |
| Grasses | 35.2 | 41.1 | 28.8 | 33.1 | 4.3 | 12.4 | 22.0 | 29.0 |
| Forbs | 32.5 | 25.4 | 14.4 | 13.6 | 10.6 | 18.9 | 18.4 | 19.3 |
| Lichens/moss | 1.7 | 1.9 | 3.5 | 2.8 | 3.1 | 7.2 | 2.8 | 5.1 |
| Total | 74.6 | 79.1 | 74.6 | 71.0 | 83.0 | 74.8 | 77.6 | 75.0 |
| Species | 34.6 | 36.6 | 33.0 | 35.7 | 18.8 | 26.2 | 28.5 | 32.8 |

sites as possible in order to increase the scientific value of the sampling and the usefulness to the NPS in making management decisions. Important considerations in site selection included: 1) a gradient in general landscape types was desired, 2) sites were selected to allow for maximum chronosequence gradient sampling, 3) sampling was concentrated on a single type of disturbance (i.e., buildings), 4) sufficient replication for adequate statistical analysis was required, and 5) specific sites important in Park management considerations were included.

At each site, the disturbed area was delineated on the ground as clearly as possible, based on historical information and visual evidence. Ten permanent line transects were placed at each sampled site, with the transects placed equidistantly along, and perpendicular to, the longest axis through the site, and extending across the disturbed area. Care was taken to assure, as much as possible, that the entire area within the grid was within the disturbed area.

Canopy cover, by species, was estimated at 1-m intervals along seven of the ten transects per site. These seven transects were randomly selected and the remaining three transects were used for biomass and soil sampling. Two 10-cm deep soil samples were taken from randomly located points along each of the three biomass/soil transects and the sample analyzed for texture and chemical properties (pH, CEC, % OM, available N, and available P). The plant biomass and soil data will not be presented in this report.

A reference area was selected near each sampled disturbed site such that the two areas (disturbed and reference) were as ecologically similar as possible except for the disturbance. The vegetation and soils of the reference area were sampled in the same manner as for the disturbed area. It should be noted that the reference area can not be considered an undisturbed area. It likely was disturbed to some degree by activities associated with the nearby disturbance. For example, if the disturbance was a homestead, the reference area was probably impacted by grazing. If the disturbance was a sawmill, the reference area may have been logged. However, there was no evidence, physical or vegetative, that structures were located on, or adjacent to, the reference area. The purpose of the reference area was to provide a measure of what the disturbed area might have been like had the disturbance structure not been present.

Paired-t tests were used to determine if there were significant differences between mean canopy cover of each major species and each soil variable from disturbed and reference areas at each site. Differences in means of minor species were not tested for significance because of the high probability that these values are not normally distributed. Analysis of variance (ANOVA) was used to test the significance of differences among sites.

A similarity index was computed for each disturbed site to estimate recovery. Canopy cover, by species, was compared between disturbed and reference areas at each site. The smaller values of each pair were summed and the sum divided by the total canopy cover of the reference area. This quotient was termed the recovery index score for that site. This results in a very conservative estimate of recovery because it requires the disturbed area to return to exactly the same species composition as the reference area. This is not likely to happen since no two portions of the reference area itself are likely to be exactly the same.

A second index was therefore computed for each site, in which the recovery standards were not as strict. The second index was computed in a similar manner to the first, except that the canopy cover value, by species, on the disturbed area was compared to the 95% confidence interval of the mean canopy cover value for that species on the reference area. This method allows for some variation among transects to be included in the index score. However, only the first index will be presented in this report.

Recovery rate (% per year) was estimated by determining mean annual rate of recovery (recovery index/number of years since disturbance) and multiplying this number by 100. This value assumes a linear relationship between rate of secondary succession and time, which may not be accurate (Whipple and Dix 1979, Leps 1987). Studies of rate of successional recovery in other ecosystems give mixed results, some suggesting more rapid rates initially (Aplet et al. 1988), some slower initial rates (West et al. 1984), and some relatively constant rates (Collins et al. 1987). However, since the values used in this study were point estimates (sampled at only one point in time), only these simple estimates are possible from the data set. More complex response curves can be estimated from the literature or could be computed if data are collected from these sites over time.

Estimated time to full recovery was computed from recovery rate. Recovery rate, expressed as percent, was divided into 100 to give number of years for full recovery of the disturbed site. Like the recovery rate estimate, this was a simple linear relationship, which is probably too simplistic. However, it is a quantitative estimate that can be recomputed as additional data become available. Simple linear regression analysis was then used to test the significance of the model:

Percent recovery = a + b(years since disturbance).

## RESULTS AND DISCUSSION

### Species Composition

Overall, composition by lifeforms was similar between reference and disturbed areas in grassland and shrubland ecosystems after an average of 57 years of secondary succession (Table 2). Webb et al. (1987) reported a similar recovery time for structural redevelopment in arid shrublands in the Mojave Desert (46-64 yr).

Disturbed forest ecosystems had not recovered as well as grassland and shrubland ecosystems. Canopy cover of trees was less than half that of reference areas and canopy cover of herbaceous species was twice that of reference areas after an average of 63 years (Table 2). Species richness between reference and disturbed areas was similar in both grassland and shrubland ecosystems but was higher on disturbed forest sites than on reference forest sites (Table 2).

Although there were only minor differences between reference and disturbed grassland and shrubland areas based on lifeform, there were major differences based on species composition (Table 3). Reference grassland areas had higher amounts of the native grasses Bouteloua gracilis and Muhlenbergia montana and lower amounts of the non-native grasses Bromus inermis and Poa pratensis and the native grass Stipa comata than did disturbed grasslands. Reference shrubland areas had higher amounts of the late-seral shrubs Artemisia tridentata and Purshia tridentata, the late-seral grasses Agropyron spicatum and Muhlenbergia montana, and the forbs Potentilla pulcherrima and Thermopsis rhombifolia than did disturbed shrubland areas. Disturbed shrubland areas supported higher amounts of the grasses Agropyron smithii, Festuca ovina, and Stipa comata and the early-seral forbs Artemisia ludoviciana and Grindelia squarrosa than reference shrubland areas.

Reference forest areas had higher amounts of the trees Abies lasiocarpa, Picea pungens, Pinus contorta, and Pinus ponderosa than disturbed forest areas and disturbed forest areas had higher amounts of Populus tremuloides (Table 3). Although both areas had the same amount of shrub cover, species composition was different. Vaccinium sp. was most abundant on reference areas and Juniperus communis on disturbed areas. Disturbed forest areas also had more herbaceous cover than reference areas (Table 2). Eight species contributed most of this difference: two grasses Agropyron spicatum and Poa pratensis and six forbs Achillea lanulosa, Artemisia

Table 3. Mean canopy cover (%) of major species on reference (Refr) and on disturbed (Dstr) sites in three types of ecosystems in Rocky Mountain National Park. Values are means of six sites per column. A "t" indicates a trace amount (< 0.05%).

| | Grassland | | Shrubland | | Forest | |
|---|---|---|---|---|---|---|
| | Refr | Dstr | Refr | Dstr | Refr | Dstr |
| *Abies lasiocarpa* | 0.0 | 0.0 | 0.0 | 0.0 | 10.2 | 1.6 |
| *Picea pungens* | 0.0 | 0.0 | 0.0 | 0.0 | 12.3 | 1.7 |
| *Pinus contorta* | 0.0 | 0.0 | 0.0 | t | 24.1 | 10.0 |
| *Pinus ponderosa* | t | 4.5 | 6.3 | 3.6 | 6.8 | 0.4 |
| *Populus tremuloides* | 3.4 | 1.9 | 0.3 | 0.0 | 0.0 | 9.0 |
| *Pseudotsuga menziesii* | 0.0 | 0.0 | 0.3 | 1.1 | 4.9 | 5.6 |
| | | | | | | |
| *Artemisia tridentata* | 0.0 | 0.1 | 12.4 | 9.2 | 0.0 | 0.1 |
| *Chrysothamnus viscidiflorus* | 0.5 | 1.0 | 1.8 | 2.2 | 0.0 | 0.0 |
| *Juniperus communis* | 0.9 | 0.2 | 0.2 | 0.0 | 0.9 | 5.3 |
| *Purshia tridentata* | 0.0 | 0.0 | 6.0 | 5.0 | 0.0 | 0.0 |
| *Vaccinium* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 4.7 | 0.2 |
| | | | | | | |
| *Agropyron smithii* | 2.1 | 2.8 | 0.3 | 2.6 | 0.0 | 0.1 |
| *Agropyron spicatum* | 0.6 | t | 3.6 | 1.4 | 0.1 | 0.8 |
| *Bouteloua gracilis* | 5.7 | 0.6 | 0.9 | 1.0 | 0.0 | 0.0 |
| *Bromus inermis* | 0.2 | 2.0 | t | 1.2 | t | 0.2 |
| *Danthonia parryi* | 4.7 | 4.0 | 0.1 | 0.1 | 0.0 | t |
| *Festuca ovina* | 0.6 | 1.4 | 0.9 | 6.3 | 0.1 | 0.1 |
| *Koeleria pyramidata* | 1.5 | 1.9 | 2.5 | 1.9 | 0.1 | 0.4 |
| *Muhlenbergia montana* | 4.0 | 2.3 | 5.3 | 2.4 | 1.2 | 1.3 |
| *Phleum pratense* | 3.0 | 1.4 | 0.1 | 0.0 | 0.3 | 1.2 |
| *Poa pratensis* | 7.3 | 16.4 | 12.0 | 13.1 | 1.2 | 6.2 |
| *Stipa comata* | 2.7 | 6.6 | 1.2 | 2.2 | 0.0 | 0.0 |
| | | | | | | |
| *Achillea lanulosa* | 1.2 | 1.2 | 0.1 | 0.1 | 0.2 | 1.6 |
| *Antennaria parvifolia* | 2.5 | 1.3 | 1.0 | 0.5 | 1.8 | 0.9 |
| *Artemisia frigida* | 2.0 | 1.2 | 0.8 | 0.7 | 0.0 | t |
| *Artemisia ludoviciana* | 0.7 | 1.1 | 0.7 | 2.0 | 0.1 | 0.9 |
| *Aster foliaceous* | 0.3 | 0.1 | t | 0.1 | 0.5 | 1.4 |
| *Carex* sp. | 3.8 | 4.0 | 1.2 | 0.7 | 2.3 | 3.9 |
| *Chrysopsis villosa* | 4.0 | 1.9 | 0.4 | 0.2 | t | 1.1 |
| *Erigeron* sp. | 3.6 | 0.1 | 0.1 | 0.2 | 0.1 | t |
| *Eriogonum umbellatum* | 0.5 | 1.1 | 1.6 | 1.8 | 0.0 | 0.1 |
| *Grindelia squarrosa* | 0.3 | 0.6 | 0.1 | 1.9 | 0.0 | 0.0 |
| *Potentilla pulcherrima* | 1.1 | 4.2 | 1.1 | 0.4 | 0.0 | 0.0 |
| *Solidago spathulata* | 0.5 | 0.7 | 0.8 | 0.9 | 1.4 | 2.0 |
| *Thermopsis rhombifolia* | 5.5 | 3.7 | 2.6 | 0.5 | 2.0 | 1.9 |

ludoviciana, Aster foliaceous, Carex sp., Chrysopsis villosa, and Solidago spathulata.

These results suggest two important aspects of successional dynamics on these sites. First, disturbed grassland and shrubland ecosystems may recover their primary structural characteristics fairly rapidly (< 50 yrs) as evidenced by similar canopy cover of lifeforms between reference and disturbed areas, but species composition takes much longer to recover. This may also be true of disturbed forest ecosystems, but the time required for even structural recovery is longer than that sampled in the chronosequence reported here. Second, non-native and "weedy" species are much more abundant on anthropic disturbance areas than on reference areas, even after an average of 60 years. Of the four non-native grasses listed in Table 3, disturbed areas had an average canopy cover of 16.4% compared to 8.6% on reference areas. Of the five forbs normally considered to be early-seral or "weedy", disturbed areas had an average canopy cover of 5.0%, compared to 3.6% on reference areas.

Recovery Rates

Overall, the mean time since disturbance was 59 years and the mean recovery index score was 0.442, suggesting a mean recovery time of 161 years (Table 4). Disturbances occurred on the grassland sites 33 to 62 years ago and recovery rates ranged from 1.2% per year on the most recently disturbed site to 0.7% per year on the oldest (Table 4). Mean estimated time to recovery of disturbed grassland sites was 112 years (Table 4). Based on soil organic matter, Dormaar et al. (1990) estimated that recovery of previously cultivated grasslands in southern Alberta through natural succession may take 75-150 years.

Shrubland sites, which were all dominated by big sagebrush (Artemisia tridentata), had a longer period of disturbance and a rate of recovery that was approximately equal to that of the grassland sites. Mean estimated time to recovery of disturbed shrubland sites was 119 years (Table 4). This compares favorably with the rate of recovery (130 years) estimated by Carpenter et al. (1986) for upper elevation sagebrush/juniper shrublands in the Mojave Desert.

Forests had slower rates of recovery, although the differences between forests and grasslands and forests and shrublands were not significant because of the high variability in the forest data set (Figure 1). Three forest sites had estimated recovery rates similar to those of grassland and shrubland ecosystems and three forest sites had much slower recovery rates (Table 4). Two of the forested

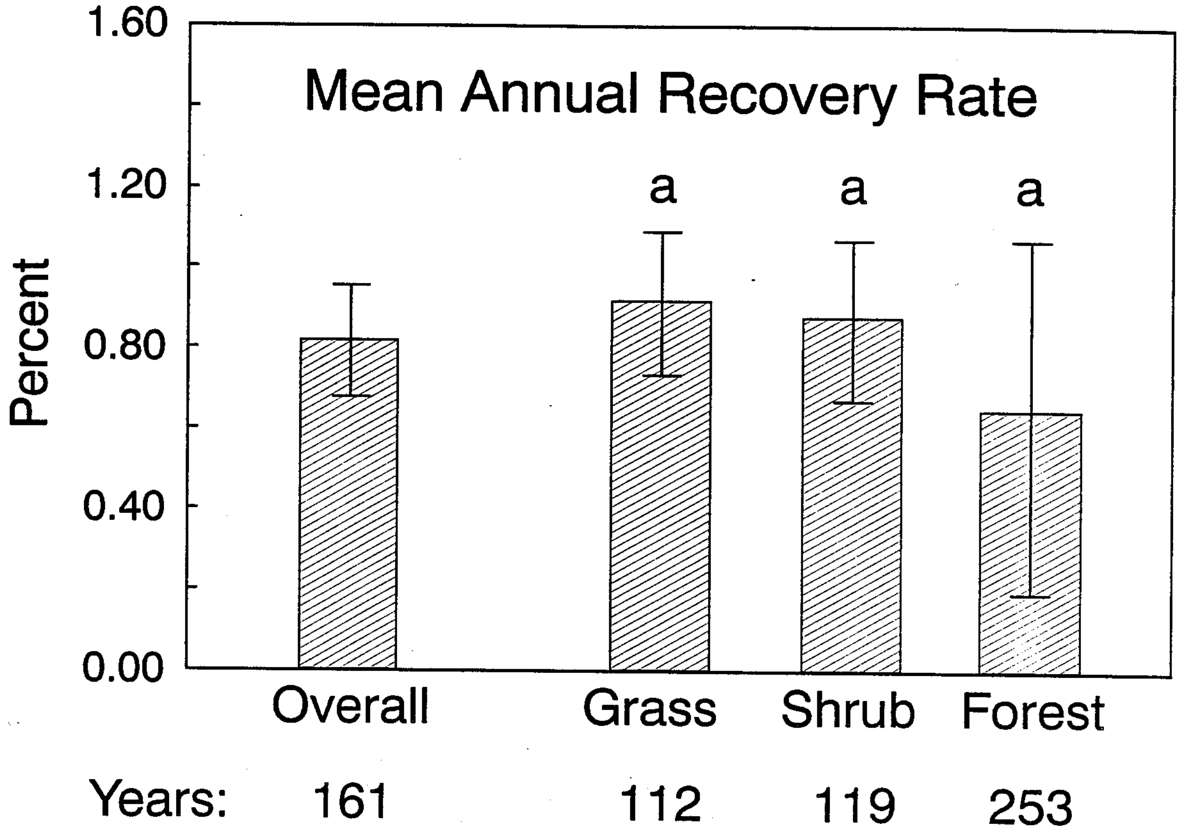



Figure 1. Mean annual recovery rates, overall and by ecosystem type, of disturbed sites in Rocky Mountain National Park. Values are means of 18 sites overall and 6 sites for each ecosystem type. Error bars represent 95% confidence intervals of the means. Letters above bars indicate significance of differences in means (95% level, Tukey's Mean Separation Test).

Table 4. Recovery index scores and rates of recovery for 18 disturbed sites in Rocky Mountain National Park, Colorado. Years refers to number of years since disturbance. Recovery rate is the recovery index score divided by number of years since disturbance, multiplied by 100 (mean annual percent basis). Estimated years to full recovery is number of years from disturbance, based on recovery rate.

| Site | Ecosystem Type | Years | Recovery Index Score | Recovery Rate (%/yr) | Estmtd Years To Full Recovery |
|---|---|---|---|---|---|
| Mill Creek Ranger Sta | Grassland | 33 | 0.394 | 1.19 | 84 |
| Ashton Homestead | Grassland | 46 | 0.438 | 0.95 | 105 |
| Barnes Homestead | Grassland | 59 | 0.447 | 0.76 | 132 |
| Osborn Homestead | Grassland | 59 | 0.579 | 0.98 | 102 |
| Horseshoe Inn | Grassland | 60 | 0.565 | 0.94 | 106 |
| Horseshoe Cabins | Grassland | 62 | 0.420 | 0.70 | 143 |
| Lynch Cabin | Shrubland | 33 | 0.214 | 0.65 | 154 |
| Hollowell CCC Camp | Shrubland | 48 | 0.321 | 0.67 | 149 |
| Hupp Homestead 1 | Shrubland | 59 | 0.542 | 0.92 | 109 |
| Hupp Homestead 2 | Shrubland | 59 | 0.573 | 0.97 | 103 |
| Allens High Drive Inn | Shrubland | 60 | 0.693 | 1.15 | 87 |
| Mill Creek Sawmill | Shrubland | 101 | 0.898 | 0.89 | 112 |
| Fern Lake Lodge | Forest | 17 | 0.187 | 1.10 | 91 |
| Bear Lake Lodge | Forest | 29 | 0.257 | 0.89 | 112 |
| Horseshoe Ranger Sta | Forest | 64 | 0.677 | 1.06 | 94 |
| Hidden Valley Sawmill | Forest | 82 | 0.344 | 0.42 | 238 |
| Mill Creek Cabin | Forest | 84 | 0.133 | 0.16 | 625 |
| Hollowell Cabin | Forest | 101 | 0.282 | 0.28 | 357 |
| Mean of grassland sites | | 53 | 0.474 | 0.92 | 112 |
| Mean of shrubland sites | | 60 | 0.540 | 0.88 | 119 |
| Mean of forest sites | | 63 | 0.313 | 0.65 | 253 |
| Overall mean | | 59 | 0.442 | 0.82 | 161 |

sites with rapid recovery rates, Fern Lake Lodge and Bear Lake Lodge, were relatively recent disturbances (Table 4) and the sites were at relatively high elevations (Table 1). This suggests that there is a rapid initial recovery pulse under upper elevation climatic conditions. This rate of recovery may slow significantly as the trees begin to mature.

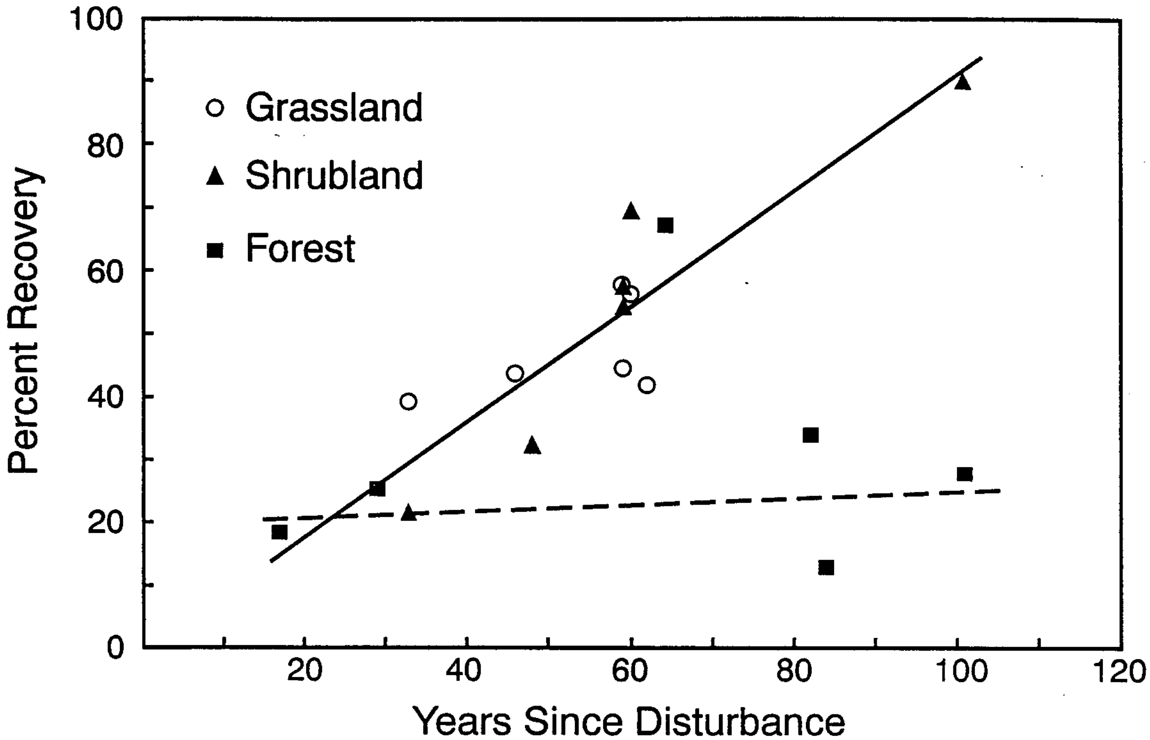
The third forest site with a rapid recovery rate, Little Horseshoe Ranger Station, was at a lower elevation (Table 1), but was a relatively small disturbance surrounded by an intact lodgepole pine forest. Lodgepole pine (Pinus contorta) has a relatively rapid initial recovery rate compared to spruce (Whipple and Dix 1979, Romme and Knight 1981) which, with the small area involved, might explain the rapid recovery rate at this site.

The remaining three forest sites were at approximately the same elevation as the Little Horseshoe Ranger Station site, but were in (Hidden Valley Sawmill and Mill Creek Cabin) or at the edge of (Hollowell Cabin) spruce forests. Their rates of recovery were much slower than the other three forest sites, but were similar to values reported in the literature for western coniferous forests (Whipple and Dix 1979, Romme and Knight 1981, Aplet et al. 1988, Boone et al. 1988).

A simple linear regression analysis of percent recovery as a function of time since disturbance was highly significant and resulted in an $r^2$ of 0.81 (Figure 2), when using the 15 sites with recovery rates $\geq$ 0.7 (Table 4). A second linear regression using five of the six forest sites (excluding the Little Horseshoe Ranger Station site) also resulted in a highly significant regression, but one with a slope much less than that of the first regression (Figure 2). These results suggest that there is a major difference between recovery rates on forests and those on grasslands and shrublands.

## CONCLUSIONS

Our results indicate that natural secondary succession is an effective method for vegetation restoration in RMNP on sites where the primary anthropic disturbance was a building. We estimate that such sites in grassland and shrubland ecosystems will take approximately 100 years to recover to a level similar to the vegetation on adjacent sites that did not support such buildings. Disturbed sites in forest ecosystems will take longer to recover, perhaps on the order of 200-300 years.




Solid line: 6 grassland, 6 shrubland, 3 forest sites

$Y = 1.01 + 0.89X \qquad r^2 = 0.810 \qquad F = 30.26$

Dotted line: 5 forest sites

$Y = 20.44 + 0.058X \qquad r^2 = 0.920 \qquad F = 40.14$

Figure 2. Linear regressions of percent recovery as a function of years since disturbance.

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# RESTORATION APPROACHES IN GRAND TETON NATIONAL PARK:

# A CASE STUDY

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## ABSTRACT

Plant community development was examined in response to various restoration approaches on an abandoned road in Grand Teton National Park in northwestern Wyoming. Various restoration methods, ranging from minimal to intense manipulation, were tested over a four year period. Experimental treatments included seedbed scarification, fertilizing, seeding (indigenous vs. commercial natives), topsoiling and mulching. Plant cover and production were estimated and soil physical attributes (bulk density, infiltration, aggregate stability) were tested to determine the effect of soil properties on restoration efforts. The specific vegetation data from the fourth year of the study are presented, along with seasonal plant community trends from the entire study. Soil properties have been identified that contribute to restoration success on various treatments.

In summary, four years of study has identified several experimental treatments which are capable of restoring the disturbed plant community to a composition and appearance that is similar to the undisturbed community. The use of topsoil in conjunction with indigenous seed and natural recolonization were successful in achieving an acceptable plant community. In absence of topsoil, soil ripping and seeding with indigenous plant materials were successful in developing a plant community that should approximate undisturbed community characteristics, with time.

## INTRODUCTION

Disturbances within National Parks may occur both naturally and anthropogenically within the same ecosystem. Disturbances typically vary in both intensity and size and may require different restoration approaches to restore natural plant communities which represent local genetic resources. The National Park Service (NPS) philosophy for plant community restoration varies from Park to Park; however, the underlying theme is to utilize natural regeneration; or, if seeding is desired, the seed should originate from local plant communities. The NPS has recently developed cooperative agreements with various SCS plant materials centers to propagate and increase seed stocks of a select group of species to facilitate restoration.

Considerable research has been conducted regarding traditional reclamation techniques for disturbances in the western U.S. Research has concentrated on the positive effects of topsoil (Packer and Aldon 1978 and Hargis and Redente 1984); amount of topsoil required (Barth and Martin 1982 and Schuman et al. 1985) and the relationship between topsoil and plant community development (Stark and Redente 1985, Depuit 1984 and Pinchak et al. 1985).

Cultural practices such as scarifying (Hodder 1975, 1978, 1979 and Richardson 1979) pitting and furrowing have also been evaluated relative to moisture conservation, increased infiltration, and compaction reduction. These techniques have proven successful in providing increased soil moisture, reducing compaction, and improving seedbed characteristics in semiarid environments. Various mulching materials have also been evaluated (Packer and Aldon 1978 and Cook et al. 1974) relative to erosion control, moisture conservation, and nutrient cycling relationships.

The appropriate selection of plant materials has been a long standing dilemma facing restoration/reclamation specialists. Plant material selection for disturbed lands should ultimately be based on climate, soils, adaptability to disturbed conditions, and management of reclaimed lands (Thornsburg and Fuchs 1978 and Depuit 1988). These considerations perpetuate the use of introduced materials combined with commercially available natives for successful revegetation. Very little research has been conducted relative to the use of indigenous (locally collected) plant materials.

The objectives of this research were intended to evaluate common reclamation approaches and identify suitable methods for restoring abandoned roads in Grand Teton National Park, Wyoming. The specific objectives included the following: 1) determine if topsoiling, scarifying, and mulching can promote community development similar to undisturbed conditions, and 2) compare the response of indigenous plant materials (collected locally) to commercial natives.

## METHODS AND MATERIALS

### Study Site

The study was conducted in Grand Teton National Park near Jackson, Wyoming; T.44N., R.115W., Sec. 31, west of the 6th Principal Meridian (Figure 1). The test plot was located within the disturbed tracks of an existing abandoned homestead road at an elevation of 2075 m.

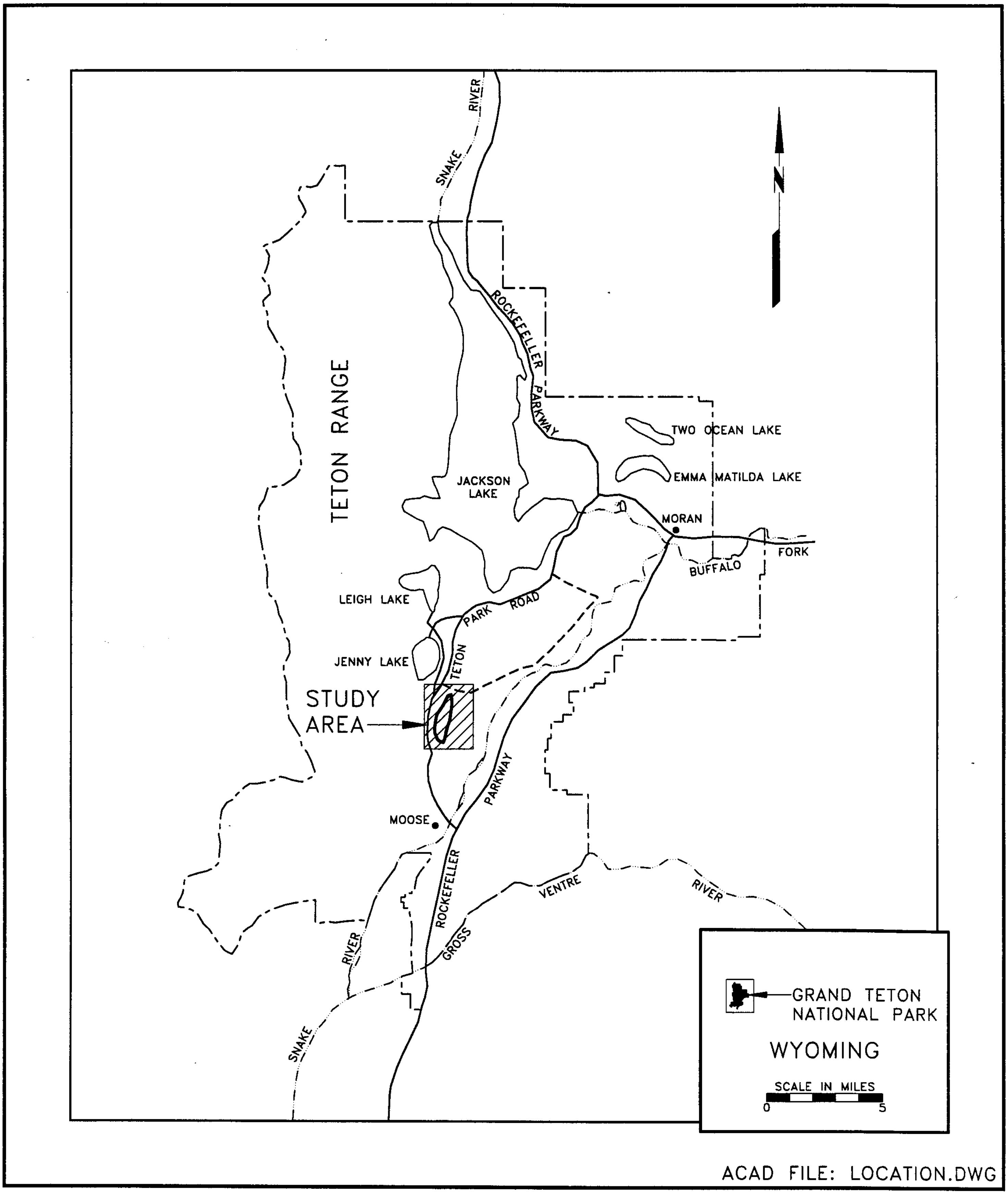


Figure 1. Location of Study Area in Grand Teton National Park.

## Local Climate, Soils, and Vegetation

The climate of the study area is typically semiarid with hot, dry summers and cool wet winters. Average annual precipitation is 68 cm (486 cm of snowfall) with a mean annual temperature of 2.2° C. Soils characterizing the site are classified as loamy-skeletal, mixed typic Cryoborolls and sandy-skeletal, mixed typic Cryoborolls. The soils have formed on stream terraces and alluvial fans as well as glacial outwash materials from the Teton Range (Soil Conservation Service 1982). The soils of this area are characterized as being well drained with moderate permeabilities. The topography is nearly level to gently sloping. The undisturbed plant community surrounding the study site was described by Sabinske and Knight (1978) as a low sagebrush - big sagebrush mosaic.

## Experimental Design

The study was designed as a completely randomized block, with 14 treatments replicated four times. The dimensions of treatments 1-8 are 0.6 m x 6 m to fit within the individual road tracks. Treatments 9-14 were 2.5 m x 6 m or the entire width of the road. The 14 treatments tested are listed below.

<u>Treatments</u>

1. Control
2. Control and aspen/cedar woodchip mulch ($\approx$45 Mg $ha^{-1}$)
3. Indigenous seed (collected within the Park) and brush beating
4. Commercial seed
5. Scarifying (30 cm)
6. Scarifying and rock raking
7. Scarifying, 55 kg P $ha^{-1}$, indigenous seed and brush beating
8. Scarifying, 55 kg P $ha^{-1}$, commercial seed
9. Topsoil (15 cm), scarifying
10. Topsoil (15 cm), scarifying, 55 kg P $ha^{-1}$
11. Topsoil (15 cm), scarifying, 55 kg P $ha^{-1}$, indigenous seed and brush beating
12. Topsoil (5 cm), scarifying, 55 kg P $ha^{-1}$, indigenous seed and brush beating
13. Topsoil (15 cm), scarifying, 55 kg P $ha^{-1}$, commercial seed
14. Topsoil (15 cm), scarifying, 55 kg P $ha^{-1}$, indigenous seed and mulch

## Test Plot Construction

The test plot was constructed in October 1988. The vegetation separating road tracks was removed from those areas designated for treatments 9-14 and topsoil was placed on the respective subplots and spread to either 5 or 15 cm. Topsoil was obtained from exposed lake bottom soils during reconstruction of the Jackson Lake dam. Soil analyses indicated that topsoil and road substrate materials were similar both texturally and nutritionally (Table 1).

Respective treatments were scarified to a depth of 30 cm with a motor grader. Scarification was included as a treatment to reduce compaction. Phosphorus (triple superphosphate) was applied across all treatments (except treatments 1 and 2, control and mulch) at 55 kg P $ha^{-1}$. A subset of these treatments received an additional 55 kg P $ha^{-1}$ as a fertilizer treatment. Nitrogen was applied at the rate of 22 kg N $ha^{-1}$ to all treatments to serve as a source of available N for initial growth. Rock raking was included as a treatment to asses the impact of surface rock on recolonization. A hand rake was used to remove the large cobble and rock from the treatment.

The seeded treatments were broadcast at approximately 35 kg of pure live seed per hectare. The seed was covered by raking to assure adequate seed burial. The seeding treatments consisted of plant materials from indigenous sources of seed and from a commercial source (Table 2). The indigenous seed came from seed collections and brush beating operations within the Park in 1988, while the commercial seed represented improved cultivars or was obtained from similar environments (i.e. elevation and climate). A brush beating operation was included as an attempt to incorporate additional seed materials to respective treatments. Plant materials in the adjacent sagebrush community were mowed, gathered and distributed on the test plot.

Experimental plots were mulched using woodchips consisting of 2 parts aspen and 1 part red cedar shredded to approximately 5 cm in diameter. Mulch was applied at approximately 45 Mg $ha^{-1}$ which resulted in uniform soil coverage to a depth of 2.5 cm.

### Vegetation Sampling

Plant cover on the test plot was estimated by species during four growing seasons from 1989-92 and production was estimated during the 1992 growing season. Sampling was conducted during the period of peak growth in late July. Plant cover was visually estimated to the nearest one percent using a 20 cm x 50 cm quadrat (0.10 $m^2$) randomly placed along a transect through each treatment (Bonham 1989). Production was estimated by clipping all plant materials within a 20 cm x 50 cm quadrat at ground level. All treatments were sampled until sample adequacy was met. Treatment mean cover values were generated by averaging all quadrats within each treatment and replicate to develop species mean cover values and total foliar cover values. Cover values estimated at less than one percent were recorded as trace values.

Table 1. Soil analysis comparisons between topsoil and roadbase soil materials.

| Sample | Paste pH | E.C. mmhos $cm^{-1}$ | Lime (est.) | O.M. % | $NO_3$-N ug $g^{-1}$ | P a | K | Zn | Fe | Mn | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ug $g^{-1}$ | | | | | |
| Topoil b | 6.8 | 0.3 | Low | 2.0 | 1 | 11.0 | 95 | 2.0 | 72 | 5.9 | 2.1 |
| Roadbase b | 5.6 | 0.3 | Low | 2.3 | 1 | 5.0 | 130 | 1.4 | 80 | 5.5 | 1.5 |

| Sample | Sand % | Silt % | Clay % | Texture |
|---|---|---|---|---|
| Topsoil | 55 | 28 | 17 | Sandy Loam |
| Roadbase | 54 | 27 | 19 | Sandy Loam |

a $NH_4HCO^3$-DTPA Extract

b Average of 4 composite samples

Table 2. Homestead plot seed mixtures.

| Indigenous Mixture (Origin: Teton Park) | Rate (kg PLS/ha) | Commercial Mixture (Variety or Origin) | Rate (kg PLS/ha) |
|---|---|---|---|
| *Agropyron trachycaulum* | 1.8 | *Agropyron trachycaulum* (Revenue) | 1.6 |
| *Bromus carinatus* | 5.3 | *Bromus carinatus* (Bromar) | 3.3 |
| *Poa ampla* | 0.26 | *Agropyron spicatum* (Secar) | 1.8 |
| *Artemisia tridentata* | 0.25 | *Poa compressa* (Reubens) | 0.07 |
| *Purshia tridentata* | 14.4 | *Agropyron smithii* (Rosanna) | 0.87 |
| *Lupinus sericeus* | 16.7 | *Artemisia tridentata* (Utah) | 0.37 |
| | | *Artemisia ludoviciana* (Utah) | 0.10 |
| | | *Achillea millefolium* (Idaho) | 0.06 |
| | | *Purshia tridentata* (Nevada) | 7.2 |
| Total | 38.71 | Total | 29.67 |

## Soil Physical Attributes

Field infiltration (Haise et al. 1953 and Wani 1987) and bulk density (Blake 1973) tests were conducted to assess the effect of soil scarifying and topsoiling on infiltration and bulk density characteristics.

Bulk density and infiltration tests were conducted on treatments that were topsoiled and scarified (2 cm and 15 cm topsoil additions), scarified, the control, and the undisturbed areas along the road. Ring infiltrometers were used to perform infiltration tests (Haise et al., 1956). The rings were a variation of the standard ring infiltrometers commonly used for infiltration analysis. The rings were 30 cm deep with a radius of 3.6 cm and were driven into the soil to a depth of 15 cm. Known volumes of water were poured into the ring and infiltration times were recorded. A total volume of 250 mls were poured into the ring infiltrometer for each test.

Bulk density tests were conducted using a volumeasure apparatus (Blake, 1973). A volume of soil was excavated and stored in a soil bag. The volumeasure was placed on the excavated hole and the volume was determined. The collected soils were sieved through a 2 mm screen to separate the coarse fragments from the fine portion of soil materials. The soils were oven dried and weighed to determine the amount of soil occupying the volume removed (the volumes of coarse fragments were subtracted from the total volumes). The bulk density equation is presented below.

$$\text{Bulk Density} = \frac{\text{Weight of oven dried soil}}{\text{Bulk volume of soil}}$$

Aggregate stability analyses were completed on soils from the ripped roadbase and the ripped topsoil treatments. The aggregate analyses employed a soil wetting technique described by Kemper and Rosenau (1986) and a wet sieving technique used by Elliot (1986).

## Statistical Analysis

Plant cover and production data were analyzed using the Analysis of Variance procedure (ANOVA). Significant differences among treatment means were determined using the Least Significant Difference (LSD) test at the 5% level.

The Friedman Block/Treatment nonparametric analysis of variance test (Zar 1984) was also conducted to determine the effect of violating parametric ANOVA assumptions (normality and homogeneity of variance) on probability levels. Tests indicated similar probability levels between parametric and nonparametric analysis techniques. Results indicated that violation of several parametric ANOVA assumptions were not critical in determining significant treatment differences. Parametric ANOVA results were selected for presentation in this paper for ease of understanding because of greater reader familiarity with this statistical approach.

Soil infiltration and bulk density measurements were subjected to the ANOVA procedure. Significant differences among treatments were determined using the Single Degree of Freedom mean separation test at the 5% level.

Statistical analyses were not conducted on the aggregate data. The main objective of conducting the evaluation was to understand the relationship between bulk density, infiltration, and aggregate size and stability of the soils in question.

## RESULTS AND DISCUSSION

### Topsoiling

Plant cover was significantly greater in all topsoiled (9-14) treatments following the fourth growing season compared to non-topsoiled treatments (1-8) (Figure 2). Non-topsoiled treatments did produce a plant community; however, the plant communities supported considerably less plant cover than the topsoiled treatments. In general, the use of topsoil improved the seedbed environment which tended to favor seed germination and contributed to more favorable soil/moisture relationships.

The seeded, topsoiled treatments (Treatments 11-14) were dominated by perennial grasses which accounted for approximately 15% of the total cover. Treatment 12 (5 cm of topsoil, indigenous seed), produced the greatest plant cover (29%) compared to other topsoiled, seeded treatments 11, 13, and 14 which had covers of 21%, 22%, and 24% respectively. In this case, the treatment with 5 cm of topsoil produced more plant cover than treatments with 15 cm of topsoil. It is assumed that over time both the 5 cm and 15 cm topsoil depths will respond similarly. However, the results indicate that a 5 cm topsoil addition was adequate to promote acceptable plant growth under the conditions found at the study site.

Topsoiling without seeding was a treatment tested to determine if natural invasion would be an acceptable means of restoring a natural plant community provided site conditions were favorable. Sousa (1984) suggested that physical manipulation (i.e. topsoiling, ripping) is a mechanism which can generate conditions favorable for recruitment, establishment and growth. Non-seeded, topsoiled treatments (9-10) produced a plant community composed of locally invading species and species whose seeds were present in the topsoil prior to replacement. *Artemisia tridentata* was the most dominant species to naturally colonize non-seeded, topsoiled treatments. In fact, treatments 9 and 10 contained a significantly greater sagebrush cover than topsoiled treatments that were seeded (Table 3). Non-seeded topsoiled treatments 9 and 10 supported 6.1% and 7.3% sagebrush cover while seeded treatments (11-14) had 2.1%, 2.3%, 3.9% and 1.2% sagebrush cover respectively. Perennial grasses and forbs were beginning to colonize the non-seeded treatments as well; however, the pattern of

Table 3. Plant life form and dominant species cover data in a 1992 sampling of the Homestead Plot.

| | Treatment * | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| | % | | | | | | | | | | | | | |
| Life Form 1 | | | | | | | | | | | | | | |
| Grasses | 1.2ef | 1.5ef | 3.8de | 0.7f | 0.4f | 0.2f | 7.7c | 1.4ef | 6.2cd | 7.5c | 14.9ab | 17.4a | 12.7b | 15.8ab |
| Shrubs | 0.8c | 0.8c | 1.5bc | 0.2c | 0.3c | 0.4c | 1.1bc | 0.7c | 10.1a | 10.8a | 3.0bc | 7.3ab | 5.3abc | 3.5bc |
| Forbs annual | 0.6cde | 0.2e | 0.4de | 1.2a-e | 2.3ab | 1.8a-e | 0.6cde | 2.1abc | 2.5a | 1.6a-e | 0.9bcde | 0.2e | 1.7a-e | 0.4de |
| perenn | 0.1ef | 0.3def | 0.3def | 0.5def | 0.2ef | T.f | 2.4abc | 1.2cdef | 1.6bcde | 1.2b-e | 1.8bcd | 3.5a | 2.2abc | 3.0ab |
| Dominant Species | | | | | | | | | | | | | | |
| Slender wheatgrass | 0.0c | 0.0c | 0.2c | 0.0c | 0.0c | 0.0c | 0.4c | 0.1c | 0.7c | 0.9c | 5.1a | 5.0a | 2.9b | 3.4b |
| Mountain brome | T.e | T.e | 2.7d | T.e | 0.0e | 0.0e | 5.3c | 0.1e | 0.1e | 0.3e | 8.9b | 10.0ab | 3.8cd | 11.7a |
| Big sagebrush | 0.1c | 0.3bc | 0.0c | T.c | 0.3bc | 0.0c | 0.5bc | 0.3bc | 9.8a | 10.6a | 2.7bc | 6.5ab | 5.1abc | 2.9bc |
| Lupine | 0.1b | 0.3b | 0.3b | 0.3b | 0.1b | T.b | 2.4a | 0.3b | 0.1b | 0.0b | 1.7a | 2.3a | 0.6b | 2.4a |
| TFC | 2.7d | 2.8d | 6.1d | 2.6d | 3.2d | 2.5d | 11.9c | 5.4d | 20.2b | 21.6b | 20.7b | 28.8a | 22.0b | 23.6b |

* Treatment: 1= Control; 2= Control with mulch; 3= Native seed; 4= Commercial seed; 5= Ripping; 6= Ripping and rock raking; 7= Phos., ripping, native seed and brush beating; 8= Phos., ripping, commercial seed; 9= Topsoil (15 cm), ripping; 10= Topsoil (15 cm), phos., and ripping; 11= Topsoil (15 cm), phos., ripping, native seed and brush beating; 12= Topsoil (5 cm), phos., ripping, native seed and brush beating; 13= Topsoil (15 cm), phos., ripping and commercial seed; 14= Topsoil (15 cm), phos., ripping, native seed and mulch.

1 Treatments with the same letter are not significantly different at the $P \leq 0.05$ level.

T Trace (< 0.10%).

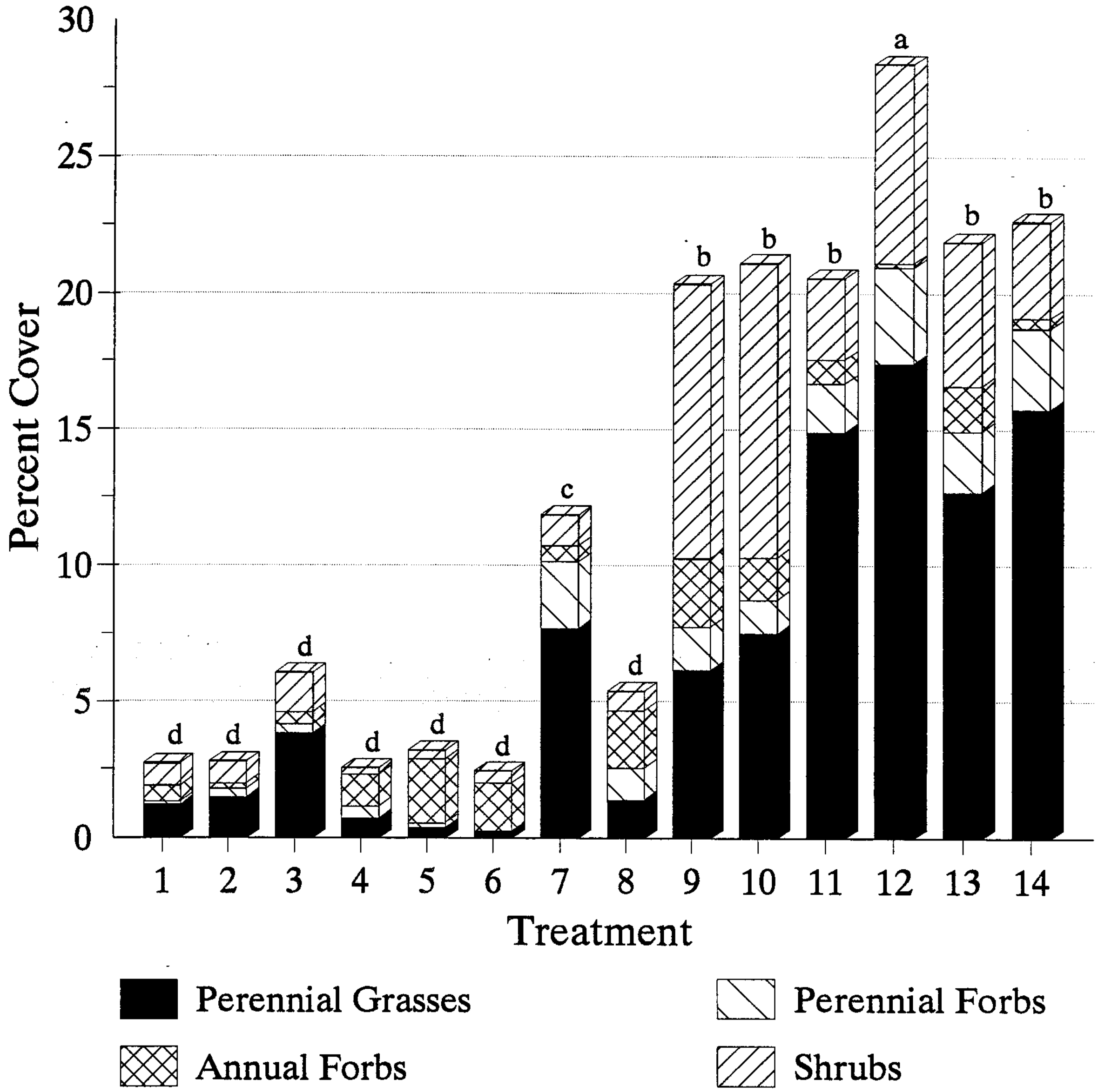


Figure 2. Total plant cover from a 1992 sampling of the Homestead Plot. Treatments with different letters show signficant differences at P≤0.05. Scarifying (30 cm); T15: Topsoil 15 cm; T5: Topsoil 5 cm; P: Phosphorus.

1. Control
2. Control and mulch
3. Indigenous seed
4. Commercial seed
5. Scarifying, no seed
6. Scarifying, rock raking
7. Scarifying, P, indigenous seed
8. Scarifying, P, commercial seed
9. T15, scarifying
10. T15, scarifying, P
11. T15, P, scarifying, indigenous seed
12. T5, P, scarifying, indigenous seed
13. T15, P, scarifying, commercial seed
14. T15, P, scarifying, indigenous seed mulch

establishment has favored shrubs first and grasses/forbs second. The seeded topsoiled treatments favored the establishment of grasses/forbs first, and shrubs second.

Oliver (1981) suggested that the establishment period for woody plants is limited to a short time frame following a disturbance. Those species which are intolerant of shade may be outcompeted when seeded with other rapidly growing species. Sagebrush plants in treatments 9 and 10 appeared taller than plants which grew on the seeded treatments. This may indicate that the seeded treatments possessed plant competition factors (among species) which slowed sagebrush development.

The success of the non-seeded, topsoiled treatments suggests that seeding may not be a required component for the restoration of disturbances of this nature (Cotts 1990). The establishment of grasses, forbs and shrubs in the non-seeded treatments indicates that natural invasion has occurred at a rapid rate considering the dry environment. One primary reason for this success is because of the small width of the abandoned road which probably facilitated plant establishment via seed rain from the surrounding intact plant community. These results provide support for the idea that a properly prepared seedbed will be receptive to natural revegetation processes and perpetuate natural colonization (Richardson 1979).

Non-topsoiled treatments (1-8) showed various plant community development responses and produced an average of approximately 5% cover. The non-topsoiled treatment seeded to indigenous plant materials (Trmt. 7) produced a significantly higher plant cover than all other non-topsoiled treatments. These results indicated that commercially available native seed does not perform as well as indigenous seed when used in the absence of topsoil. In addition, seeding directly onto the road surface with indigenous seed (not scarification) produced a similar plant community as scarification and seeding with commercially available native seed.

Soil analyses of the topsoil and the existing road substrate indicated that both chemical and physical properties were almost identical. This result provided evidence that nutrients may not be an important factor in explaining the differences between topsoiled and non-topsoiled treatments. If this hypothesis is true, then water availability may be the factor most responsible for the differences in plant growth between these treatments (Cotts 1990). Plant cover on non-topsoiled treatments were always significantly lower than the topsoiled treatments (Figure 2).

**Indigenous vs. Commercial Seed Mixtures**

Questions regarding the selection of genetically adapted species (Bengson 1986; Thornsburg and Fuchs 1978 and NPS 1988) as well as the use of indigenous versus commercially available native plant materials for revegetation has long been a concern for reclamation specialists and more recently for those involved in restoration projects.

During the fourth growing season, topsoiled treatments seeded to the indigenous mixture produced similar plant cover as the treatment seeded to the commercial natives (Trmt. 13) with the exception of treatment 12 (5 cm of topsoil, indigenous seed). However, the plant community on the commercial native treatment had a much different composition and was composed of invading perennial grasses and shrubs. Treatment 13 resembled the non-seeded, topsoil treatments (Trmts. 9 and 10) moreso than the other seeded treatments. This seemed to indicate that the commercial seed mixture was not persistent and quickly gave way to invasion from the surrounding plant communities. The commercial native treatments had less perennial grass cover, but appeared to support more shrub cover. The indigenous treatments averaged 20% perennial grass cover while the commercial treatments averaged only 12% perennial grass cover.

There was a significant difference among indigenous plant materials and commercial natives in the non-topsoiled treatments. Treatment 7 (scarifying, indigenous seed) produced a greater plant cover than treatment 8 (scarifying, commercial seed) following four growing seasons. Treatments 3 (indigenous seed) and 4 (commercial seed) were not significantly different; however, it was difficult to locate many surviving plants in the commercial treatment while the indigenous treatment contained actively growing plants. These results indicate that commercially available native seed does not perform as well as indigenous seed when used in the absence of topsoil. In addition, seeding directly onto the road surface with indigenous seed produces a similar plant community as scarifying and seeding with commercially available native seed.

Overall, the indigenous plant materials outperformed the commercial natives. Under favorable soil conditions (topsoil), both seed mixtures supported adequate plant communities; however, under poor soil conditions (no topsoil) the commercial natives were not able to sustain growth. The decline in plant cover in the commercial treatments indicated that these species were not able to survive environmental conditions. In contrast, the indigenous materials showed continued growth in all lifeform categories.

The differences between the two sources of plant materials is probably an ecotypic response. The commercial seed mixture consisted of common varieties which were thought to be adapted to the Teton environment. However, it appears that these common varieties may not be the most adapted and a different selection of plant materials may result in a more favorable response (Thornsburg and Fuchs 1978).

**Mulching**

In general, the use of woodchip mulch significantly delayed plant community development during the initial growing season, but the suppression was not evident during the fourth growing season. It is possible that the mulch delayed germination by maintaining a cool soil temperature as noted by Hopkins (1954). Once established, the plants were unaffected by the presence of mulch.

It appears that mulch is not an important factor in plant community development under these growing conditions. Mulch may maintain an increased soil moisture content during dry periods (McGinnies 1987), but it may also prevent small amounts of moisture from reaching the soil (interception → evaporation) during low duration-low intensity rainfall events which are common during the growing season at this site.

### Soil Scarification

Soil scarification produced a positive result when done in conjunction with direct seeding of the road surface. This result was most evident when comparing treatments 3 and 7 and treatments 4 and 8 (Figure 2). We believe that the positive response to scarifying was associated with improved seedbed conditions. Soil scarification has been shown to improve the probability of adequate seed (Richardson 1979) burial which is necessary to ensure seed germination. Treatments that were not scarified produced very little plant cover, while the scarified treatments consistently produced greater plant cover.

### Fertilizing, Rock Raking, and Brush Beating

There was no apparent plant response to the addition of P, rock raking, or brush beating following four growing seasons. These treatments did not improve the physical plant growth environment which seemed to be the limiting factor controlling plant community establishment.

### Plant Production

Plant biomass samples were collected in 1992 to evaluate the herbaceous production of each treatment. 1992 was the first year that biomass was estimated and the results showed that herbaceous production closely followed plant cover/treatment responses. Topsoiled treatments that were seeded (Treatments 11-14) produced the greatest herbaceous production. Treatments which were dominated by perennial grasses showed a significantly greater production than treatments that were dominated by shrubs (Treatments 9 and 10). Plant production responses are shown in Table 4 and illustrated on Figure 3.

Since biomass data was only collected in 1992, it is not possible to discuss trends in production over time. The 1992 production data will provide a baseline that will become more useful in future sampling events to determine the relative change overtime. We assume that future sampling will show that as the shrub component continues to increase, the overall herbaceous production of the test plots will decrease until an equilibrium is achieved.

### Plant Community Trends Over Four Growing Seasons

The effect of different restoration treatments were manifested during the initial plant community development phase on the Homestead Plot. These differences have been documented in previous publications (Cotts, 1990; Cotts et al., 1991; Cotts and Redente, 1991) and will not be reiterated in depth. Dramatic treatment responses provide insight into restoration techniques which improve initial plant establishment, and

Table 4. Plant life form and dominant species production data in a 1992 sampling of the Homestead Plot.

| | Treatment * | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| | ----- g $m^{-2}$ ----- | | | | | | | | | | | | | |
| Life Form 1 | | | | | | | | | | | | | | |
| Grasses | 2.5e | 3.0e | 8.0de | 1.8e | 2.5e | 0.8e | 30.3bc | 2.3e | 20.2cd | 44.8b | 63.3a | 66.0a | 41.6b | 61.7a |
| Forbs annual | 0.9d | 2.0cd | 1.4d | 1.3d | 2.8bcd | 2.0cd | 1.1d | 2.0cd | 13.3a | 4.9bcd | 2.1cd | 0.7d | 7.4bc | 7.9ab |
| perenn | 0.8c | 0.8c | 5.5abc | 1.4c | 0.3c | 0.2c | 4.6bc | 3.9c | 3.4c | 6.5abc | 4.0c | 13.0a | 11.9ab | 4.7bc |
| Dominant Species | | | | | | | | | | | | | | |
| Slender wheatgrass | 0.0e | 0.0e | 0.4e | 0.0e | 0.0e | 0.0e | 1.0e | 0.0e | 4.4de | 12.7bc | 22.8a | 20.2a | 11.1cd | 19.2ab |
| Mountain brome | 0.0d | 0.1d | 4.7cd | 0.1d | 0.0d | 0.0d | 25.8b | 0.5d | 1.2d | T.d | 38.0a | 40.0a | 13.4c | 41.3a |
| Lupine | 0.3d | 0.1d | 1.0cd | 0.5cd | 0.2d | T.d | 3.9bc | 1.1cd | T.d | 0.5cd | 3.0bcd | 8.1a | 5.4ab | 3.5bcd |
| Total Productivity | 4.2d | 5.9d | 15.1d | 4.5d | 5.6d | 3.1d | 36.1c | 8.2d | 37.7c | 57.1b | 69.4ab | 79.8a | 60.9b | 74.2ab |

* Treatment: 1= Control; 2= Control with mulch; 3= Native seed; 4= Commercial seed; 5= Ripping; 6= Ripping and rock raking; 7= Phos., ripping, native seed and brush beating; 8= Phos., ripping, commercial seed; 9= Topsoil (15 cm), ripping; 10= Topsoil (15 cm), phos., and ripping; 11= Topsoil (15 cm), phos., ripping, native seed and brush beating; 12= Topsoil (5 cm), phos., ripping, native seed and brush beating; 13= Topsoil (15 cm), phos., ripping and commercial seed; 14= Topsoil (15 cm), phos., ripping, native seed and mulch.

1 Treatments with the same letter are not significantly different at the $P \leq 0.05$ level.

T Trace (< 0.1 grams).

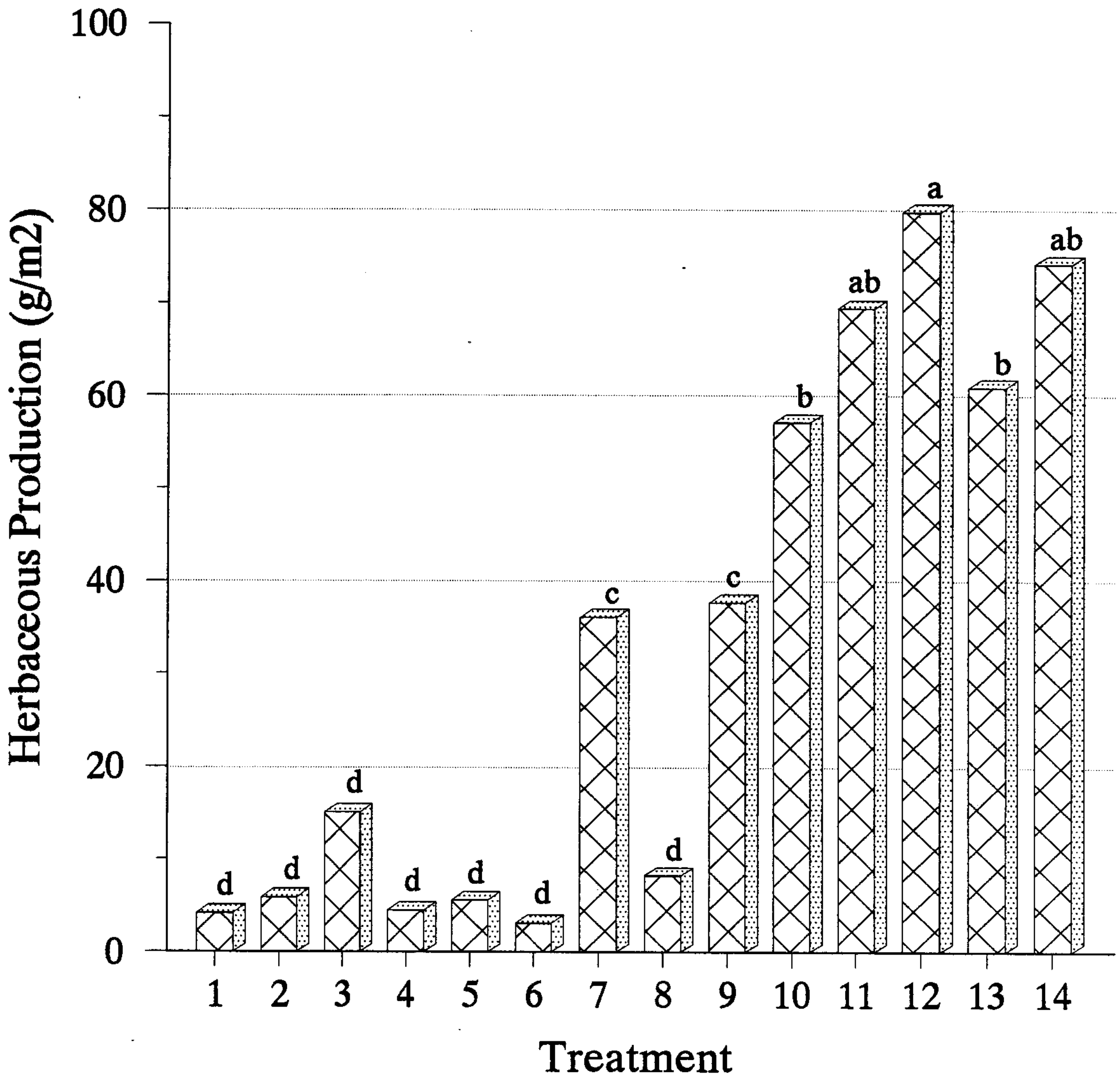


Figure 3. Herbaceous production during 1992 on the Homestead Plot. Treatments with different letters show signficant differences at $P<0.05$. Scarifying (30 cm); T15: Topsoil 15 cm; T5: Topsoil 5 cm; P: Phosphorus.

1. Control
2. Control and mulch
3. Indigenous seed
4. Commercial seed
5. Scarifying, no seed
6. Scarifying, rock raking
7. Scarifying, P, indigenous seed
8. Scarifying, P, commercial seed
9. T15, scarifying
10. T15, scarifying, P
11. T15, P, scarifying, indigenous seed
12. T5, P, scarifying, indigenous seed
13. T15, P, scarifying, commercial seed
14. T15, P, scarifying, indigenous seed mulch

treatments which are capable of supporting plant communities that assume a natural appearance. Plant cover was significantly greater in all topsoiled (9-14) treatments during the 1992 growing season. Total foliar cover ranged from 20% in the non-seeded topsoiled treatment (9) to 29% in the seeded (indigenous) topsoiled treatment 12 (Table 3). Topsoiled treatment 12, seeded to the indigenous seed mixture, produced the highest cover of all topsoiled treatments.

The most interesting treatment response occurred relative to climatic fluctuations between the 1991 and 1992 growing seasons. In 1991, vegetation in the Homestead Plot, in general, appeared to be very stressed. The soil surface was extremely dry and dusty indicating poor soil moisture conditions due to below normal growing season precipitation levels. In 1992, the overall plant cover for all treatments in the Homestead Plot increased from 1991 (Table 5, Figure 4). The increases in plant cover were significant for all topsoiled treatments with the exception of treatment 10. In addition, a significant increase in plant cover occurred on the non-topsoiled treatment 7. In most cases, an increase in perennial grass cover was responsible for the increase in overall plant cover (Table 5 and Table 6).

The topsoiled treatments also showed evidence of increasing shrub cover. Although not significant, shrub cover continued to increase indicating a successional gradient towards a shrub dominated plant community.

These results indicate that the plant communities developing on the Homestead Plot are dynamically fluctuating in response to climatic variations. This response is evident for the perennial grass/forb component which is responsible for the changes in overall plant cover. The shrub component is least affected by the seasonal precipitation fluctuations as evidenced by a slow, gradual increase in shrub cover.

Shrub density was also estimated across all treatments to evaluate trends. Shrub density has been decreasing since the initial growing season (Figure 5) as individual shrub size increases. This change was expected to occur as dominant individuals increase in size and the demand for resources increases. Smaller, less dominant plants are out-competed and the overall density tends to decrease. It seems probable that this trend will continue until only a few dominant shrubs persist.

Total shrub cover continues to increase across all treatments on the Homestead Plot as density decreases. These results indicate that the developing plant communities are moving towards a shrub dominated community, consistent with the surrounding vegetation. The increased shrub cover is progressing at various rates depending upon the treatment. Treatments 9 and 10 (topsoiled, not seeded) have produced a shrub dominated plant community that has a minor perennial grass component. The shrub component established more quickly in these treatments, relative to the seeded topsoiled treatments, because of less competition from seeded perennial species. The reduced competition allowed the shrubs to use more available resources and increase establishment and growth. These treatments will likely approach undisturbed plant community characteristics more quickly than the seeded topsoiled treatments.

Table 5. Plant life form cover comparison from 1989-1992 on the Homestead Plot.

| | Treatment * | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| | % | | | | | | | | | | | | | |
| Life Form | | | | | | | | | | | | | | |
| Grass 89 | 0.8 | 0.5 | 3.0 | 1.2 | 0.3 | T | 5.2** | 2.3 | 1.1** | 1.1** | 9.7** | 14.2** | 5.2** | 10.1** |
| 90 | 0.6 | 0.8 | 3.8 | 0.8 | 0.3 | 0.2 | 8.7** | 2.2 | 5.0 | 6.4** | 19.3** | 19.8** | 11.6** | 20.7** |
| 91 | 0.7 | 0.4 | 2.8 | 0.5 | 0.2 | 0.2 | 5.2 | 1.2 | 3.7 | 3.7** | 13.1 | 13.0** | 7.0** | 12.9** |
| 92 | 1.2 | 1.5 | 3.8 | 0.7 | 0.4 | 0.2 | 7.7 | 1.4 | 6.2 | 7.5 | 14.9 | 17.4 | 12.7 | 15.8 |
| LSD = 2.599 | | | | | | | | | | | | | | |
| Shrub 89 | 0.2 | 0.3 | 0.5 | 0.1 | 0.2 | 0.2 | 0.6 | 0.2 | 3.1 | 3.2 | 1.7 | 1.6 | 2.2 | 1.5 |
| 90 | 0.5 | 0.4 | 0.7 | 0.1 | 0.3 | 0.3 | 0.5 | 0.2 | 6.3 | 7.6 | 2.4 | 3.0 | 3.9 | 1.8 |
| 91 | 0.6 | 0.3 | 0.7 | 0.1 | 0.2 | 0.3 | 0.4 | 0.2 | 6.1 | 10.0 | 1.7 | 3.4 | 3.7 | 1.8 |
| 92 | 0.8 | 0.8 | 1.5 | 0.2 | 0.3 | 0.4 | 1.1 | 0.7 | 10.1 | 10.8 | 3.0 | 7.3 | 5.3 | 3.5 |
| LSD = 4.889 | | | | | | | | | | | | | | |
| Forbs (annual) | | | | | | | | | | | | | | |
| 89 | 1.5 | 0.6 | 1.0 | 1.2 | 2.3 | 1.7 | 3.1** | 2.4 | 7.7** | 7.7** | 3.4** | 3.4** | 3.6** | 2.2** |
| 90 | 1.5 | 0.1 | 0.7 | 0.9 | 1.4 | 1.5 | 1.1 | 1.6 | 2.1 | 2.0 | 0.3 | 0.6 | 1.2 | 0.2 |
| 91 | 0.4 | 0.1 | 0.4 | 0.7 | 1.1 | 1.3 | 0.4 | 1.1 | 1.3 | 1.3 | 0.1 | 0.0 | 0.3** | 0.1 |
| 92 | 0.6 | 0.2 | 0.4 | 1.2 | 2.3 | 1.8 | 0.6 | 2.1 | 2.5 | 1.6 | 0.9 | 0.2 | 1.7 | 0.4 |
| LSD = 1.342 | | | | | | | | | | | | | | |
| Forbs (perennial) | | | | | | | | | | | | | | |
| 89 | 0.0 | 0.1 | 0.6 | 0.6 | T | 0.0 | 1.1 | 1.5 | 0.1** | 0.2** | 1.8 | 2.2 | 2.4 | 1.2 |
| 90 | 0.1 | 0.0 | 0.2 | 0.2 | 0.1 | 0.0 | 1.2 | 0.8 | 2.6** | 2.6** | 1.3 | 2.3 | 2.5 | 1.2 |
| 91 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 1.0** | 0.7 | 0.9 | 0.7 | 1.5 | 2.1** | 2.0 | 1.3** |
| 92 | 0.1 | 0.3 | 0.3 | 0.5 | 0.2 | T | 2.4 | 1.2 | 1.6 | 1.2 | 1.8 | 3.5 | 2.2 | 3.0 |
| LSD = 1.016 | | | | | | | | | | | | | | |
| Total Cover | | | | | | | | | | | | | | |
| 89 | 2.6 | 1.4 | 5.0 | 3.4 | 2.9 | 1.9 | 10.0 | 6.3 | 12.0** | 12.1** | 16.3** | 21.3 | 14.0** | 14.8** |
| 90 | 2.6 | 1.3 | 5.4 | 2.0 | 2.1 | 2.0 | 11.7** | 4.8 | 16.1 | 18.6 | 23.3** | 25.7** | 19.2** | 23.8** |
| 91 | 1.7 | 1.2 | 4.1 | 1.3 | 1.9 | 1.7 | 6.9** | 3.3 | 12.0** | 15.7** | 16.5 | 18.4** | 13.1** | 15.8** |
| 92 | 2.7 | 2.8 | 6.1 | 2.6 | 3.2 | 2.5 | 11.9 | 5.4 | 20.2 | 21.6 | 20.7 | 28.8 | 22.0 | 23.6 |
| LSD = 4.444 | | | | | | | | | | | | | | |

* Treatment: 1= Control; 2= Control with mulch; 3= Native seed; 4= Commercial seed; 5= Ripping; 6= Ripping and rock raking; 7= Phos., ripping, native seed and brush beating; 8= Phos., ripping, commercial seed; 9= Topsoil (15 cm), ripping; 10= Topsoil (15 cm), phos., and ripping; 11= Topsoil (15 cm), phos., ripping, native seed and brush beating; 12= Topsoil (5 cm), phos., ripping, native seed and brush beating; 13= Topsoil (15 cm), phos., ripping and commercial seed; 14= Topsoil (15 cm), phos., ripping, native seed and mulch.

** Treatments for that year are significantly different than the following year at the $P \leq 0.05$ level.

T Trace (<0.10%).

Table 6. Dominant plant species cover comparisons from 1989-1992 on the Homestead Plot.

| | Treatment * | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| | % | | | | | | | | | | | | | |
| Dominant Species | | | | | | | | | | | | | | |
| Slender wheatgrass | | | | | | | | | | | | | | |
| 89 | 0.0 | 0.0 | 0.7 | 0.1 | 0.0 | 0.0 | 1.7 | 0.3 | 0.9 | 0.9 | 2.4** | 3.3** | 1.6** | 2.5** |
| 90 | 0.0 | 0.0 | 0.9 | T | 0.0 | 0.0 | 1.7 | 0.2 | 1.0 | 1.1 | 5.7** | 6.8** | 3.2** | 5.9** |
| 91 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.8 | 0.2 | 4.4 | 4.2 | 0.8** | 4.0 |
| 92 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.4 | 0.1 | 0.7 | 0.9 | 5.1 | 5.0 | 2.9 | 3.4 |
| LSD = 1.156 | | | | | | | | | | | | | | |
| Mountain brome | | | | | | | | | | | | | | |
| 89 | 0.0 | 0.0 | 1.8 | 0.7 | 0.0 | 0.0 | 3.6** | 1.7 | 0.0 | 0.0 | 7.2** | 10.7 | 3.1** | 7.5** |
| 90 | 0.0 | 0.0 | 2.3 | 0.3 | 0.0 | 0.0 | 6.5 | 1.4 | 0.0 | 0.0 | 12.4 | 12.0 | 5.1 | 14.0 |
| 91 | 0.0 | 0.0 | 1.9 | 0.0 | 0.0 | 0.0 | 3.7** | 0.1 | 0.0 | 0.0 | 8.1** | 8.5** | 3.5** | 8.4** |
| 92 | T | T | 2.7 | T | 0.0 | 0.0 | 5.3 | 0.1 | 0.1 | 0.3 | 8.9 | 10.0 | 3.8 | 11.7 |
| LSD = 1.730 | | | | | | | | | | | | | | |
| Big sagebrush | | | | | | | | | | | | | | |
| 89 | 0.2 | 0.2 | 0.3 | 0.1 | 0.2 | 0.2 | 0.3 | 0.2 | 3.1 | 3.2 | 1.4 | 1.3 | 2.1 | 0.8 |
| 90 | 0.0 | 0.2 | 0.3 | T | 0.1 | T | 0.5 | 0.2 | 6.1 | 7.3 | 2.1 | 2.4 | 3.9 | 1.2 |
| 91 | 0.0 | 0.2 | 0.5 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 6.1 | 10.0 | 1.4 | 3.2 | 3.5 | 1.6 |
| 92 | 0.1 | 0.3 | 0.0 | T | 0.3 | 0.0 | 0.5 | 0.3 | 9.8 | 10.6 | 2.7 | 6.5 | 5.1 | 2.9 |
| LSD = 4.885 | | | | | | | | | | | | | | |
| Lupine | | | | | | | | | | | | | | |
| 89 | 0.0 | 0.1 | 0.6 | 0.5 | T | 0.0 | 1.1 | 1.4** | T | 0.1 | 1.8** | 2.2 | 1.7 | 1.2 |
| 90 | 0.1 | 0.0 | 0.2 | 0.2 | 0.1 | 0.0 | 1.2 | 0.6 | 0.0 | 0.0 | 1.1 | 1.9 | 1.3 | 0.8 |
| 91 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 1.0** | 0.4 | 0.0 | 0.0 | 1.5 | 2.0 | 1.1 | 1.2** |
| 92 | 0.1 | 0.3 | 0.3 | 0.3 | 0.1 | T | 2.4 | 0.3 | 0.1 | 0.0 | 1.7 | 2.3 | 0.6 | 2.4 |
| LSD = 0.669 | | | | | | | | | | | | | | |

* Treatment: 1= Control; 2= Control with mulch; 3= Native seed; 4= Commercial seed; 5= Ripping; 6= Ripping and rock raking; 7= Phos., ripping, native seed and brush beating; 8= Phos., ripping, commercial seed; 9= Topsoil (15 cm), ripping; 10= Topsoil (15 cm), phos., and ripping; 11= Topsoil (15 cm), phos., ripping, native seed and brush beating; 12= Topsoil (5 cm), phos., ripping, native seed and brush beating; 13= Topsoil (15 cm), phos., ripping and commercial seed; 14= Topsoil (15 cm), phos., ripping, native seed and mulch.

** Treatments for that year are significantly different than the following year at the $P \leq 0.05$ level.

T Trace (< 0.10%).

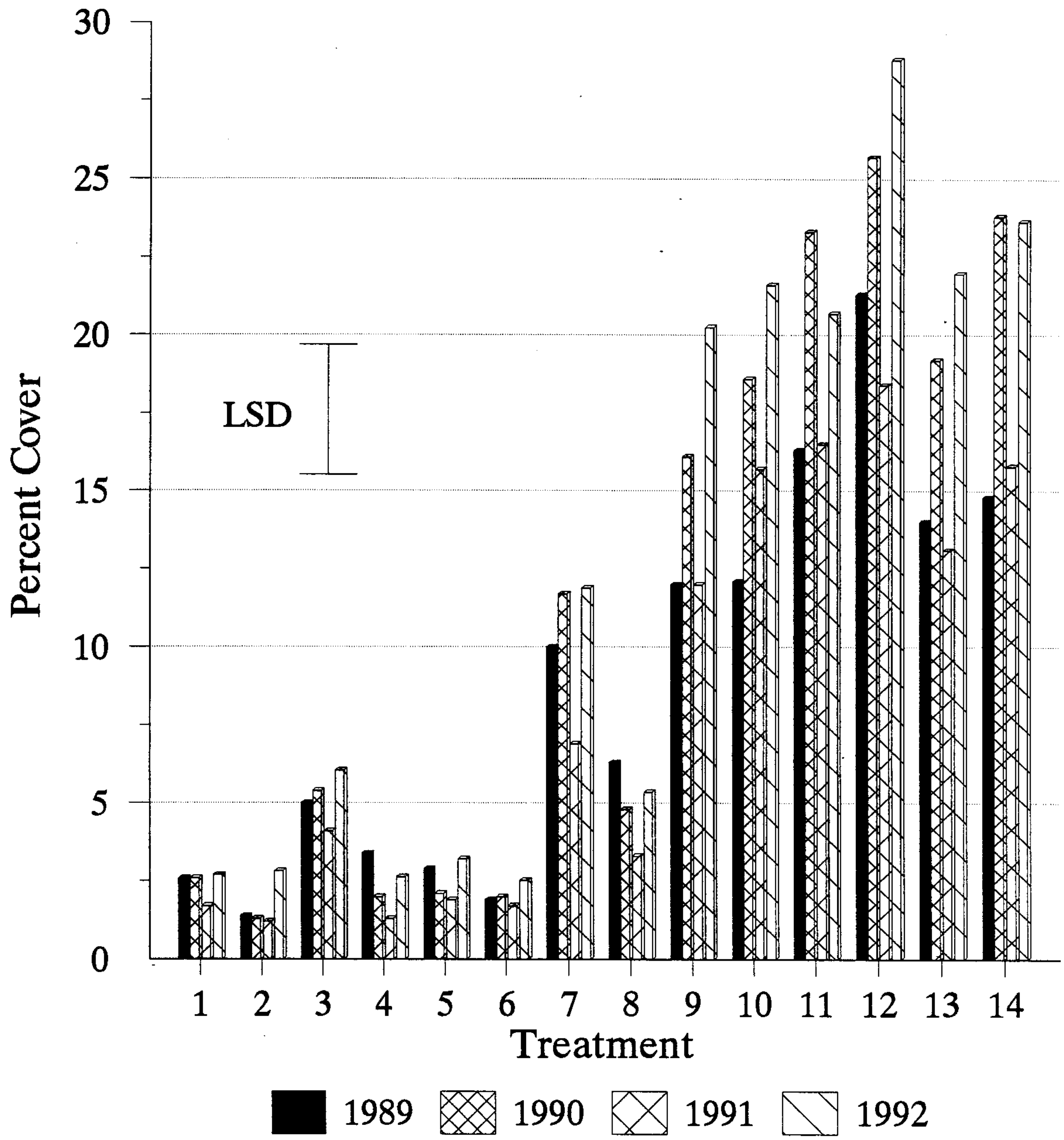


Figure 4. Total plant cover comparison from 1989-1992 of the Homestead Plot. Scarifying (30 cm); T15: Topsoil 15 cm; T5: Topsoil 5 cm; P: Phosporus.

1. Control
2. Control and mulch
3. Indigenous seed
4. Commercial seed
5. Scarifying, no seed
6. Scarifying, rock raking
7. Scarifying, P, indigenous seed
8. Scarifying, P, commercial seed
9. T15, scarifying
10. T15, scarifying, P
11. T15, P, scarifying, indigenous seed
12. T5, P, scarifying, indigenous seed
13. T15, P, scarifying, commercial seed
14. T15, P, scarifying, indigenous seed mulch

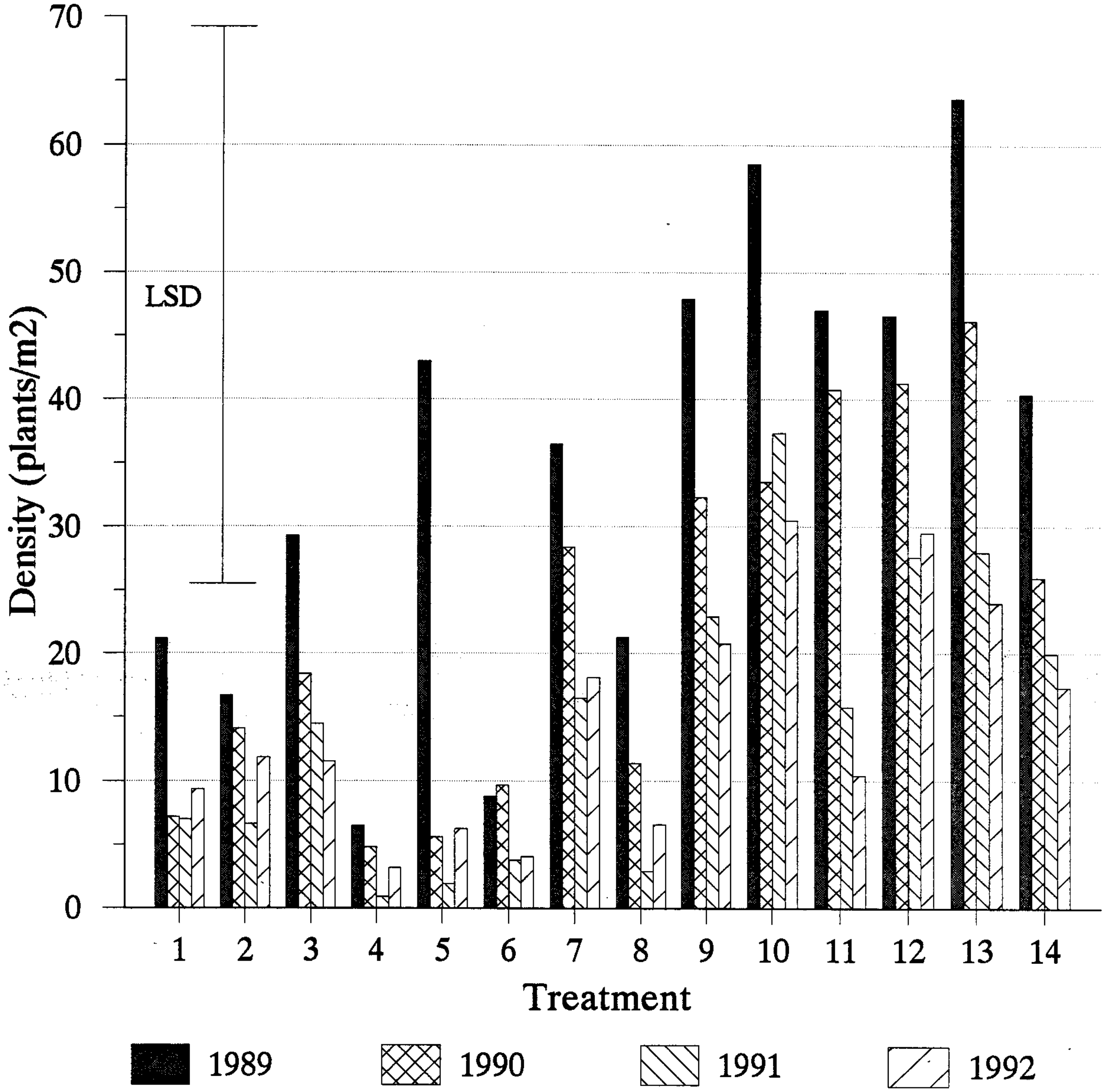


Figure 5. Shrub density comparison from 1989-1992 on the Homestead Plot. Scarifying (30 cm); T15: Topsoil 15 cm; T5: Topsoil 5 cm; P: Phosporus.

1. Control
2. Control and mulch
3. Indigenous seed
4. Commercial seed
5. Scarifying, no seed
6. Scarifying, rock raking
7. Scarifying, P, indigenous seed
8. Scarifying, P, commercial seed
9. T15, scarifying
10. T15, scarifying, P
11. T15, P, scarifying, indigenous seed
12. T5, P, scarifying, indigenous seed
13. T15, P, scarifying, commercial seed
14. T15, P, scarifying, indigenous seed mulch

## Comparisons to Undisturbed Plant Communities

Data were collected during the 1989 and 1990 growing seasons in the undisturbed plant community adjacent to the Homestead plot. These data provide baseline information from which restoration success can be judged.

The undisturbed plant community, which borders the test plot, is dominated by shrubs (sagebrush species), with perennial grasses as subdominant. This community is patchy in nature with clumps of shrubs interspersed with grasses and forbs with considerable bare ground present throughout the area. This vegetation description typifies the Teton valley vegetation scheme in dry upland sites.

Topsoiled treatments 10 (not seeded), 12 (5 cm topsoil, indigenous seed), and 13 (commercial seed) were compared to the undisturbed community following four growing seasons (Figure 6). The non-seeded, topsoiled treatment (Treatment 10) compared most favorably to the undisturbed community. This treatment was dominated by shrub and perennial grass species and should approach undisturbed conditions in a relatively short time period provided the plant community continues to develop along the established pattern.

The remaining topsoil treatments which were seeded (Treatments 11, 12, 13 and 14) are showing varied responses in community development following four growing seasons. These treatments are dominated by perennial grasses with a minor shrub component. It may be speculated that the aggressive nature of resource capture by grasses will promote their continued dominance over the long term. This response may be avoided in future restoration efforts by reducing the seeding rates of quickly establishing species.

The non-topsoiled treatments (Treatments 1-8) were not evaluated with respect to the undisturbed plant community. Treatment 7 (scarifying and seeding indigenous mixture) most closely resembles the undisturbed plant community and will most likely approach "natural" conditions more quickly than any other non-topsoiled treatment. The scarification provided an improved seedbed for germination and establishment.

## Soil Physical Attributes

Infiltration and bulk density analyses were conducted to determine if compaction was a problem and if the selected experimental treatments of scarifying and topsoiling improved the physical parameters of the road substrate. It is important to note that both the road substrate and the topsoil material have the same textural and organic matter characteristics. These factors eliminate the water holding capacity advantage of the topsoil material over the road substrate as indicated by these properties.

The infiltration rates and bulk densities for the treatments tested are shown in Figure 7. The bulk density data followed an expected gradient. The undisturbed soil had the lowest bulk density while the untreated road surface (control) had the highest bulk density. This confirms that the road surface had been compacted as a result of surface activity over the life time of the road.

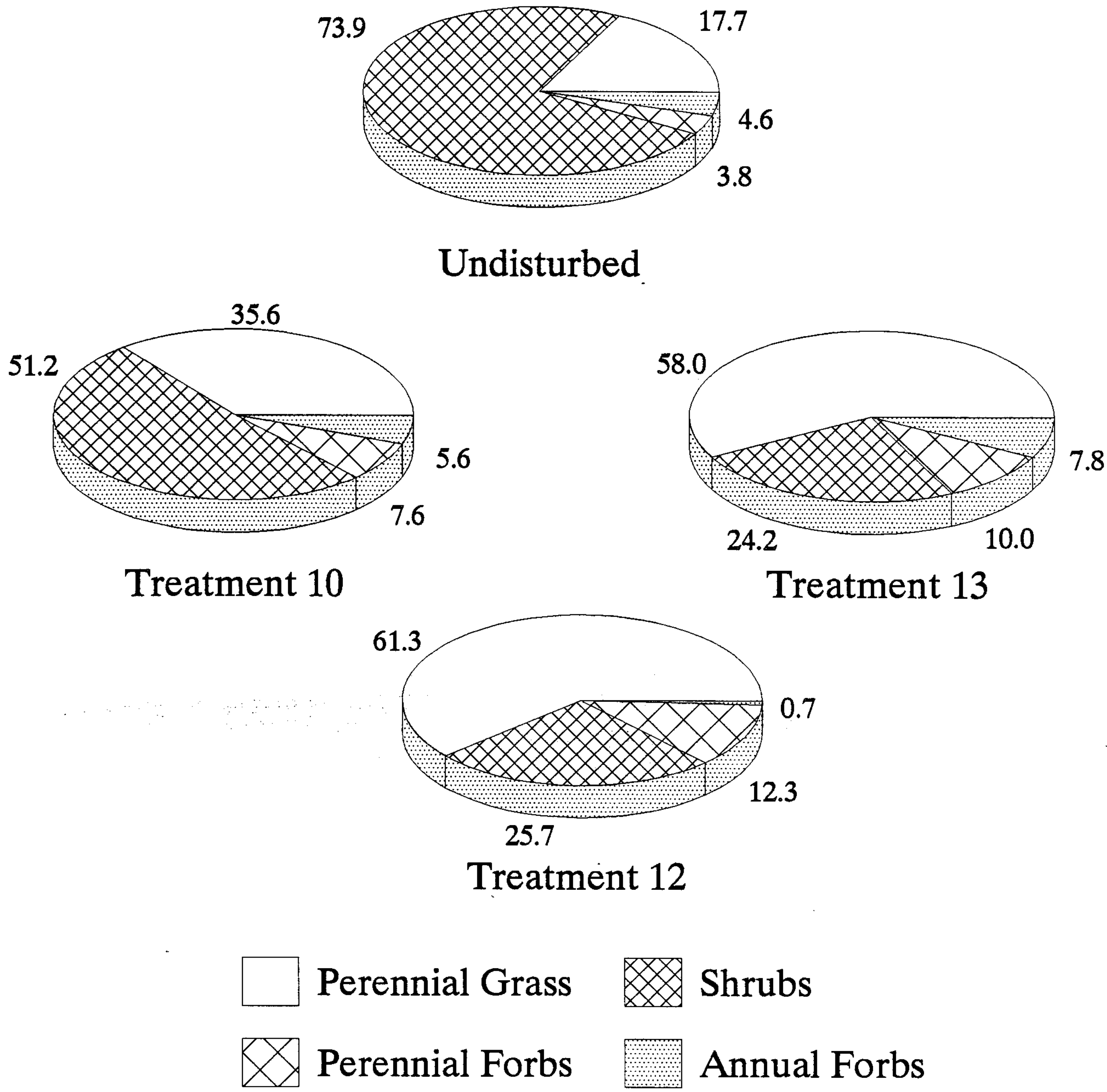


Figure 6. Plant life form comparisons (relative cover) between the undisturbed community adjacent to the Homestead Plot and the topsoil treatments. Treatment 13: topsoil (15 cm), scarifying, P, commercial seed; Treatment 12: topsoil (5 cm), scarifying, P, indigenous seed; Treatment 10: topsoil, scarifying, P, no seed.

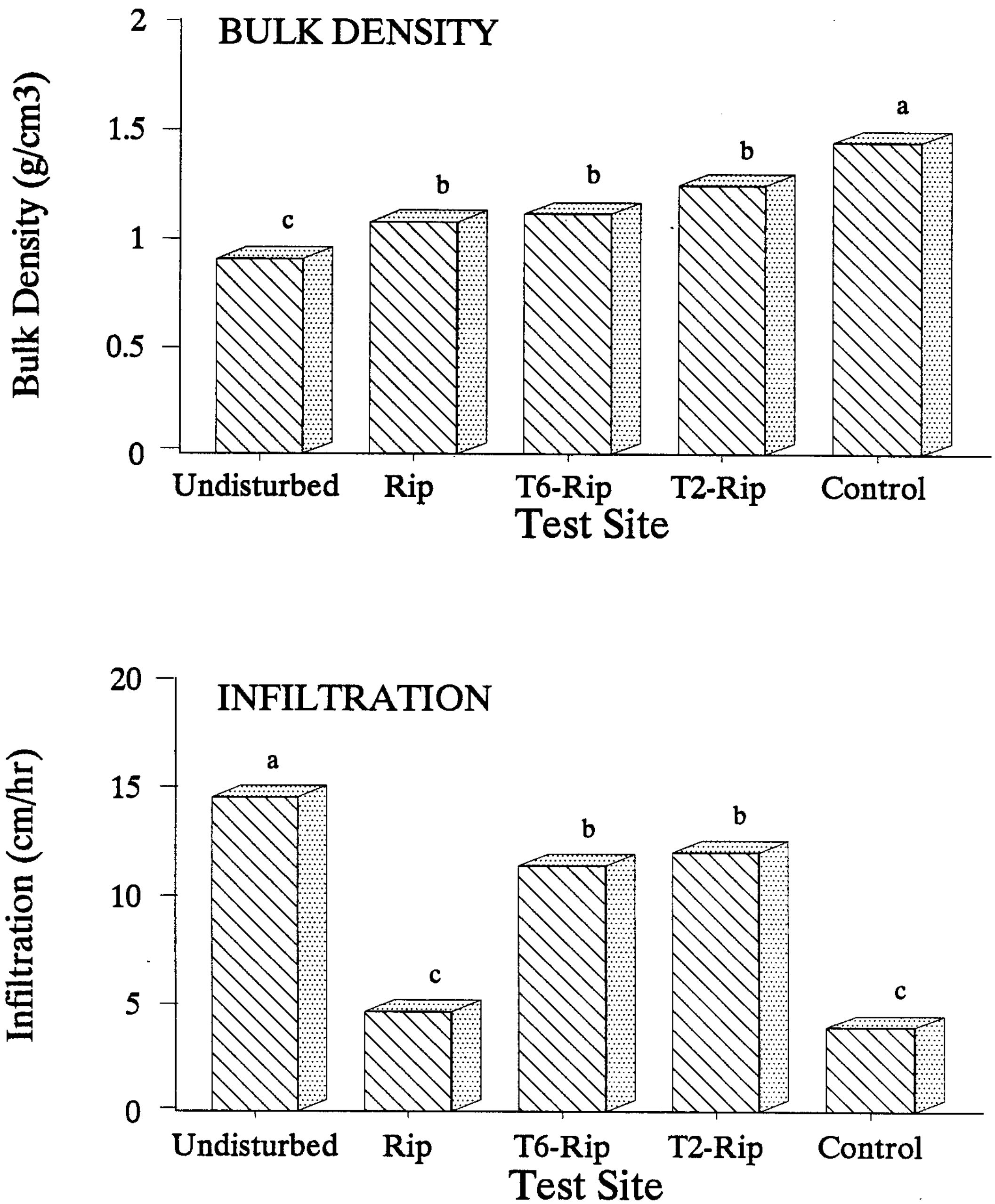


Figure 7. Soil bulk density and infiltration characteristics of the Homestead Plot substrate and undisturbed areas. Treatments with the same letter are not significantly different ($P < 0.05$). Undisturbed: Soils adjacent to the test plot Rip: Treatments that were scarified; T15-Rip: Topsoil (15 cm) and scarification; T2-Rip: Topsoil (5 cm) and scarification; Control: Undisturbed roadbase.

Infiltration and bulk density are normally correlated as bulk density often controls the rate of infiltration (Hillel 1982). However, infiltration rates did not parallel the bulk densities in this case. The infiltration rate of the undisturbed soil was quite high as expected. The infiltration rates of the topsoil treatments were high as well, due to the fact that this soil has not been compacted or disturbed in the past. The infiltration rate of the scarified treatment (without topsoil) was not significantly different than the control. This indicates that scarifying did not improve the infiltration rate of the soil. The fact that soil scarification decreased the bulk density of the road substrate, but did not increase the infiltration rate of these soils suggests that neither the bulk density nor the textural properties of this soil limit infiltration rates. In our case, infiltration may be more dependent on aggregate size, pore size distribution, aggregate stability and surface sealing.

Aggregate stability analyses were completed on soils from the ripped roadbase and the ripped topsoiled treatments. Results indicated that the topsoil material has more larger stable aggregates following wet sieving destruction than the roadbase soils (Figure 8). This indicates that soil aggregates in the topsoil material are more resistant to physical destruction upon wetting and are less likely to break apart. The roadbase soils have more particles in the silt size range and less soil particles contained in larger stable aggregates. Aggregates which disintegrate upon wetting result in pore sealing and ultimately decrease infiltration (Hillel 1982). These soils also have smaller relative aggregates following wet sieving than the topsoil materials. Smaller soil aggregates are likely to cause pore plugging and a decrease in infiltration due to the loss of macropores which occur with macro-aggregate structured materials (Hillel 1982). The aggregate size relationship between the topsoil and the roadbase soil including pore size variations explains the observed differences in infiltration rates which were independent of soil bulk density.

The relative variations in aggregate size following wet sieving may be explained by the history of each soil. The roadbase soil has been driven on, puddled, and physically disturbed since the road was established. This would result in a soil with smaller inherent aggregate characteristics on the exposed surface. The topsoil material has not been disturbed as it was taken from exposed Jackson Lake bottom soils. The topsoil material is actually buried alluvial soils, similar to other soils throughout the Teton valley, which were inundated with the creation of Jackson Lake. The inherent aggregate size has not been decreased through disturbance. Therefore, the topsoil used in this study had more large aggregates than the roadbase soils prior to wetting, which resulted in better infiltration rates and possibly better soil water relations for plant growth. This is especially true in the environment of our study site that is characterized by high intensity, short duration precipitation events.

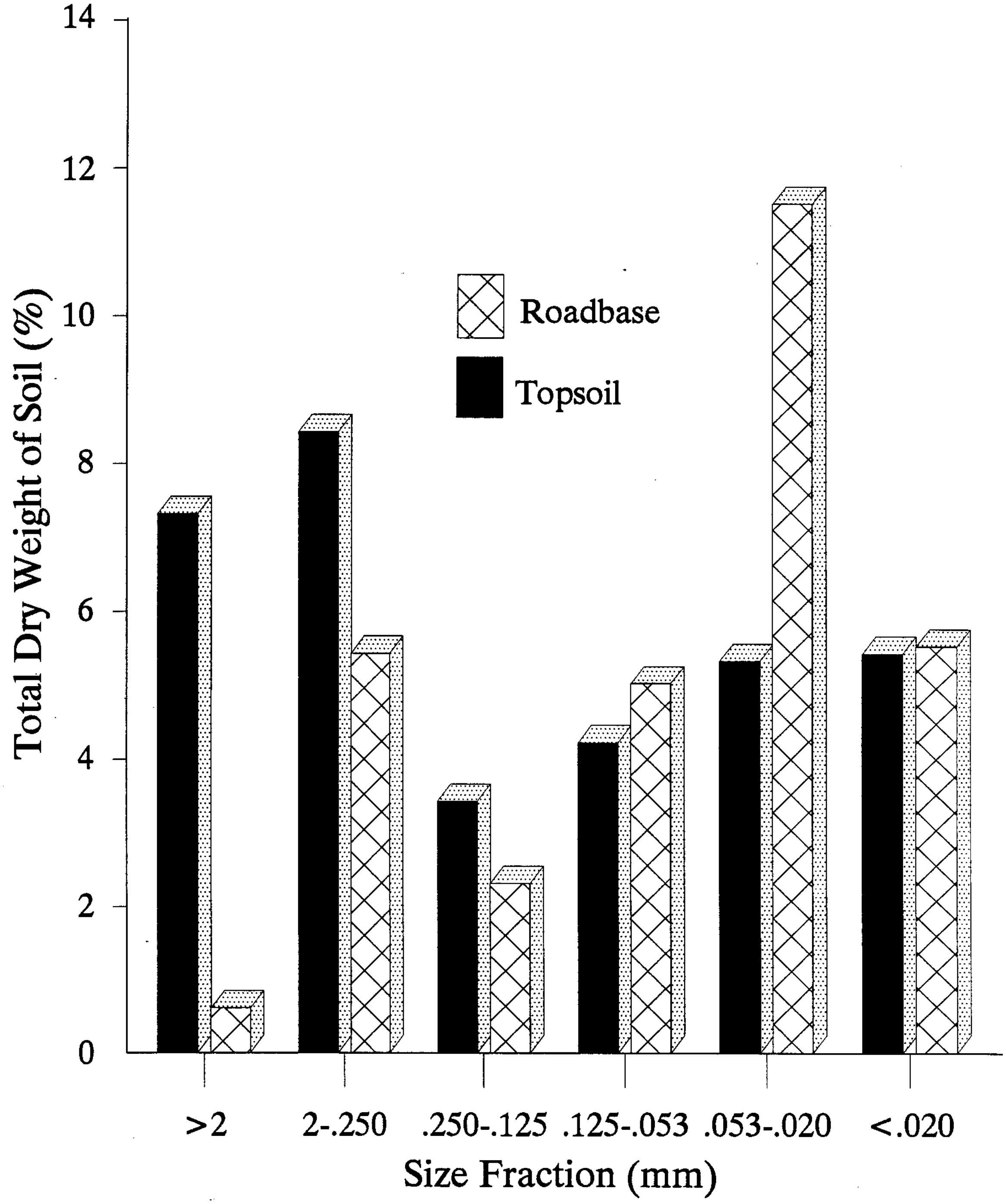


Figure 8. Aggregate stability analyses for soils from the topsoil treatment and the scarified roadbase treatment. Higher percents of soil material in larger size classes indicates greater aggregate stability.

## CONCLUSIONS

The ultimate goal of restoration is to reestablish plant communities which are similar in appearance and composition to surrounding undisturbed communities, and in the case of the National Park Service, to maintain the genetic and ecological integrity of the community. The Homestead Plot was developed to evaluate commonly applied reclamation approaches in achieving a restoration objective. The results of this study indicate that restoration success can be promoted using various approaches. However, whether reclamation or restoration, one cannot overlook the basic underlying principle of understanding the most limiting factors responsible for plant growth. The Teton environment yielded two limiting factors including soil physical conditions coupled with natural climatic conditions. Restoration approaches that improved the soil physical properties resulted in the establishment of plant communities that were capable of withstanding the natural climatic conditions and are beginning to resemble undisturbed plant communities.

**Acknowledgements**

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# HIGH PLAINS RECLAMATION AND RESTORATION AT THE BLACK THUNDER MINE, CAMPBELL COUNTY, WYOMING

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## Introduction

Reclamation of coal mined lands in the West has been driven by rules and regulations established under the Surface Mining Control and Reclamation Act of 1977 (SMCRA). Provisions of this legislation set performance standards for reclamation goals which focused on plant cover, biomass production, woody plant density and species diversity. Reclaimed lands also must support defined post-mining land use goals. While restoration was not the intent of SMCRA, it is interesting that successful reclamation goals closely parallel restoration objectives.

When SMRCA was enacted it was hoped by many reclamation practitioners that plant communities established on reclaimed areas would be stable, that is resilient relative to severe environmental perturbations, but would also be capable of allowing for colonization by native species that could never reasonably be included in reclamation seed mixes. (The underlying intent was that reclaimed areas would eventually come to resemble the original vegetation that had been lost during the mining process).

## Relationship Between Restoration and Reclamation

In order to understand the relationships between restoration and reclamation it is necessary to examine the basic goals of each activity.

### Goals of Restoration

While it is likely that not all restoration practitioners would agree with one set of goals for restoration, the following basic objectives and goals summarize the focus of restoration activities:

Restoration focuses on recreating ecological systems that are comparable to those that were present on sites prior to disturbance. Restoration tends to focus on the re-creation of ecosystems rather than on the re-establishment of individual species.

Restored communities should be comparable to original systems both in terms of structure and composition.

Native species of local genetic origin should be used to repopulate disturbed lands.

Species diversity should be re-established to levels that were present prior to disturbance.

Plant communities should be created so that they include species necessary for the survival of vertebrate and invertebrate animal populations.

These objectives rarely are given any time constraints. The process of restoration is on-going. Levels of restoration activity may be driven only by available funds or available time. Ultimately, restoration is complete when it is impossible to detect differences between restored lands and native ecosystems.

Goals of Reclamation on Coal Mined Lands

Reclamation goals tend to be not as far-reaching as restoration goals. In general, reclamation focuses on establishing vegetation on disturbed lands such that erosion is minimized and land uses consistent with regional practices can be maintained. For surface coal mined lands these goals have been somewhat more succinctly defined:

Establish plant communities with cover and production levels that are comparable to native comparison areas.

Use native species unless the desired post-mining land use is dependent on planting non-native species.

Establish diverse communities that are climatically resilient and that will support designed post mining land uses (livestock grazing and wildlife habitat)

Establish shrublands over a portion (for example, ten percent) of the mined lands

It is important to recognize that both reclamation and restoration are linked with the ecological process of succession. If all disturbed lands were left in their disrupted state, they would eventually become vegetated, ecologically diverse and capable of supporting a great variety of animal species. This might, however take 5,000 years. Reclamation and restoration activities serve to dramatically shorten this time interval.

## The Black Thunder Mine Study Area

The Black Thunder Mine is operated by Thunder Basin Coal Company and is located in northeastern Wyoming in the southern part of Campbell County approximately 45 miles south and east of Gillette. The mine began operations in the late 1970's and is currently the largest surface coal mine in the Western Hemisphere. Permanent reclamation was started in 1981 and over the last 13 years approximately 1800 acres have been reclaimed.

The native vegetation on the mine site and surrounding areas consists primarily of mixed grass prairie and big sagebrush shrubland vegetation types with less common vegetation types including bunchgrass prairies, playa grasslands, streamside meadows and areas of broken topography with sparse vegetation. The dominant species on upland prairie and shrubland sites include species of wheatgrasses *(Agropyron* spp.*)*, needlegrasses *(Stipa* spp.*)*, prairie Junegrass *(Koeleria macrantha)*, blue grama *(Bouteloua gracilis)*, big sagebrush *(Artemisia tridentata)*, and plains prickly pear cactus *(Opuntia polyacantha)*. These species consistently account for more than 75 percent of the cover by all species on upland areas.

Permanent reclamation of mined areas at the Black Thunder Mine began in the early 1980's. Since that time, reclamation has been conducted concurrently with mining and, monitoring of revegetation success has been conducted on a regular basis. Results of this monitoring program have been used to modify seed mixes and seeding techniques.

### Reclaimed Areas

<u>Areas seeded prior to 1986</u>. Disturbed areas that were reclaimed prior to 1986 have a relatively consistent community structure and species composition. In these early years of reclamation, the seed mixes contained relatively high seeding rates for cool season perennial grasses. Dominant species in these areas, once they were established, included thickspike wheatgrass *(Agropyron dasystachyum)*, western wheatgrass *(Agropyron smithii)*, slender wheatgrass *(Agropyron trachycaulum)*, and green needlegrass *(Stipa viridula)*. In nearly all of the reclaimed areas, it is not uncommon for the vegetation during the first growing season to be dominated by annual forb species. In succeeding years, however, life form groups other than cool season perennial grasses (both native and non-native), play minor roles in the functioning of these reclaimed areas (Figure 1).

The areas reclaimed prior to 1986 have attributes that are consistent with the major goals of reclamation, that is, the community structure is such that cover and production are comparable to the native prairie communities and numerous species occur within the reclaimed areas. Shrubs are scattered. While these areas show high levels of reclamation success, restoration goals are only partially met.

<u>Areas seeded after 1986</u>. After 1986, certain changes were instituted in the reclamation techniques at the mine. Modifications were made in the seed mix used on upland sites and changes were made in the seeding techniques. The seed drill was modified so that light, chaffy seeds and small seedes were scattered just above the soil surface rather than being drilled into the soil along with the larger seeded cool season grass species. Seed mixes were altered by increasing seeding rates for warm season perennial grasses and shrubs and decreaseing seeding rates for cool season perennial grasses in areas that were to be reclaimed as shrublands.

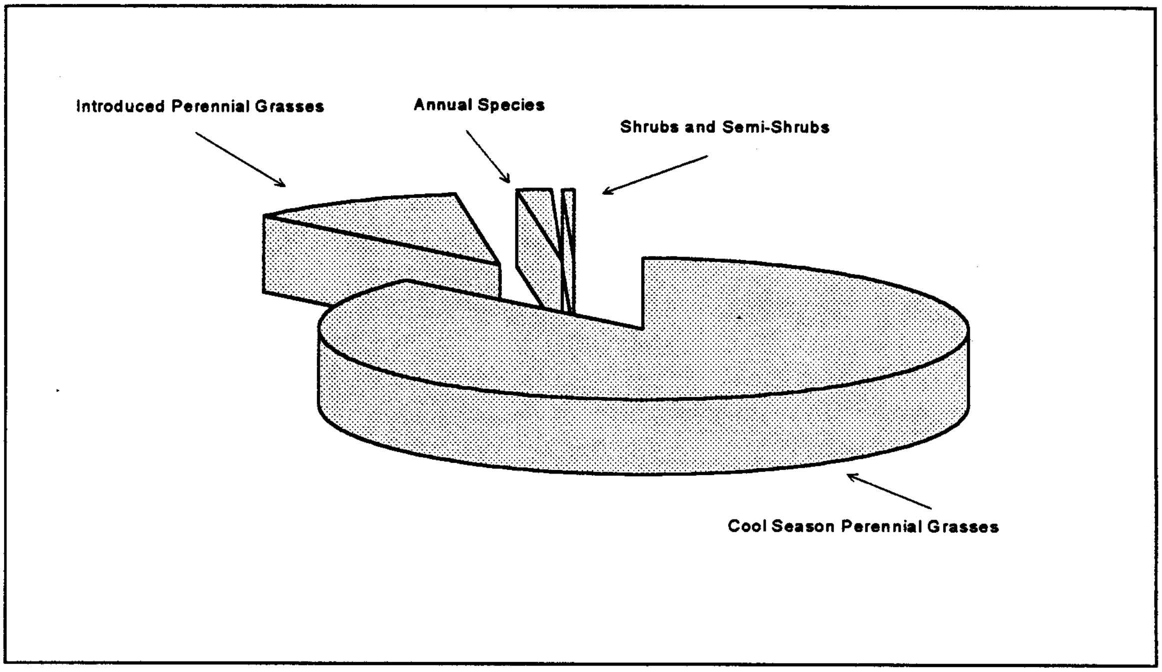


Figure 1. Relative Cover for Life Form Groups for Areas Reclaimed in 1981. Based on Data Collected in 1987.

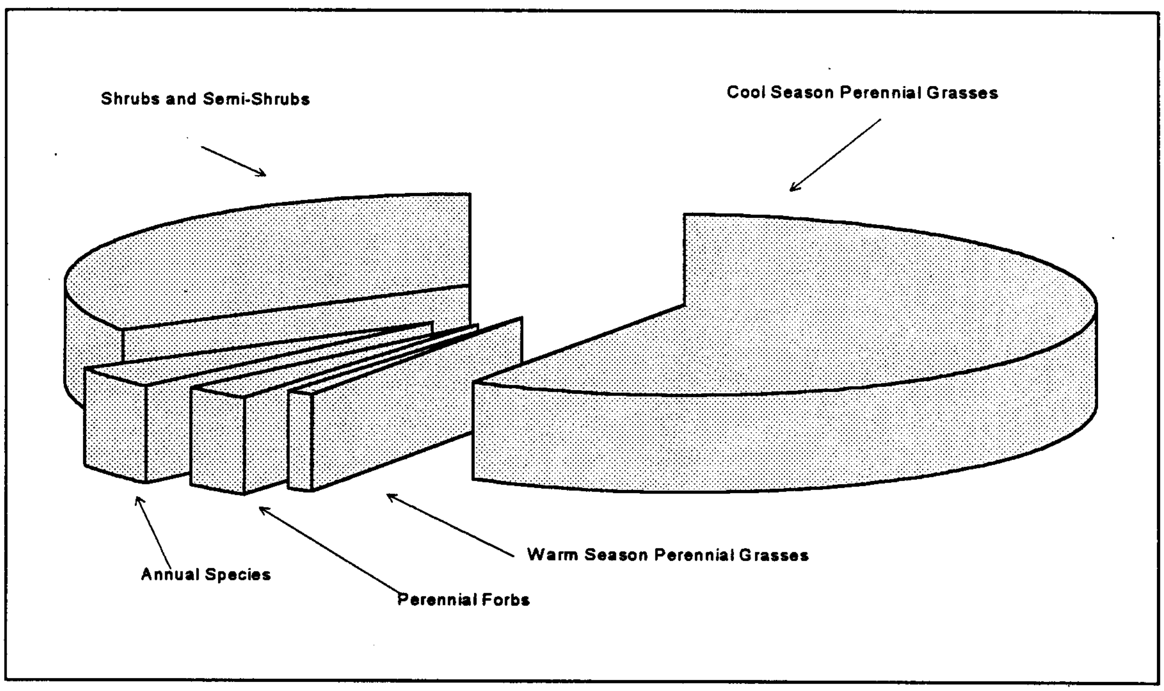


Figure 2. Relative Cover for Life Form Groups for an Area Reclaimed in 1986. Based on data collected in 1988.

The dominant species in the areas reclaimed after 1986 are also cool season perennial grasses. Thickspike wheatgrass, slender wheatgrass, western wheatgrass and green needlegrass all continue to occur as the major species within the reclaimed areas. The difference between these most recently reclaimed areas and the earlier areas is that other life form groups are present in great enough amounts that they begin to consistently appear in the sampling data (Figure 2). While the cover values for warm season perennial grasses are usually low, these species are almost always present in the reclaimed areas and commonly encountered in the sampling plots. Another difference between the earlier and later reclaimed areas is the abundance of shrub species. Shrub species were only occasionally encountered in the older areas. In the more recent areas, shrubs are commonly encountered. This is especially true for areas that were planted as shrublands where big sagebrush, rubber rabbitbrush, four-wing saltbush *(Atriplex canescens)* and Gardner saltbush *(Atriplex gardneri)* can account for as much 20 percent of the total cover by all species (Figure 3). Species density, as measured by the number of species per square meter, is also greater on the more recently reclaimed areas (Figure 4). The overall trend on the reclaimed areas has been for increasing species density. The total number of species observed on each of the reclaimed areas has been relatively constant (Figure 5). Older areas have the same number of total species as the newer areas, but in the newer areas the species are more widely distributed.

All of the areas reclaimed since 1986 have attributes that are consistent with successful reclamation. Cover and production values are comparable to native grasslands, species density values (number of species per square meter) approach values measured in native communities, and shrub density values (in areas reclaimed as shrublands) approach those measured in native shrublands. In addition to achieving successful reclamation standards, these areas also approach meeting the objectives of restoration, especially with regard to species diversity and diversity of community structure (Figures 6 and 7).

The reasons for the observed changes between the older and newer reclaimed areas relate to the factors that were mentioned earlier (changes in seed mix and changes in the seeding methods). Also, yearly precipitation since 1989 has been equal to or above long-term means for the region, except for 1992 which tended to be a drought year.

## Role of Ecological Processes in Creating Change

Once reclamation activities have been completed, increases in species and structural diversity become dependent on natural processes of colonization and recruitment. Species can be introduced into reclaimed areas as wind blown seed or by the actions of animals. These processes are likely to be slow. While grazing animals can commonly be seen on reclaimed areas, their movement patterns are such that they may not be carrying much seed from the native areas to the reclaimed areas. During the summer, they tend to stay on the reclaimed areas on a consistent basis. In winter, they may move off the reclaimed areas and spend more time on native sites. This pattern reduces the chances of carrying seed from one area to the other. Wind can play an important role in moving seeds, but in general, the seeds of most plants are not carried very far by the wind. It is common for large reclaimed areas to be located at substantial distances from native areas and thereby reduce the potential recruitment by wind blown seed.

Even if seeds of native plants are naturally carried into reclaimed areas, there is also the problem that many of these sites may not have open spaces where seeds can germinate and grow. The communities on the reclaimed areas have the potential to quickly become ecologically closed,

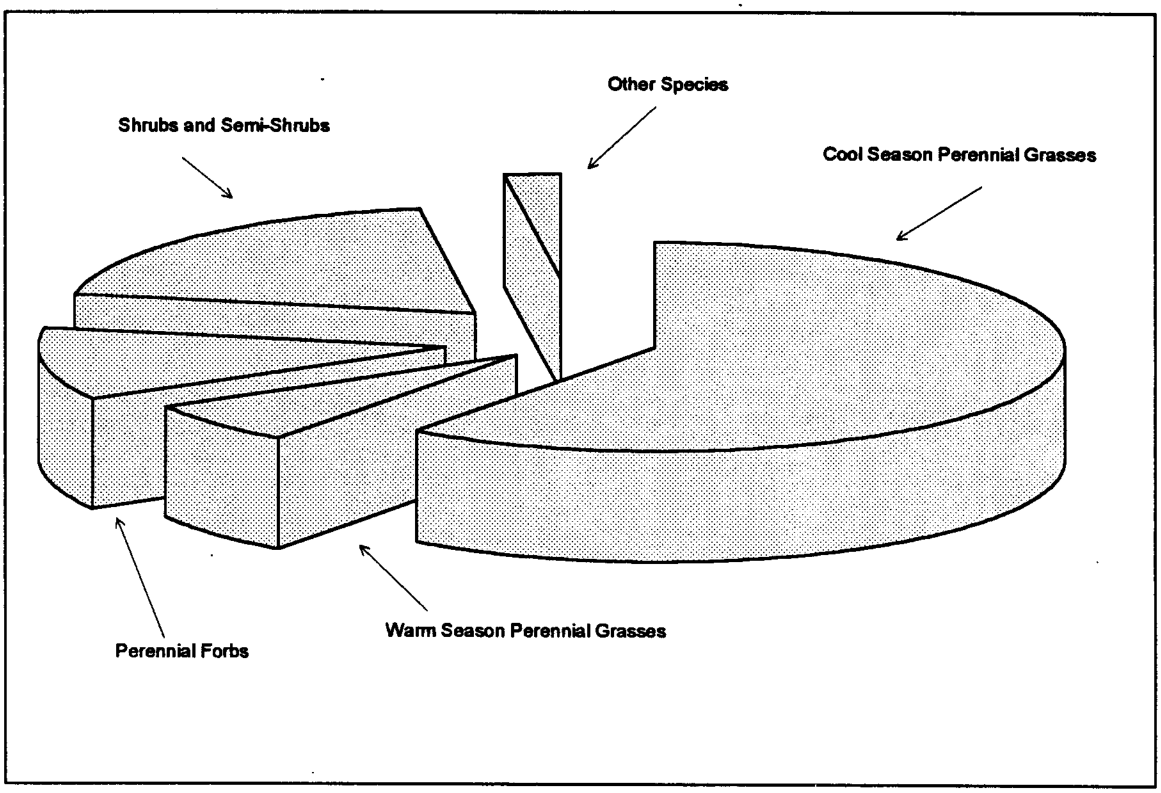


Figure 3. Relative Cover for Life Form Groups in an Area Reclaimed in 1991. Based on Data Collected in 1993.

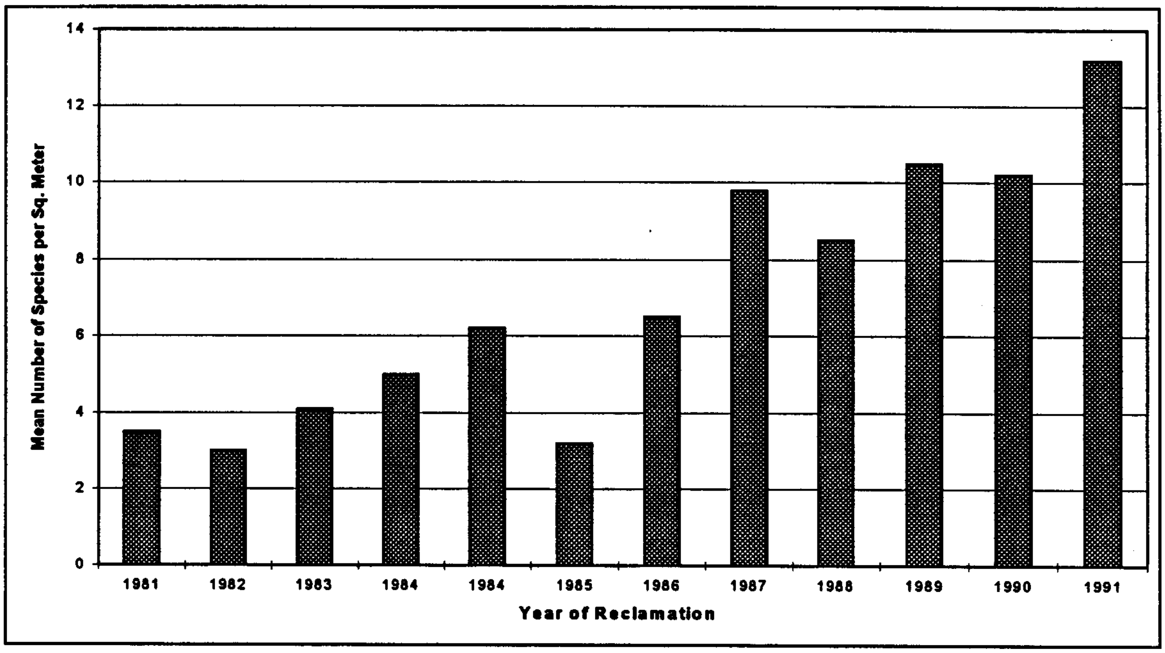


Figure 4. Relationship Between the Year of Reclamation and the Mean Number of Species per Square Meter.

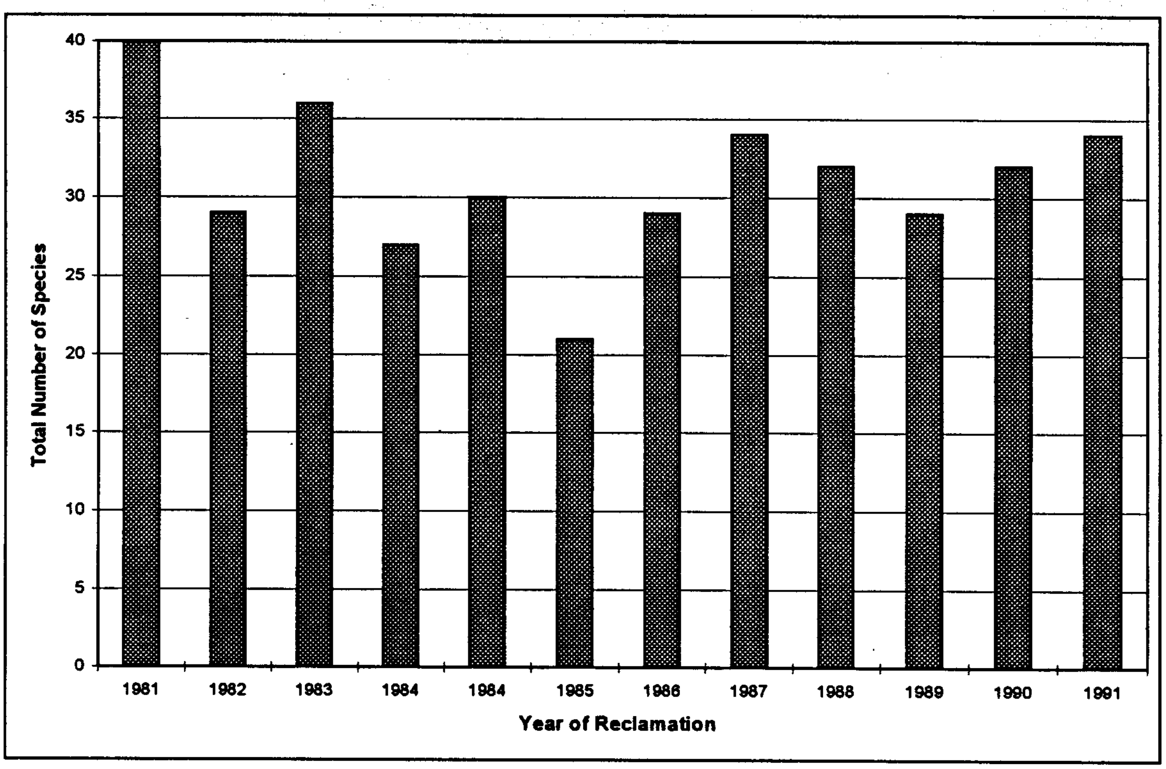


Figure 5. Relationship Between the Year of Reclamation and theTotal Number of Species Present in the Reclaimed Area.

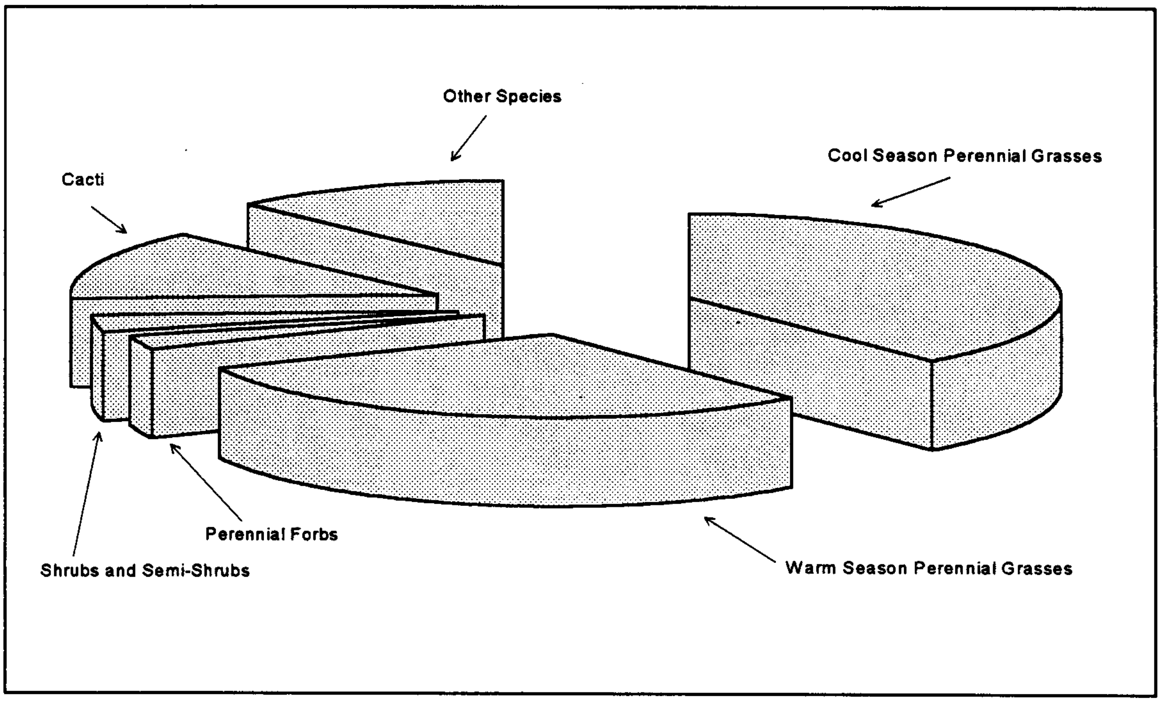


Figure 6. Relative Cover for Life Form Groups for Native Mixed Grass Prairie. Based on Data Collected in 1991.

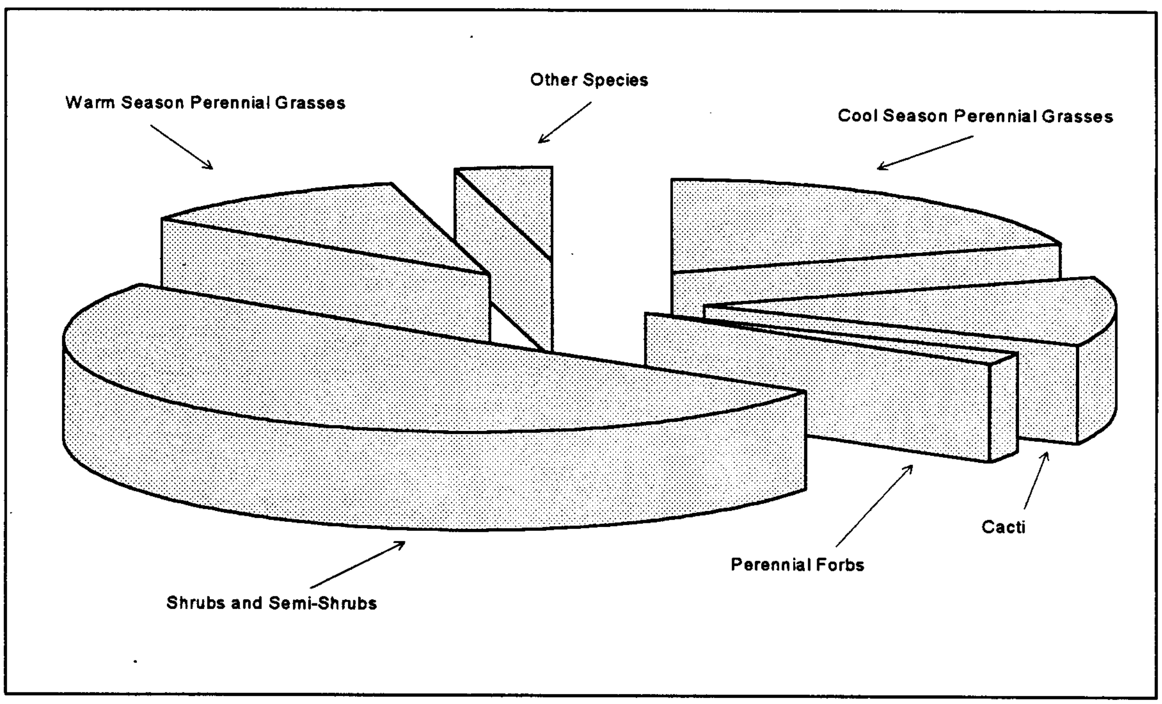


Figure 7. Relative Cover for Life Form Groups for Native Big Sagebrush Shrubland. Based on Data Collected in 1991.

especially if the seedings are successful. Any new seedlings must compete with already established grasses. These factors serve to reduce the recruitment rate for native species.

### Management Activities That Can Create Change

While the ultimate restoration of mined lands could take quite a long time when it is dependent only on natural recruitment, it is possible to increase the rate of establishment. Some activities like direct haul of topsoil, using diverse seed mixes, sod transplants and shrub transplants can be implemented concurrently with other reclamation activities. These practices serve to bring seeds and plant propagules directly into reclaimed areas and shorten the time period that would be required to accomplish the same goal by natural recruitment processes.

### Summary and Comments

Data collected from reclaimed areas at the Black Thunder Mine suggest that the goals of reclamation are being met on all the lands that have been evaluated since the mid-1980's. As well as meeting reclamation goals, some of the more recently reclaimed areas are also meeting goals that are consistent with restoration projects. It is interesting to note that the current technology available for reclaiming large tracts of disturbed lands is such that structurally diverse communities can be created. The end result of creating these diverse communities is that the total length of time required for the ultimate restoration of the sites will be reduced.

# SUMMITVILLE: A THIRD PARTY REVIEW

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## Abstract

The Summitville project has become the center of attention in the mining and environmental communities since early December, 1992. "Much-to-do" has been made over the management, operational and regulatory involvement in this "environmental disaster".

After reviewing the Knight, Piésold and Co. document entitled Chronologic Site History, Summitville Mine, Rio Grande County, Colorado, indications are that many interpretations have been colored by emotion rather than fact. The reports submitted to the state appear to report that there was cyanide, in the french drain water, but the water chemistry seems to discount this possibility. When mass balance analysis is applied to the submitted data, it appears that early leak information may have not been correct. A review of the pertinent cyanide chemistry and analysis was conducted to try to clarify what actually happened on site. The main problems at Summitville are previous mining impacts, mine waste dumps and communication problems, not cyanide releases.

Using 20/20 hindsight, the events that happened on site are reviewed from a "dispassionate" point of view.

## Introduction

The Summitville project was operated by Summitville Consolidated Mining Company, Inc. (SCMCI), which was a subsidiary of Galactic Resources, Inc., which was a subsidiary of Galactic Resources, Ltd. of British Columbia, Canada. SCMCI began development in 1984 and started mining activities in 1986. The mine is located in South-Central Colorado at an elevation of about 11,500 feet. The project site is about 25 miles southwest of Del Norte, in Rio Grande County. The mining method used by SCMCI was open pit mining. The extraction method was cyanide heap leaching, using the valley-fill technique. The annual rainfall appears to be in question since initially, the precipitation rate was given as 44.6 inches and the mean pan evaporation was 49 inches per year measured for a time period between 1950 and 1959. The rate is also later shown as having a 25-year yearly precipitation of 55 inches based on a Wolf Creek Pass location and 24.18 inches of annual evaporation based on Platoro Reservoir weather station data.

Initial permitting indicated that the project would operate as a "zero-discharge " facility. The pad site was in an area that had slopes ranging from 5 to 15%. The original pad design contained three leaching compartments with ore stacked to a height of 60 feet. Before the project start-up, the pad design was changed to a single cell with ore stacked to a height of 300 feet. The lining system contains two separate sections, the synthetic liner was originally 30 mil high density polyethylene (HDPE), but was changed to 60 mil linear low density polyethylene (LLDPE) below 11,560 feet. The natural liner is a 16 inch of low permeability clay. The entire liner system is underlain by a french drain system. Above the clay and under the synthetic liner, there is a leachate collection and recovery system. On top of the synthetic liner is a friction sand layer, a geotextile, an 18 inch layer of crushed and screened ore and a final coarse layer of ore.

Precious metal extraction was accomplished by using a sodium cyanide lixivant and lime/cement pH buffering. The ore is described as being in "porous quartz and quartz-alunite vein rocks". The primary minerals in the sulfide zone are pyrite and enargite. The oxidized zone extends down from 300 to 450 feet below the surface. The mine appears to have been excavated to about the 11,500 level. The mining right held by SCMCI are stated as "minerals above a horizontal plane 200 feet below the floor of the Reynolds Tunnel".

Pad loading commenced in May, 1986, and application of leach solution began June 5, 1986. On June 10, 1986, cyanide solution was detected by SCMCI in the leak detection system beneath the primary liner. On June 18, an MLRD inspection found cyanide in the french drain solution beneath the secondary liner. SCMCI first identified cyanide in the french drain solution on July 11, 1986.

Knight, Piésold and Company put together a three volume chronologic review of the Summitville operation for the Summitville Study Group. This group included mining executives and interest groups. This document is the major source of information used to analyze the Summitville project.

**Basic Cyanide Chemistry Review**

Cyanide has been used in the mining industry since 1898 as a lixivant for precious metals. The cyanide form normally used in mining application is sodium cyanide. In solution, the sodium cyanide is normally found as sodium and free cyanide ions

$$NaCN \_ Na^{+} + CN^{-}$$

The free cyanide reacts with hydrogen ions found in the water to form hydrogen cyanide in solution. The $pK_a$ of hydrogen cyanide is 9.21 at 25°C. Figure 1 shows the relationship of HCN and $CN^-$ with pH. In cyanide leaching, the solution pH is usually held above a pH of 10. Cyanide complexes with various metals to form linear, planar, tetrahedral, square planar, trigonal bipyramidal, and octahedral complexes. The various compounds and complexes of cyanide are found in Table 1.

Therefore, depending on the pH of the solution, metals will be sequestering cyanide in complexes. Copper complexes reduce in degree of order as the pH changes. As the pH lowers, the tricyano cuprite and then the dicyano cuprite complexes become the dominate species. At pH levels below 4.5, insoluble copper cyanide becomes the prevalent species. At pH levels below 3 the copper cyanide begins to dissolve and form $Cu^{+2}$ and HCN. Table 2 shows approximate percentages of the various copper species.

This relationship of pH and copper species is important because the pH of the solution will determine the possible ratio of copper concentration and cyanide as measured by Method C (weak acid dissociable cyanide analysis). This ratio is important when attempting to obtain a mass balance when reviewing analysis information. Table 3 contains the molar copper to cyanide ratios of the various species.

Table 3
COPPER TO CYANIDE MOLAR RATIOS REQUIRED BY THE VARIOUS COPPER CYANIDE COMPLEXES

| Copper Complex | Ratio of Cu : CN | mg Cu Required by 1 ppm WAD $CN^-$ |
|---|---|---|
| $Cu(CN)_4^{-3}$ | 1 : 1.64 | 0.61 |
| $Cu(CN)_3^{-2}$ | 1 : 1.23 | 0.81 |
| $Cu(CN)_2^{-1}$ | 1 : 0.82 | 1.22 |
| CuCN | 1 : 0.41 | 2.44 |

Normally, if the ppm of copper is close to the value of WAD cyanide, as measured by Method C, then the analysis is considered close. As can be seen from Table 2, this is only the case at pH levels around 7, when the di- and tricyano complexes concentrations are nearly equal.

Using this data, it becomes problematical that any cyanide was present in the early french drain solution. What may have been reported is the reaction of sulfate with silver chloride rather than with cyanide. The data in the KP&C report (1986 Environmental Report) shows that there was no gold or silver present in the french drain solution but there was supposedly cyanide. Precious metals appeared in the french drain solution in early 1987. The pH of the french drain solution eliminates the possibility of free cyanide being present in solution. Process solution has significant copper present and therefore WAD cyanide could be present but only in an equal ratio of copper to precious metals. This is not the case, because throughout most of 1986 the reported cyanide would have required gold and silver concentrations of 0.003 rather than none detectable. Ultimately, precious metals did show up in the french drain solution due to a leaky liner system, but the contamination found in the early days of leaching was most likely due to using incorrect analytical methods.

**Review of the Summitville Pad Design**

In 1984, when the initial Summitville design was released, it should be noted that lined containment systems were used in the mineral industry mainly for evaporation ponds. The lessons learned since that time have gone a long way to standardize the pad design. Even today, some states favor certain liner materials and pad designs over others. The SCMCI pad design of choice was a valley leach pad. This design is usually favored when pad slopes exceed 5%. The valley leach contains all the ore in a pond and stores the pregnant solution in the heap rather than in ponds. In a normal heap leach design, the required design for a pond is a double synthetic liner separated by a geo-netting. The side slopes are usually covered by a geo-textile. A valley leach design would include that same double liner, plus internal slip berms to reduce the possibility of the liner ripping the upper liner, if that liner slides on the under liner. Additionally, a valley leach design would most likely include a roughened surface liner instead of a standard smooth surface liner.

The Summitville design utilized a combination of synthetic and natural (low permeability clay) liners. This design incorporated a french drain system below the natural liner, 16 inches of low permeability clay, a two foot leak detection layer above the clay (sand with drain pipe embedded), 30 mil high density polyethylene (HDPE) below 11,560' elevation and 60 mil linear low density polyethylene (LLDPE) above 11,560' elevation, a thin layer of friction sand, a 7.5 oz non-woven geotextile and 2 feet of crushed and screened ore on top of the geotextile. The ore placement was accomplished using truck dumping and dozer pushing. Permeability ripping was done to a depth of 2 feet from 1986 to 1988 and to a depth of 5 feet from 1989 to 1991.

After the original ore placement (to an elevation of 11,560 feet) intermediate liners were used to isolate new ore from old ore. Additionally, an area (the "Burner Bowl") was shaped and lined to serve as a reservoir for french drain pump back solution (from 1988 to 1990). This area was prepared by trucking clay ore fines and compacting this material via truck traffic. This pond was drained in 1990 and later used as leach area. When the intermediate lining system was used, the leach areas were designed to act as individual cells.

## Summitville Operating Parameters

The Summitville ore placement operations were done on a seasonal basis. 100% of the ore was mined, crushed and stacked between April and October, weather permitting. Gold recovery operations were done on an around the clock basis. Due to snow and ice build-up, a solution flooding (drilled HDPE piping) and later drip irrigation was utilized to wet the ore (when possible) during the winter. The large internal storage of the valley leach design allowed for solution application problems. Gold recovery was accomplished by using a carbon-in-solution (CIS) system. This system utilized carbon columns to absorb the precious metals, a pressure stripping (Pressure Zadra) system, electro-winning system and doré melting furnace to make ingots for shipping to a refiner.

Site access was a continual problem during the winter recovery operations, requiring substantial snow removal. Operational philosophy reflected the adverse weather conditions and was quite novel for an operation of this type.

## Operational Problems

No exact knowledge of the operational problems encountered at the Summitville site is revealed in this section. This account is pieced together from reports, conversations with both people involved on site and third parties knowledgeable of the happenings on site.

For numerous reasons, including design changes, financing, permitting and weather, the Summitville construction was started later than anticipated. During the final stages of the lining of the pad, snowfall occurred hampering lining operations. If lining operations were not completed, subsurface soil work would be compromised, therefore the lining contractor erected half tunnels over the seams and continued the seaming operations in extremely adverse conditions. It has been reported that two avalanches occurred during this time (on March 5 and again on an unnamed date in April, 1986) which exposed the liner causing damage. Due to the potential resulting problems caused by the damaged liner, the pad design consultant, Klohn-Leonoff, subcontracted GeoServices, "to certify the synthetic liner integrity". GeoServices certified the liner on May 21, 1986, excluding areas that could not be inspected due to snow accumulations and "... the liners on the east slope and pad bottom, which had been damaged by several avalanches." It appears that records of a follow-up certification for the excluded areas were found in the search done by Knight, Piésold and Co (KP&C). The site was inspected on April 2 and

May 29, 1986 by Mined Land Reclamation Department (MLRD). During MLRD's last visit, SCMCI was testing for leaks.

Pad loading of the layer of crushed and screened ore started in May, 1986 (no specific date given), followed by regular ore placement. This layer acts as a buffer to the synthetic liner. Leach solution was applied to the ore starting on June 5, 1986. On June 10, 1986, cyanide was detected by the operator in the leak detection system below the primary liner. On June 18, 1986, an MLRD inspection found cyanide in the french drain solution beneath the secondary liner. SCMCI detected cyanide in the french drain solution on July 11, 1986 and reported it to MLRD.

**A Critique of the Problems incurred at Summitville**

20/20 hindsight is a phenomenon enjoyed by all after the fact, but unfortunately denied to anyone doing the work during the event being reviewed. Starting lining operations before a complete cessation of winter weather is a gamble at anytime. It is reasonable to believe that the gamble was justified by the site personnel because winter weather can occur at any time (spring or summer) at the Summitville site. There are many ways that the lining operations can be accomplished under adverse conditions and most of these were employed at Summitville. Were all the possible precautions taken? Obviously no, they were not.

Who is to blame? Management for demanding that operations start "as soon as feasibility possible" to start the ability to repay loans, the banks for pressuring management to meet performance requirements, management of negotiating performance criteria into their loans, the consultants for not standing firm under pressure to "get on with it", SCMCI construction management for being willing to make management happy under any circumstances, the regulators for being inexperienced with the potential problems and lulled into a false sense of trust "that everything was under control" or all of the above and more.

Heap leaching was in the early stages of development for high precipitation environments in 1986. This means that many of the mistakes made at Summitville had not yet been identified before they were encountered at Summitville. Many can point to the fact (using 20/20 hindsight) that these problems should have been anticipated. This discussion is appropriate is for a boardroom or a bar room, but definitely not when personnel are barraged from all sides demanding action (dictated by individual needs and requirements). Maybe if the site personnel had been less concerned with making everyone happy, things might have been better. If unlimited funds were available, I know that things could have been different (money does not always make the determining difference).

Summitville's pad lining was the victim of every possible application of "Murphy's Law and various corollaries", a limited knowledge of the potential problems and the need of environmentalists to have a shining beacon to show why mining should not be allowed in the United States.

It is possible that if a different group of individuals has been operating Summitville at that time, there would not have been any significant difference in the outcome. The problems associated with Summitville can be pointed to as a example of what not to do, but quite contrary to common belief, the same problems would most likely have occurred to anyone. Besides all of the rhetoric about the "perceived" cyanide problem at Summitville, the reason that the creeks are not active fisheries is because of copper contamination, not cyanide contamination. Cyanide contamination in the creek water would self detoxify a very short distance from any discharge, either by off-gassing or precipitating out of solution. Therefore, reviewing the gold operation at Summitville may give a tangible target to identify but that target may only serve as a convenient lightning rod for the public's righteous indignation.

The major problem in the operation was allowing the water management to get out of balance and allowing water head to build up on the liner. The head on the liner caused significant transmission of the leach solution to be forced through the secondary liner to the french drain. The operating philosophy should have been altered to maintain a minimum of head on the liner rather than storing large amounts of winter melt-off in the heap. If the decision was made to treat or hold the excess water in another facility, the problems may have been significantly different. The acid generation by the surrounding underground mines and the open pit mine waste are the true problem at Summitville, although the problems that received the most press and attention (cyanide) were of little consequence.

**The Real Problem at Summitville**

The main problem at Summitville is not the cyanide leaking from the SCMCI facilities or the perceived financial abuses by Robert Friedland. It comes from the copper flowing from the abandon mine portals and mine waste dumps on site. There were minor discharges of cyanide to surface and ground water, but if there was any impact on the environment from the discharged cyanide, it cannot be detected or quantified.

The creeks below Summitville and a portion of the Alamosa River down stream from the Summitville Mine are devoid of fish because of the acid mine drainage (AMD) from previous mining endeavors dating back to the 1870's. Some AMD is being contributed by the Summitville operation, but a majority of the impact began long before SCMCI's presence on site. A case has been made that the open pit mining activities are impacting the underground AMD, but any statistical evaluation is hampered by a lack of historical data and any attempt to utilize that non-statistically relevant data base to draw conclusions can leave the conclusion open to various interpretations. The analysis, that the increase of copper coming from the Reynold's adit is due to SCMCI activity, does not appear to take precipitation variations into account. The main basis for the conclusion is that the water quality analysis from the Wrightman Fork is different from analysis made in October, 1980. No data as to stream flow rate is given, no evidence of Reynolds adit flow rate or contaminate analysis is given, just an opinion that the SCMCI activity has impacted. It cannot be denied that there has to be some impact to the site due to the AMD coming from the SCMCI mined material, but the "leap of logic" that the increase in the Reynold's adit contaminate concentration should require more rigorous demonstration that has been presented in the KP&C document. Ultimately, it may be proven that the mining activity impacted the AMD from the old workings, but no matter what level of proof surfaces in the future, no thought by the operator, state or federal authorities brought forth any mention of this possibility. It should be noted that during the planning stages, it would have taken a rigorous examination of the subsurface hydrology to identify the potential to cause changes in the old workings' AMD. Additionally, a good engineering case could have been made that the potential to cause change was only that, a potential, and could not be proven one way or other.

The only option open at this time is to work to eliminate the sources of contamination and attempt to return both the Wrightman Fork and the effected section of the Alamosa River to fishery potential. The substantial costs associated with accomplishing this effort will have to be borne under Superfund or some other governmental program, since SCMCI and its parents no longer exist.

Table 1

| Cyanide Species | Example |
|---|---|
| Free Cyanide | $CN^-$ |
| Readily soluble simple cyanide compounds | NaCN, KCN<br>$Ca(CN)_2$, $Hg(CN)_2$ |
| Relatively Insoluble Cyanide compounds | $Zn(CN)_2$, CuCN,<br>$Ni(CN)_2$, AgCN |
| Weak acid dissociable complexes (complexes that dissociate above a pH of 7 | $Zn(CN)_4^{-2}$,<br>$Cd(CN)_3^{-1}$,<br>$Cd(CN)_4^{-2}$ |
| Complexes that dissociate above a pH of 4 but below a pH of 7 | $Cu(CN)_2^{-1}$,<br>$Cu(CN)_3^{-2}$,<br>$Ni(CN)_4^{-2}$,<br>$Ag(CN)_2^{-1}$ |
| Complexes that dissociate below a pH of 4 | $Fe(CN)_6^{-4}$, $Fe(CN)_6^{-3}$,<br>$Co(CN)_5^{-3}$, $Co(CN)_6^{-4}$,<br>$Au(CN)_2^{-1}$, $Hg(CN)_4^{-2}$ |

Table 2
RELATIONSHIP OF pH AND PERCENT COPPER SPECIES

| pH | % $Cu(CN)_4^{-3}$ | % $Cu(CN)_3^{-2}$ | % $Cu(CN)_2^{-1}$ | % CuCN | % $Cu^{+2}$ |
|---|---|---|---|---|---|
| 10 | 100 | 0 | 0 | 0 | 0 |
| 8 | 0 | 100 | 0 | 0 | 0 |
| 6 | 0 | 40 | 60 | 0 | 0 |
| 5 | 0 | 0 | 100 | 0 | 0 |
| 4 | 0 | 0 | 80 | 20 | 0 |
| 3 | 0 | 0 | 0 | 100 | 0 |
| 2.5 | 0 | 0 | 0 | 0 | 100 |

The constant cry that the Summitville gold leaching project got away with criminal behavior and someone should be made to pay is only so much inflammatory rhetoric. Someone is and will continue to pay, the American taxpayer. When Superfund sites such as Iron Mountain and the Walker Mine were identified, the Summitville AMD was not, why? What unique knowledge did SCMCI personnel and its consultants have that makes them to be solely blamed? Why is the state wasting money on a criminal investigation, when that money could be used to augment the DMG's budget rather than appear to appease state government critics? Many questions can be asked but few definite answers will ever be given.

## So what, then?

What can be done at Summitville? The old portals can be plugged, the pit reclaimed, the waste piles isolated, the cyanide water in the heap detoxified and the heap reclaimed. These are all planned to be accomplished.

The mining regulators have learned much and will continue to learn from the Summitville "experience". This knowledge will be incorporated into future dealings with all mining endeavors in the state. Industry and industrial consultants will be smarter, due to the knowledge gleaned from this project. The public will have access to the accumulated knowledge and studies garnered from the investigation and reclamation efforts, if it wishes to wade through the voluminous data that is yet to be produced for the public record.

The only thing that can't be predicted with any certainty is will there ever be fish in that 17 miles of the river system. The return to fishery status is in question, because there is no guarantee that plugging the portal will keep the AMD from finding another uncontrolled surface release point. It cannot be guaranteed that if all the contamination from the Summitville site is eliminated that other natural areas will not continue contributing enough contaminates to keep the fish from returning.

The only certainty is that massive amounts of money will be spent to pay consultants, equipment operators and lawyers and very few people will be satisfied with any of the final answers.

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# The Process at Summitville - Is CERCLA Working?

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CERCLA was originally crafted to deal with industrial dump sites, things such as Love Canal or Valley of the Drums in Kentucky. The scheme under CERCLA is designed around a fairly well defined process of study, evaluation, selection of remedial options and execution of these options. Liability for the costs associated with the process is placed with the owner of the site, the operator of the site and those that arranged for hazardous substances to be placed at the site.

Allocation of responsibility among these parties is not a process defined by CERCLA. Instead, liability is typically strict, joint and several. Simply put, any person having any liability is potentially liable for the entire cost without regard of fault or other factors typically considered in allocating responsibility.

At mining sites, there are CERCLA issues that complicate the process. Obviously, there has typically been a succession of owners and operators. Many of these entities may not be viable. Given the succession of mining activities, it is typically unclear what sort of work occurred at different times. Lastly, mining waste rock is typically not a hazardous substance, thus putting agencies and responsible parties in the position of trying to evaluate environmental damage without considering the management of waste rock.

Summitville has been a mining district since the 1870s. Extensive underground workings were established by a variety of entities. Substantial ore was removed and tailings were produced. Adits were driven in to remove ore and to drain the mountain, which has resulted in highly acidic drainage.

There is no evidence that the area streams have never supported fish. Undisturbed drainages nearby have very low pHs and are known to be impacted by mineral seeps and exposed sulfur bearing rocks. Even though it is likely that mining activities have had an impact by increasing the discharge of acidic materials, the magnitude of this impact is unknown and may not be very significant in comparison to native conditions.

In this century, several mining companies operated on the site. Some held leases to evaluate and expand the existing underground workings. Others contemplated more extensive operations. Ultimately, Galactic resources obtained the assignment of a lease for the property.

They bought designs for a heap leach operation from a prior operator and set about to obtain the necessary permits and approvals for operations.

The process of obtaining these permits and the technical quality of the permits is an example of the regulatory process gone very wrong. In a report entitled *The Summitville Mine: What Went Wrong* a member of the Mined Land Reclamation Board, at the time of permitting, portrayed the situation where no agency exercised regulatory control of the design and installation of the heap leach operation (Danielson and McNamara 1993). As a result, conditions constituting permit violations quickly appeared. The agencies attempted to work with the operator; however, the fixes attempted had the net effect of limiting the economic value of the mine. Ultimately, and for many reasons, the operator went bankrupt.

At the time of bankruptcy, the agencies believed that imminent hazards existed at the site. They believed that water treatment systems would fail causing acidic waters to be discharged at increasing rates. They also believed that water would overflow the heap leach retention dam causing a catastrophic failure and the discharge of cyanide and tailings materials into the local drainage.

EPA came onto the site to run an emergency response action under CERCLA the day after the bankruptcy. The identified emergencies included not only conditions caused by Galactic by also discharges from the adits and certain tailing piles that had been present for decades.

Emergency response actions do not follow the typical CERCLA process. Instead, the agency decides what it wants to do and does it. There is no public oversight. There is no opportunity for public comment. There is no potential for the review of their activities until the much later point where they attempt to collect the costs from the responsible parties. EPA simply sweeps onto the site and excludes past operators and the owner. It does what it feels is necessary, without consideration of the impacts of these actions save that they address the emergency conditions.

In the case of Summitville, EPA is treating water from the adits and from the heap leach. They have moved large quantities of waste rock back into the mining pit. They are plugging adits. Ultimately, they plan on either moving the entire heap leach or hydrologically isolating it from the surrounding area.

None of these remedies has been subjected to a public analysis. It is not at all clear that all these steps are truly necessary to address emergencies at the site. The ultimate environmental goal of these actions have not been determined. Instead, these activities have been selected because they seem to be the correct actions given the EPA's view of proper efforts.

The tax payers are currently paying for these efforts. As such, one would hope that EPA's efforts were the bare minimum necessary to stabilize the site as it was in recent decades. Instead, the EPA seems focused on completing a cleanup of the site within their view of appropriate, ultimate solutions. These solutions are not consistent with additional mining of the site, but instead seem designed to achieve EPA's views on the future use of this property.

The CERCLA process in routine situations is designed to consider future use of the property and these other factors. Not only would EPA normally consider these factors, but they would do so with an opportunity for full public comment and review.

## Conclusion

CERCLA itself was never designed for mining sites. Much less, the emergency response process was intended for quick operations designed to achieve an immediate reduction in risk from leaking drums or other uncontrolled conditions. At Summitville, the emergency response process is being used to accomplish cleanup of a site for reasons and to standards that may make no sense in the context of this site. The emergency response process is being subverted at Summitville to avoid public comment and input on the appropriate remedies and goals.

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# ALTERNATIVES FOR PREVENTION AND REMEDIATION OF ACID ROCK DRAINAGE

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## ABSTRACT

Acid rock drainage (ARD) is a persistent problem associated with sulfide bearing rock and soil. A number of alternatives exist to prevent the onset of ARD; to arrest progress of ARD at various stages of its development, and to remediate effects of ARD. This paper provides an overview of the important chemical and biological processes involved in the formation of ARD, and uses this framework to review current engineering approaches to prevention and remediation of ARD with respect to feasibility, effectiveness, cost, and incidental impacts.

Factors which influence the onset, rate, and results of ARD include availability of oxidants, water and sulfides; net acid neutralizing potential; and the presence of bacteria of the genus *Ferrooxidans*. Approaches to prevention and control of ARD utilize one or more of these factors. Reactant availability can be limited by capping, flooding, mixture with low permeability materials, removal of sulfides, and armoring reactive sulfides. Acid generation can be controlled or prevented by chemical means, including admixture with neutralizing materials such as lime, limestone and phosphate rock. Finally, control of ARD can be achieved by preventing bacteriological activity using bactericides, or creating an unfavorable environment for bacterial growth.

## GEOCHEMISTRY OF ACID ROCK DRAINAGE

Acid rock drainage (ARD) is the result of natural oxidative weathering of sulfide minerals, primarily pyrite, by meteoric water to produce an acidic iron sulfate solution. Mine spoil piles derived from sulfide-bearing ore-minerals are a common source of ARD, which has proven to be a persistent environmental problem. To be able to arrest the progress of ARD at various stages of its progress or remediate its ultimate effects requires that two fundamental aspects of the geochemistry of its formation be recognized: the oxidation of pyrite (sulfide minerals) and the oxidation of iron. The oxidation of ferrous iron and pyrite are closely linked in the

ARD environment. The oxidative dissolution of pyrite produces ferrous iron, which oxidizes to form ferric iron, which in turn acts as an oxidant for pyrite. Thus, the rate at which each of these processes occurs is critical to the evolution and propagation of ARD. Williamson et al. (1994) provide a detailed comparison of these rates, which is summarized below.

Pyrite Oxidation

The aqueous oxidation of pyrite, $FeS_2$, can proceed with either dissolved oxygen (DO) or ferric iron, $Fe^{3+}$. These two reactions are typically represented as follows

$$FeS_2 + 7/2\ O^2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H+$$

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15\ Fe^{2+} + 2SO_4^{2-} + 16H+$$

Although written as equilibrium reactions, the combination of pyrite with water and either ferric iron or dissolved oxygen is far from equilibrium and proceeds to the formation of products. The reactions do not, however, proceed at equal rates.

The rate at which each pyrite oxidation reaction proceeds is a direct function of the concentration of the oxidant ($Fe^{3+}$ or DO), and can be expressed mathematically as a rate law. The derivation of these rate laws must be evaluated experimentally and is discussed in detail by Williamson and Rimstidt (1994) and Williamson (1992). In general, the rate of reaction with $Fe^{3+}$ is the faster reaction at pH's normally associated with ARD between 2 and 3.5. Figure 1 is taken from Williamson, et al. (1994) and illustrates the comparison of pyrite oxidation rates, in terms of their relative rates of $Fe^{2+}$ production. For the comparison, the total amount of $Fe^{3+}$ in solution is assumed to be controlled by the solubility of ferrihydrite ($Fe(OH)_3$ and the total concentration of DO is set at 9 ppm, or $2.8 \times 10^{-4}$ mol/L). From this figure it can be seen that the rate of pyrite oxidation is faster with $Fe^{3+}$ than with DO at pH's consistent with ARD (2-3.5), due primarily to the strong pH dependance of ferric iron. Thus, the oxidation of pyrite by DO is an important process only in the absence of ferric iron, such as at the onset of ARD (pH > 5).

Iron Oxidation

Iron in the pyrite mineral structure is in the reduced, ferrous ($Fe^{2+}$) state, which upon exposure to dissolved oxygen will react to form ferric iron.

$$Fe^{2+} + O_2 + 4H^+ = Fe^{3+} + 2H_2O$$

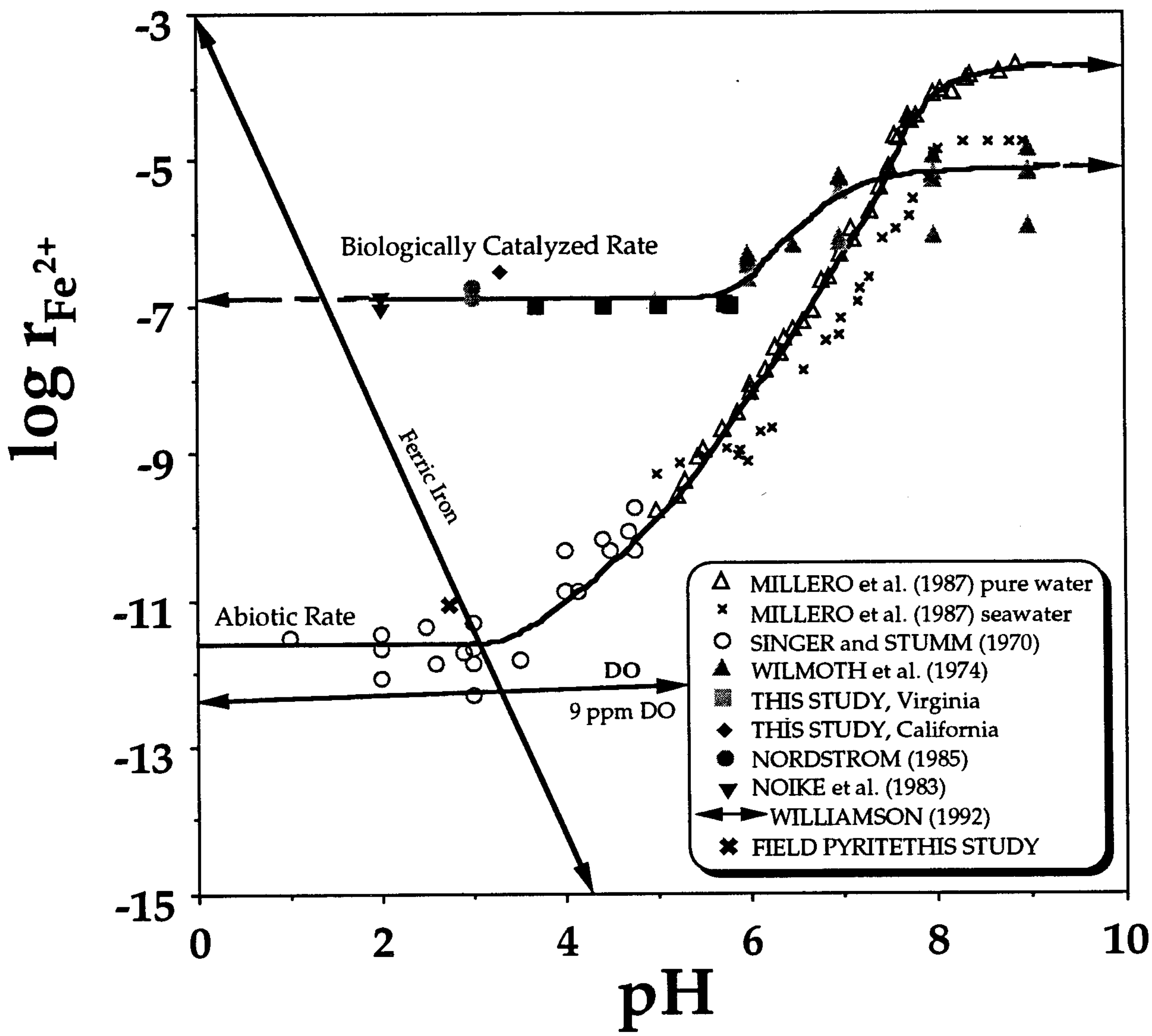


**Figure 1** - Pyrite oxidation rates (Williamson et al, 1994)

As is the case with the aqueous oxidation of pyrite, the aqueous oxidation of ferrous iron proceeds at a specific rate, dependant upon the composition of the aqueous solution. The rate of oxidation of ferrous iron is greatly accelerated by the presence of the bacterium *Thiobacillus ferrooxidans,* commonly found in ARD, compared to the reaction with DO alone. A detailed comparison of these two rates is presented in Williamson, et al. (1994) and shown here in Figure 1.

Figure 1 compares the relative rates of $Fe^{2+}$ consumption during oxidation by DO and by the bacteriologically-mediated reaction. From this figure it is clear that the bacterially mediated reaction dominates the reaction with DO at pH below 6. In general, over the pH range normally encountered in ARD (2-3.5), the bacteriological rate of iron oxidation proceeds approximately 5 orders of magnitude faster (100,000x) than the reaction with DO.

The Relationship Between Iron and Pyrite Oxidation

The propagation and evolution of ARD cannot be understood only in terms of equilibrium concepts generally employed to evaluate natural water systems. In ARD systems, the oxidation of $Fe^{2+}$ to $Fe^{3+}$ by the bacterium *Thiobacillus ferrooxidans* and the oxidation of pyrite by $Fe^{3+}$ are intimately related and limited by the relative rates of each process.

The rates of oxidation of $Fe^{2+}$ and pyrite illustrated in Figure 1 can be used to clearly identify the rate determining step of the propagation of ARD. In this figure, over the pH range normally associated with well-developed ARD (2-3.5), the bacteriological production of $Fe^{3+}$ exceed the capacity of pyrite to consume it. Under these circumstances, the aqueous oxidation of pyrite is the rate-determining step because it proceeds at the slowest rate. In contrast, however, in the absence of bacteriological activity, the rate of $Fe^{2+}$ oxidation is slower than the rate that pyrite will consume the resultant $Fe^{3+}$. In this instance, the rate of ion oxidation is the rate determining step (Singer and Stumm, 1970). Thus, from Figure 1, the important role of *Thiobacillus ferrooxidans* is clear and actions that limit the activity of this bacterium can greatly reduce the magnitude of the effect of ARD.

Stages of ARD Development

The geochemistry of ARD systems evolves from near-neutral pH water-rock interactions to acidic conditions. Consistent with this overall geochemical evolution, Kleinmann, et al. (1981) presented a model for these systems in terms of three stages of development. Each of these stages presents specific requirements for the amelioration of ARD. The three stages of Kleinmann, et al. (1981) are presented in Table 1.

Table 1. Summary of the three stages of ARD formation (modified from Kleinmann, et al., 1981).

| STAGE | PYRITE | IRON | CHEMISTRY |
|---|---|---|---|
| 1 | biotic/abiotic with DO | abiotic with DO | pH >4.5<br>high $SO_4$<br>$E_H$ < 450 mV |
| 2 | biotic/abiotic with DO | biotic/abiotic with DO | pH 2.5 - 4.5<br>high $SO_4$<br>increasing $Fe_{tot}$<br>$E_H$ = 450 - 600 mV |
| 3 | abiotic with $Fe^{3+}$ | biotic by *Thiobacillus ferrooxidans* | pH < 2.5<br>high $SO_4$<br>high $Fe_{tot}$<br>high $E_H$ (>650 mV) |

As discussed by Kleinmann, et al. (1981), the importance of these stages to the prevention, arrest and remediation of ARD is to recognize the biogeochemical factors that are dominant at each stage of development, thus encouraging activities that most directly target the most influential processes.

From a geochemical standpoint, the prevention, arrest and remediation of the effects of ARD must include

- limiting the availability of reactants
- limiting the rate of oxidation of pyrite and iron
- amending mine waste rock with excess alkalinity to avoid acidification

Prior to acidification, addition of alkalinity will discourage acid production and limit the transport of contaminant metals. Once acidity has exceeded alkalinity, treatments which target a reduction in the activity of

*Thiobacillus ferrooxidans* will reduce the rate of supply of $Fe^{3+}$, the dominant oxidant of pyrite in acidic environments. In conjunction with attempt to reduce the supply of oxidants to weathering pyrite, strategies to retard the reactivity of this mineral through isolation or armoring by precipitated secondary phases are consistent with the general characteristics of ARD formation outlined here.

Neutralization

Once acid generation has occurred, the acid created can be neutralized and the formation of further acid prevented or retarded by neutralization. This can be achieved by a wide range of materials, including the addition of lime or other base chemicals, or contact with limestone or other materials with neutralizing capacity (e.g. feldspars). In particular, calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and siderite ($FeCO_3$) are commonly encountered in orebody host rock sequences and along groundwater flow paths. The reaction of calcite with the $H^+$ ion is typical:

$$CaCO_3 + H^+ = Ca^{++} + HCO_3^-$$

This reaction solubilizes the calcium and bicarbonate, while neutralizing the acidity. It proceeds relatively slowly, and may result in armoring of the remaining active material to further slow this reaction (particularly true of the siderite reaction). It requires two moles of calcite to neutralize the acid generated by a single mole of pyrite.

Due to the armoring effect on limestone, lime is frequently used to neutralize acid formed from acid mine drainage. The gross reaction for this process is:

$$CaO + 2H^+ = Ca^{++} + H_2O$$

Thus one mole of lime neutralizes two moles of $H^+$ ion. The lime can be slurried, and it is very effective in reacting completely with the acidity in water.

Summary of chemistry of ARD

Based on the above evaluation, the oxidation of one mole of pyrite:

1. requires about 3.5 moles of oxygen;

2. requires between 1 and 3.5 moles of water;

3. produces between 2 and 4 moles of $H^+$; and

4. requires between 2 and 4 moles of $CaCO_3$ or between 1 and 2 moles of CaO to neutralize the acid if completely consumed.

Converting these values to mass terms, the oxidation of (say) one ton of pyrite:

1. requires about 0.9 tons of oxygen (200,000 cubic feet of air);

2. requires about 0.3 tons of water (70 gallons);

3. produces about 0.02 tons (50 pounds) of $H^+$.

4. requires about 2.5 tons of limestone or about 0.7 tons of lime to neutralize the produced acid.

## PREVENTION OF ARD

Prevention of acid rock drainage depends on control of the limiting factors associated with the formation of ARD:

- pyrite control;
- oxygen control;
- water control;
- bacteria control; and
- acid control.

Each of these is considered below.

### Pyrite control

The production of acid requires a pyrite mineral. Clearly, if there is insufficient sulfide in a material to initiate and sustain ARD, then ARD will not be a problem. As noted above, ARD occurs as a function of the amount of pyrite which is present in an exposed material. The pyrite level at which ARD occurs is site specific: it depends on a range of factors, including the nature of the mineralization, the nature of the host rock(s), the climate, and the degree of fracturing of the rock. A rough rule of thumb is that:

| Pyrite Content | Likelihood of ARD generation |
|---|---|
| >10% | Very high and rapid |
| 5% - 10% | High |
| 2% - 5% | Probable |
| 1% - 2% | Possible in places |
| <1% | Unlikely |

This suggests three strategies for prevention of ARD by controlling sulfide concentration:

1. Removal of sulfide. If sulfide is removed such that the sulfide concentration in the processed rock is not greater than the threshold reaction level for the rock, then ARD is not initiated, and will not in general proceed. The removal of pyrite is, however, difficult and expensive, and is not an economic response to sulfide removal except in a mineral processing context where flotation or leaching are used. In processing, the rock is ground and the pyrite is removed by flotation. The pyrite is then processed for minerals or used to produce sulfuric acid. In leaching, ARD processes are encouraged, the resulting acid and metal products removed, resulting in sulfide removal.

2. Removal of "hot spots". It is sometimes possible to selectively remove those materials which have sulfide concentrations which are high enough to initiate and support the creation of ARD. The removed materials can be either processed or disposed of in such a way to prevent formation of ARD, and the remaining material will then not initiate or support the formation of ARD. This selection is commonly practiced in mining, particularly for final reclamation of pit slopes and other disturbed materials, but is less attractive for the control of ARD in more disseminated sulfide occurrences.

3. Dilution of sulfide. A final strategy which can be used is to dilute the sulfide concentrations in the material to a level where ARD cannot be initiated or sustained. This strategy is available particularly if large quantities of material are disturbed, of which only a small portion contain sufficient sulfide concentrations to create ARD. The sulfide-containing material is intimately mixed with the non-sulfide materials, resulting in a material which has (generally) less than 1% sulfide. This approach is used in the disposal of mixtures of mined tailings from which sulfide minerals have been extracted, with waste rock from which they have not, to produce a non-ARD producing material.

In general, however, these strategies are not widely used; indeed, sometimes the sulfides separated during the milling of ores are re-mixed with the tailings, which results in re-establishing the ARD generating potential of the mixture.

Oxygen control

The production of acid from pyrite requires the presence of an oxidant. In general, the ultimate oxidant is atmospheric oxygen. Unfortunately (from the point of view of acid generation at least) oxygen is ubiquitous in the environment. It forms 16% of the atmosphere, and is generally present in water, including groundwater (the saturation concentration of oxygen in water is about 10 parts per million at normal temperatures and pressures). Fortunately (from the point of view of control of acid generation), the oxidation of sulfide to acid requires a considerable amount of oxygen. Thus it is attractive to consider oxygen limitation or denial strategies for control of acid generation.

First, flooding potentially acid generating sites, or placing them below the groundwater table, essentially guarantees cessation of significant acid production. Flooding can take a variety of forms:

- Underground mines. Flooding requires the plugging of exit points, and either allowing the void to refill with water, or filling it from an external source. While this approach has been very successful in some cases (e.g. the Walker Mine, California), it has failed in others (e.g. the Eagle Mine, Colorado). Plugging is a very site-specific remedy, and requires detailed investigation and design.

- Surface mines. Surface mine flooding can often be achieved by simply filling the pit with water, or allowing it to fill naturally. Generally this leaves the rim of the pit unprotected, which may require alternate ARD protection. Quality of the water which remains in the pit may be compromised by dissolution of ARD products from the pit walls, or by inflow of ARD water, but this can be remedied during the filling process if required.

- Waste rock. Waste rock flooding can be achieved by placing the waste rock under water, for example in a worked out, flooded pit or in an existing lake or ocean disposal area. A less common approach is to reduce the permeability of the rock so that the rock mass will resaturate as a result of natural infiltration. This can be achieved by low permeability additives, cementation, or co-disposal with low permeability materials (for example tailings).

Second, prevention of ARD can be achieved by eliminating air flow through or to the pyritic material. This approach also has a variety of applications, depending on the setting in which the ARD control is required:

- Underground mine. Air control involves the blocking of all points of air ingress and egress, thus preventing air flow. This is generally achieved by bulkheads, backfilling, or covering or burying the sulfide-containing area with non-acid generating material. However the control of air ingress into underground mines has proven to be difficult, because all subsurface areas "breathe", in response to diurnal and seasonal air pressure differentials between the mine void and the atmosphere. The most promising methods of air control in mines have been total or partial backfilling of the mine; this can sometimes be achieved by the use of mine development waste, hydraulic or pneumatic backfill, or mixtures of tailings and waste rock. The material which is used can be potentially acid generating, providing the backfilling achieves its goal of air exclusion.

- Surface mine and waste materials. Air control can be achieved in some circumstances in surface materials by covering with a material which has low permeability to air. Air flow through the cover is caused by the pressure differentials between the air in the subsurface material and the atmosphere (resulting from diurnal pressure variations, and buoyant pressure differentials due to the exothermic ARD process). The rate of flow is a function of the permeability of the cover to air. Accordingly, the cover is usually required to be:

  - thick (two to three feet of non-acid generating material is generally needed);

  - low permeability (a soil or amended rock which has a <u>saturated hydraulic</u> conductivity of less than about $10^{-5}$ cm/sec);

  - protected (the cover must be protected against disturbance and erosion by a further one to two feet of non-acid generating rock, so that the protection is permanent).

  In some cases these requirements can be met by inert waste material from a mining or other operation; more often, the materials have to be imported or created, which adds significantly to the cost of prevention.

Water control

The next strategy for control of acid generation, and one which is commonly advocated, is to deny water to the process. However, this strategy is almost always unsuccessful, for the following reasons:

- It takes only a very small mass of water to allow acid generation to occur: the oxidation of a ton of pyrite consumes only 70 gallons of water (this infiltrates in a 100 square foot area in a year in the west).

- Water is ubiquitous in the environment, so it is always available at the surface, and must be continually denied to the process. Further, many materials contain significant amounts of water within them, and this water alone is often sufficient to support ARD (a ton of soil, rock, or tailings contains in the order of 100 pounds of water, far more than enough to allow the oxidation of more than any sulfide in the material).

- There is a strong gravitational gradient driving water through unsaturated surface materials, and it requires a very low permeability cover to deny water to a potentially acid generating material (around $10^{-8}$ cm/sec material is needed, which is difficult to obtain, install, and maintain).

- The humidity present in air generally contains enough moisture to sustain an acid generation system if the pyritic materials are present; accordingly, air circulation must also be largely prevented as part of a water denial strategy (as well as having benefits in denying oxygen to the system).

Reduction in water flow may serve the purpose of limiting the amount of water that is impacted by acid generation. The cost of collection and treatment of this water is to some extent a function of its quantity, so flow limitation may have some utility for remedial cost control, even if it does not fundamentally limit the production of acid.

Biotic control

Biotic control of ARD has as its objective the removal of the bacteriological assistance to the rate determining step in ARD, particularly in situations where oxygen is limited. As noted above, bacterially-aided oxidation increases the rate of ARD reactions by about 5 orders of magnitude. If the bacteria can be prevented from assisting this process, the generation of acid and the liberation of metals can be dramatically slowed, to the point where the process effectively ceases.

The most common method of treatment is to use dilute solutions of surfactants (such as detergents, shampoos, and toothpaste) as bactericides. Concentrations of 10 ppm slow acid production, while concentrations of 25 ppm generally sterilize materials (Kleinmann et al, 1981). These have been able to reduce acid generation by up to 95%, if used frequently (three times per year). An alternative approach is to use a time-release capsules of vulcanized rubber and detergents, which result in a continual dosage of surfactant over a number of years. After sustained use over a number of years, it is believed that natural soil bacterial activity will sufficiently limit available soil oxygen to prevent re-population by the iron-oxidizing bacteria; at this time the treatment could be terminated.

Acid control

As noted above, the rate of reaction and the amount of acid produced increases as the pH of the water at the reaction site drops. This is due to both abiotic and biotic reasons. Consequently acid generation is a process that "feeds on itself", using its own acid production to increase the rate and quantity of the generation of further acid. As a result, neutralization is both a remedial strategy and a control strategy.

The principal approach to neutralization is the addition of limestone or lime to the reaction site. This has the effect, if done prior to the initiation of acid generation, of discouraging the lowering of pH which favors acid generation. If done after the initiation of acid generation, it raises the pH by neutralizing the acid, and also reduces the rate of future acid production. In neither case can it truly prevent acid generation: this will take place at some rate regardless of the pH.

The application of acid control to specific mine elements is as follows:

- Mines. In-mine neutralization is frequently practiced as a method of controlling acid generation and acid discharge from mines, by placement of neutralizing material in the mine openings; neutralization of in-mine water; directing acid inflow through limestone beds, or addition of neutralizing materials to influent water. These measures are generally only partially successful in preventing ARD.

- Waste materials. Many mining and processing waste materials contain within them considerable neutralization capacity (natural or added), which can assist in reducing or essentially eliminating the potential for acid generation. If a waste material lacks this capacity, it is possible to add neutralizing materials (generally crushed limestone) to the rock to enhance its ability to neutralize any acid generated. The cost of doing this includes the cost of the limestone, and the increased cost of the disposal facility due to the increase in volume of waste material. If neutralizing material is added to the waste rock pile, it is greatly advantageous if the pile is segregated, so that the treatment is only applied to the high sulfide portion of the rock.

The quantity of neutralizing agent required for acid prevention is difficult to assess. A reasonable approach is to apply a proportion or all of the neutralizing agent which would be required to neutralize all of the acid produced if the entire sulfide mass were oxidized. This involves using approximately the same percentage of neutralizing material by weight as the pyrite percentage by weight in the acid generating material.

## REMEDIATION

Once AMD has occurred, there are a range of remedial actions that can be undertaken to control the effects, in circumstances where prevention of further AMD is not desirable, possible, and/or economic. There are a number of remedial actions which can be taken to deal with the effects of ARD on water, including: neutralization, sulfate reduction, and metal removal (SME, 1994). All may be followed by further water treatment to meet discharge or use criteria for the water.

### Neutralization

#### Active neutralization

Active neutralization involves the addition of limestone or lime to neutralize the acid. In addition to neutralization, dissolved metals may have to be oxidized before precipitation normally occurs, using aeration or possibly oxidant addition. Precipitates are settled out and the sludge removed for disposal, or possible metal extraction. The sludge may be a characteristic hazardous waste.

Passive neutralization

Passive neutralization techniques have been developed in recent years to provide remediation for ARD problems which are remote, or which are not readily resolved using the active systems above. These systems generally use anoxic dissolution of limestone. Mine water is passed through an enclosed limestone-filled drain before it is exposed to the atmosphere. The iron is kept in the reduced ($Fe^{2+}$) state, and the limestone dissolves without becoming armored by ferric hydroxide, as it would in the oxidized state. A well designed system can produce about 300 mg/l alkalinity (as $CaCO_3$) (SME, 1994). Effluent requires an oxidation/settling pond to allow formation and precipitation of ferric hydroxide; processed water is often passed through a wetland for polishing.

Sulfate reduction

If ARD water is passed through a reducing environment, it is possible to cause the sulfates in the flow to be reduced to metal sulfides, using biologically mediated reactions. This technology has been used extensively in the treatment of ARD from coalfields, using constructed or natural wetlands to achieve the reducing conditions required to achieve the fixation. The wetlands generally consist of a substrate of composted organic material, and may include limestone within the compost, creating a passive neutralization component in the anoxic conditions of the wetland.

Passive sulfate reduction wetlands are generally applied for flows of less than 100 gpm, due to the considerable acreage which they require for successful long-term application. A rule of thumb for size is that each 10 gpm of water requires approximately one acre of wetland. It is important to note that the metals captured by these facilities remain in the wetland, and if it should erode or dry out or erode, remobilization is possible. As a result, removal of the metal-bearing substrate materials at some point should be part of the design of these facilities.

## CONCLUSION

Acid rock drainage (ARD) forms when sulfide-bearing rock is exposed to air or another oxidant in the presence of moisture. Formation of ARD is often mediated by bacterial action, greatly increasing the rate of oxidation of sulfides. The products of ARD are acid and mobilized metals, and the effluent is frequently toxic to aquatic life, and not potable by humans.

ARD can be prevented by controlling the reagents: sulfide, water, and oxygen; or controlling the mediating bacteria. The most attractive methods have been found to be removal of oxygen (by flooding or capping), and removal of bacterial mediation using bactericides. Removal of sulfides and removal of water are in general found to be ineffective and/or too expensive.

The products of ARD, metal bearing acidic water, can be remedied by neutralization or sulfate reduction. Active and passive methods are available to remove the products of ARD, and these have proven very effective in controlling relatively low concentrations of ARD products. Methods include constructed wetlands and anoxic dissolution of limestone.

ARD can be treated, but prevention is both easier and ultimately more cost effective as a way of dealing with the problem of potentially acid generating waste materials.

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# RECLAMATION AT THE RICHMOND HILL MINE
# LAWRENCE COUNTY, SOUTH DAKOTA

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## ABSTRACT

Acid rock drainage (ARD) was identified from the waste dump of the Richmond Hill mine in the spring of 1992. Since that time interim reclamation measures have been implemented at the mine to prevent discharge of these waters. Recently, the long term reclamation plan which has been developed since the identification of ARD has been approved by the State of South Dakota. Final reclamation will begin this spring.

The reclamation plan consists of the removal of all potential acid forming material from the waste dump along with sulfide material form the leach pad area. This material will be back-filled into the Richmond Hill pit. A complex cap will be placed over this material, and will consist of a limestone layer, a low permeability clay liner, a 4 foot layer of benign material for frost protection, and topsoil. The placement of this material in the pit will isolate it from the shallow ground waster system and reduce flow into the reactive material thereby reducing discharge to the environment. The pit impoundment area will be seeded with grasses, predominantly cool-season, and a legume species. Grasses are being used to precluded tap-rooted species that could penetrate the clay liner.

## INTRODUCTION

### Setting

The Richmond Hill mine is located in western Lawrence County, South Dakota, about five miles northwest of the city of Lead. It lies in the extreme northern part of the Black Hills within the Lead gold mining district. The operation consists of a single open pit mine, located in the central part of Section 22, T. 5N., R. 2E., a waste dump centered about 1500 feet to the southeast, and a processing area consisting of three heap leach pads located about 1 mile to the north (Figure 1). Topography is moderate to steep with elevations ranging from 5000 to over 6000 feet within the mine area. Drainage from the Richmond Hill mine area reports to Squaw Creek in the west, Rubicon Gulch in the north, and Burno Gulch in the east. The mine itself reports to the Squaw Creek drainage while the processing facilities report to Rubicon Gulch. Vegetation is typical of the northern Black Hills and consists of predominantly mature stages of the climax ponderosa pine forest.

### History

The Richmond Hill mine was discovered in 1984, with a Life of Mine permit granted by the State of South Dakota in March 1988. Mining and processing were initiated late in 1988 and mining has continued intermittently through 1993, when ore reserves were exhausted. Processing of the heap leach pads are continuing at the present time. The majority of

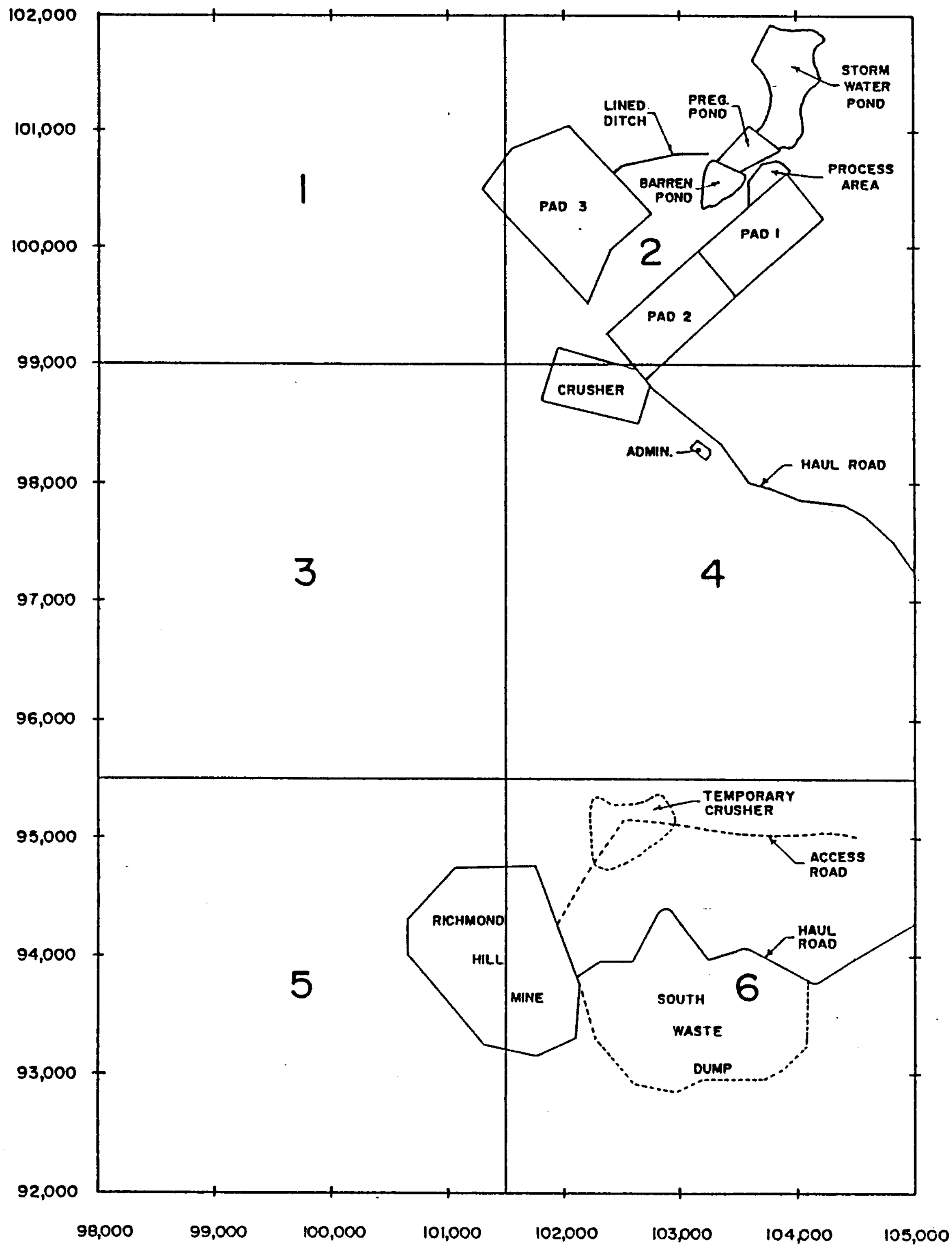



Figure 1. Layout of the Richmond Hill Mine

the Richmond Hill deposit consists of oxidized material, but is underlain by primary sulfide material. Because of the configuration of the ore body, minor sulfide-bearing material was encountered early in the mine life, with later stages of mining becoming increasingly higher in sulfide content. As part of the mining sequence, a 188,000 ton sulfide ore stockpile was developed on the waste dump in 1991.

Minor acid rock drainage (ARD) was detected from the toe of the waste dump in April 1992 within Spruce Gulch, a small intermittent drainage to Squaw Creek. Acid drainage has continued to the present time, with flows ranging from a few gallons a minute to over 400 gpm during the spring freshet. This drainage typically has a pH from 3.0 to 3.5 with moderate to high metal values. Flow rates and pH have an inverse relationship with lower pH at higher flow rates.

Richmond Hill temporarily ceased mining, removed the sulfide stockpile to the processing area, and began interim mitigation measures in July 1992. The interim mitigation measures, completed in the fall of 1992, included the construction of a retention pond in Spruce Gulch, treatment of the discharge from the toe of the waste dump, construction of an anoxic limestone drain, and diversion of the water from the waste dump to the storm water pond. In addition, the State of South Dakota required a Permit Amendment to be submitted which would address the long term closure plan to mitigate ARD from the Richmond Hill mine. This permit amendment was approved in February 1994.

## CURRENT STATUS

Nearly 8 million tons of material have been removed from the Richmond Hill mine since production began in August 1988. At the present time 5.2 million tons are contained on the leach pads and 3.65 million tons are located in the waste dump. Waste production data from the Richmond Hill pit (Figure 2) shows an increasing proportion of sulfide-bearing waste through time. Generally speaking, the waste dump development can be divided into three main stages. An early stage, through late 1989, with less than 10 percent sulfide material, an intermediate stage with 10 to 20 percent sulfide material, and a late stage, from the latter part of 1991 to the middle of 1992, containing 30 to 40 percent sulfide material. Overall, about 883,000 tons of sulfide material (24%) are contained within the Richmond Hill waste dump.

Composition of the Richmond Hill leach pads show a similar trend in composition through time (Figure 3). One complicating factor was the placement of 188,000 tons of sulfide bearing ore from the sulfide stockpile onto the leach pads in July 1992. While only about 2 percent of the ore on pads 1 and 2 are sulfide bearing, pad 3 contains over 23 percent sulfide material, with much higher levels later in the mine life. Of the total of 751,000 tons of sulfide material contained within the leach pad area, 702,000 tons are contained on pad 3.

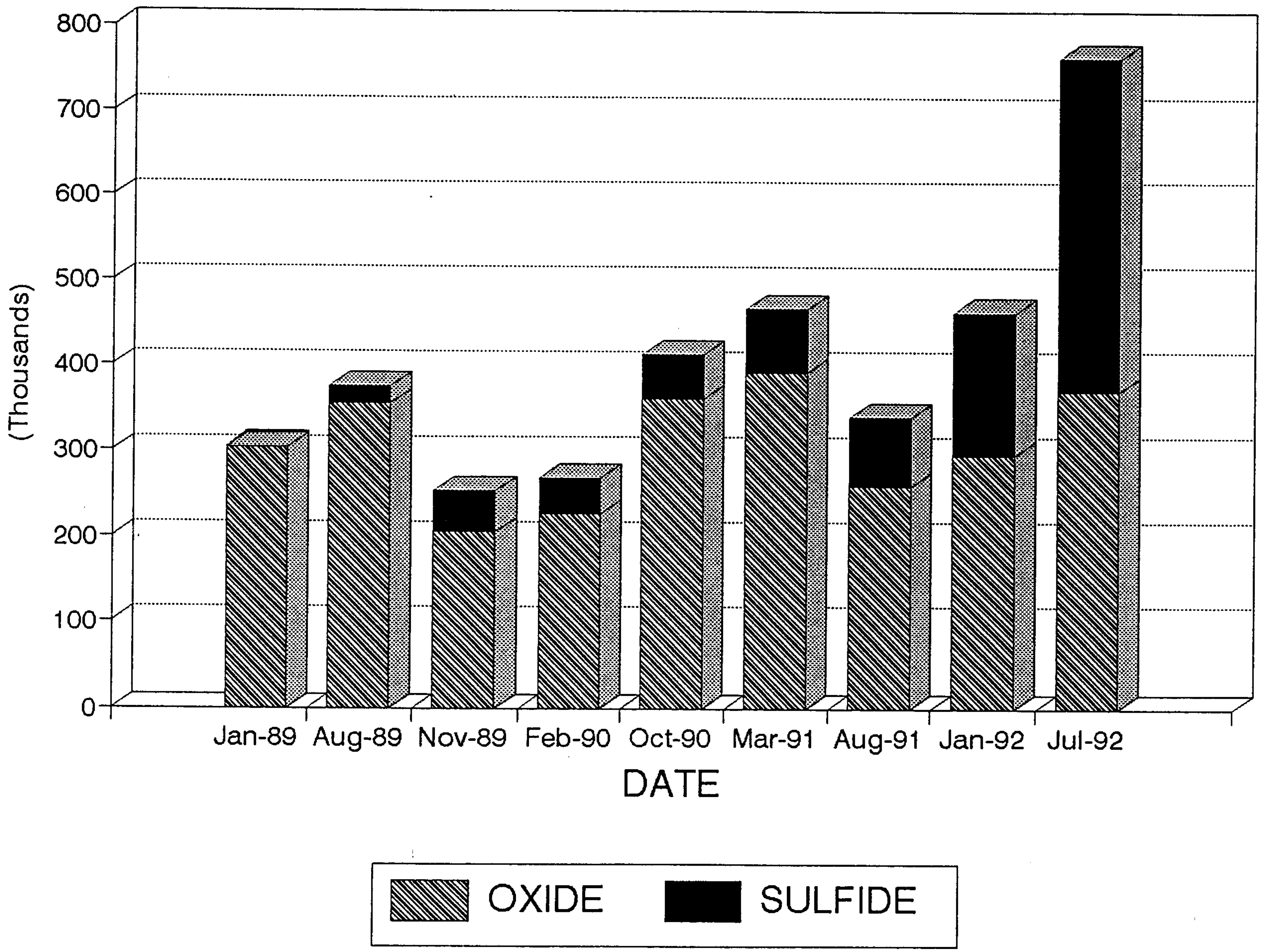
## TEST RESULTS

### Static Tests

Because discharge is occurring at the toe of the waste dump and since the leach pads are under active leaching and are therefore isolated

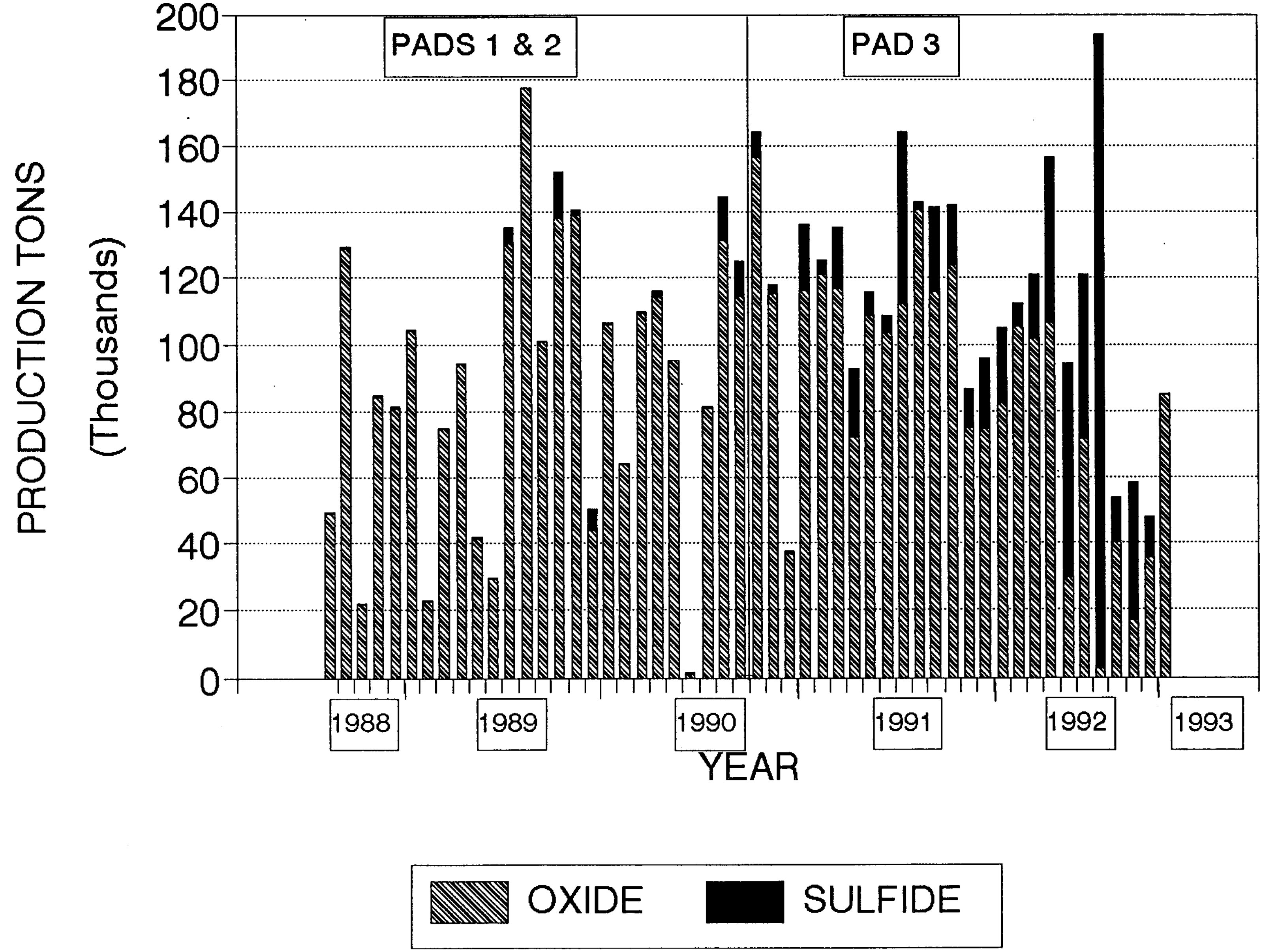
# RICHMOND HILL WASTE PRODUCTION

**Figure 2.**



# RH ORE PRODUCTION

**Figure 3.**



from the environment, the primary emphasis of testing to date has been the waste dump. Over 200 static tests have been conducted on the material in the waste dump taken from a series of trenches which accurately reflect the composition of the waste dump. The results of this static testing correlate well with the geologic observations presented above. The sulfur data indicates a good differentiation between the oxide and sulfide material, with the materials averaging less than 1 percent and over 5 percent total sulfur, respectively. The testing also shows little neutralization potential for most of the material. Because of the sequencing of the waste production with increasing sulfide content through time, the overall trend in static tests shows a corresponding decreasing ABA value (Figure 4). As with the geologic description, the three phases of waste dump construction are well illustrated.

Without a doubt, the latter phases of waste dump construction, from late 1991 through July 1992, are most certainly acid generating. The observation of steam vents from this portion of the dumps supports this conclusion. Conversely, the initial stages of waste dump construction, through late 1989, have average ABA values which are positive which suggests that these materials probably are non-acid forming. The material placed in the waste dump in the intervening period have small negative ABA values and are at least in part acid generating.

Static test from the leach pad material is limited to 69 grab samples from the pads and 46 monthly crusher composite samples. Data from this testing again confirms the overall geologic descriptions of the mine sequencing, with decreasing ABA values through time (Figure 5). One major difference of this material has been the lime added to the ore for metallurgical purposes which raises the corresponding ABA values for material on the pads. The values given in Figure 5 are for the ore prior to the addition of lime. The processing of the ore increases the ABA value by about 20 units. As with the waste dump, a significant portion of the early phases, most of pads 1 & 2, are believed to be non-acid generating, while the latter phases, most of pad 3, have significant acid potential.

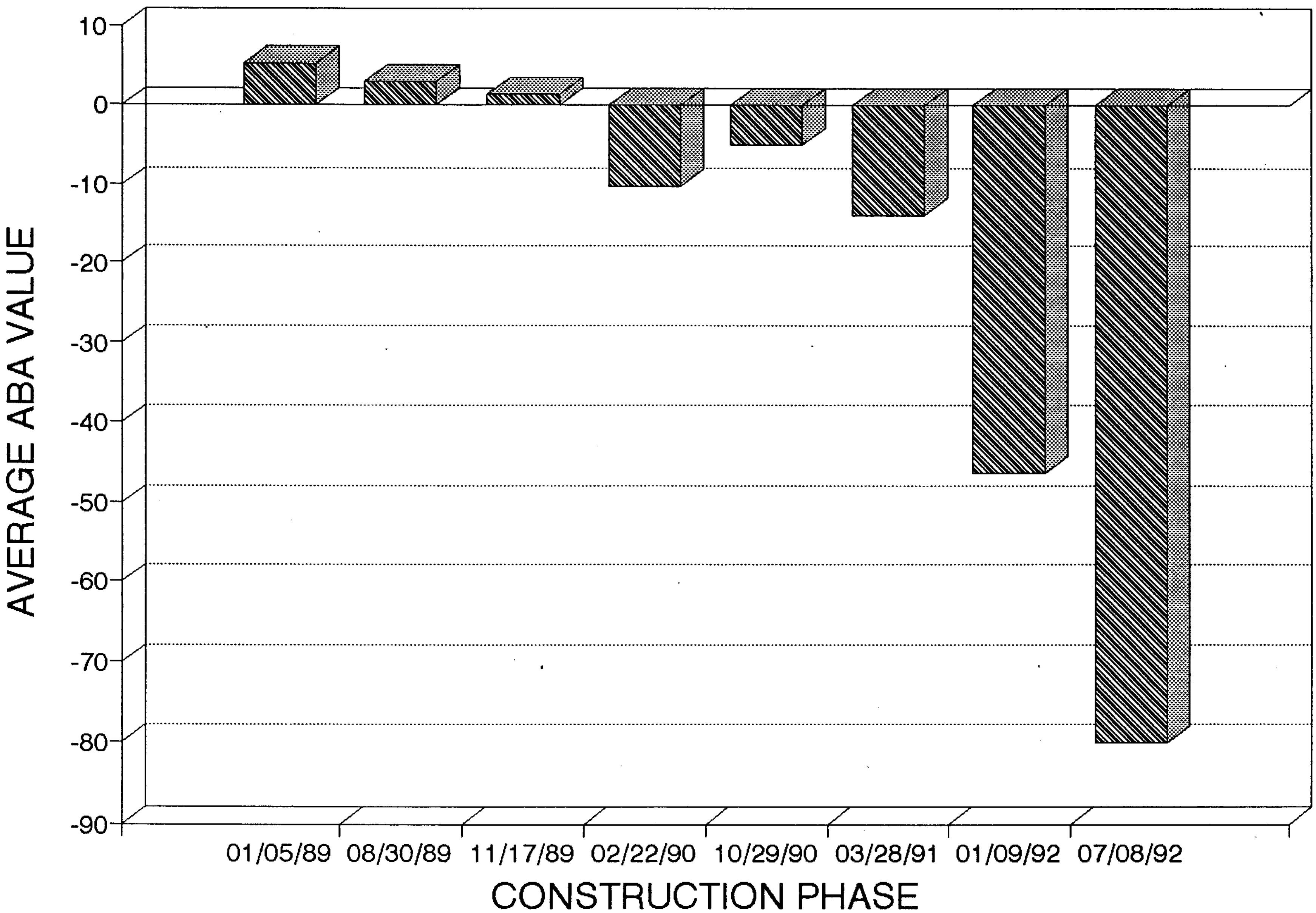
Kinetic Tests

Kinetic humidity cell tests were performed on 14 samples from the waste dump, six samples from the pit, and 5 samples from the leach pads. The results from this testing confirmed the interpretation of the static testing that the sulfide bearing material was a very active acid former and therefore is the major contributor to the ARD problem at the Richmond Hill mine. However, the testing also demonstrated that almost totally oxidized material could also generate significant acid in of itself. In these cases the acid former is most probably jarosite which is common in lower portions of the deposit.

Based on the results of approximately 20 weeks of humidity cell testing, it was determined that material with ABA values as high as -5 could generate acid. These tests confirmed that the main acid producers were pyrite/marcasite and jarosite. The only other major sulfur-bearing minerals, barite and svanbergite, were stable during the kinetic tests.

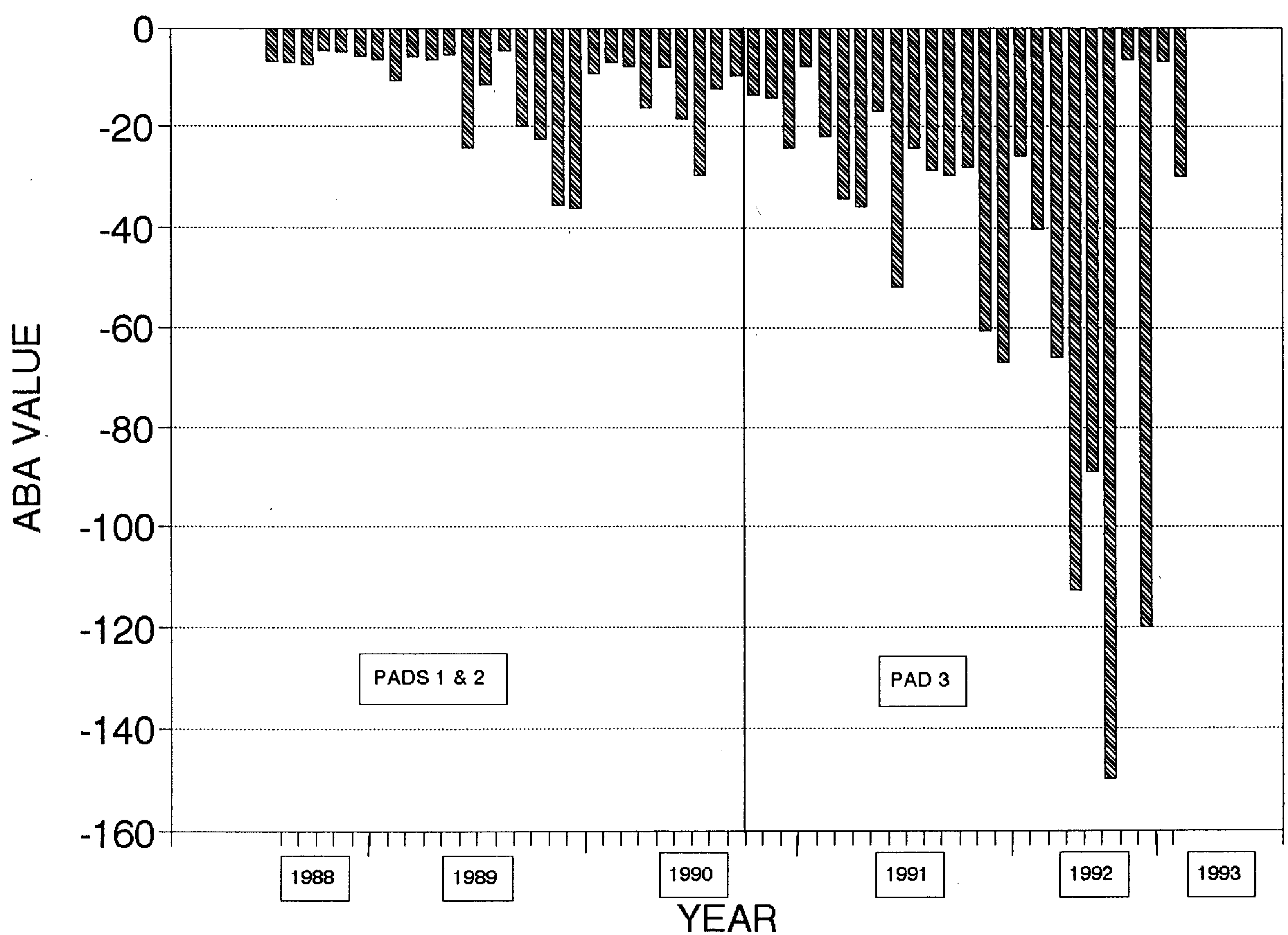
# RICHMOND HILL WASTE PRODUCTION

Figure 4. Static Test Results



# RH ORE PRODUCTION

**Figure 5. Static Test Results**



Summary

Based on testing to date, it has been determined that approximately 2.7 million tons (75 %) of the waste dump at the Richmond Hill mine is potentially acid forming. This includes most of the material in the waste dump placed after late 1989. In addition, the vast majority of leach pad #3, material placed after October 1990, and minor portions of leach pads #1 and #2 have acid formation potential. It should be noted that significant exposures of sulfide material are present in the pit, which can also produce acid.

## CLOSURE PLAN

The Richmond Hill closure plan was designed to minimize long term ARD from the waste dump, leach pad, and pit areas. Numerous options were evaluated to achieve this goal, with the final version being arrived at after 18 months of evaluation. This option achieves the best balance between cost and long term liability to Lac Minerals.

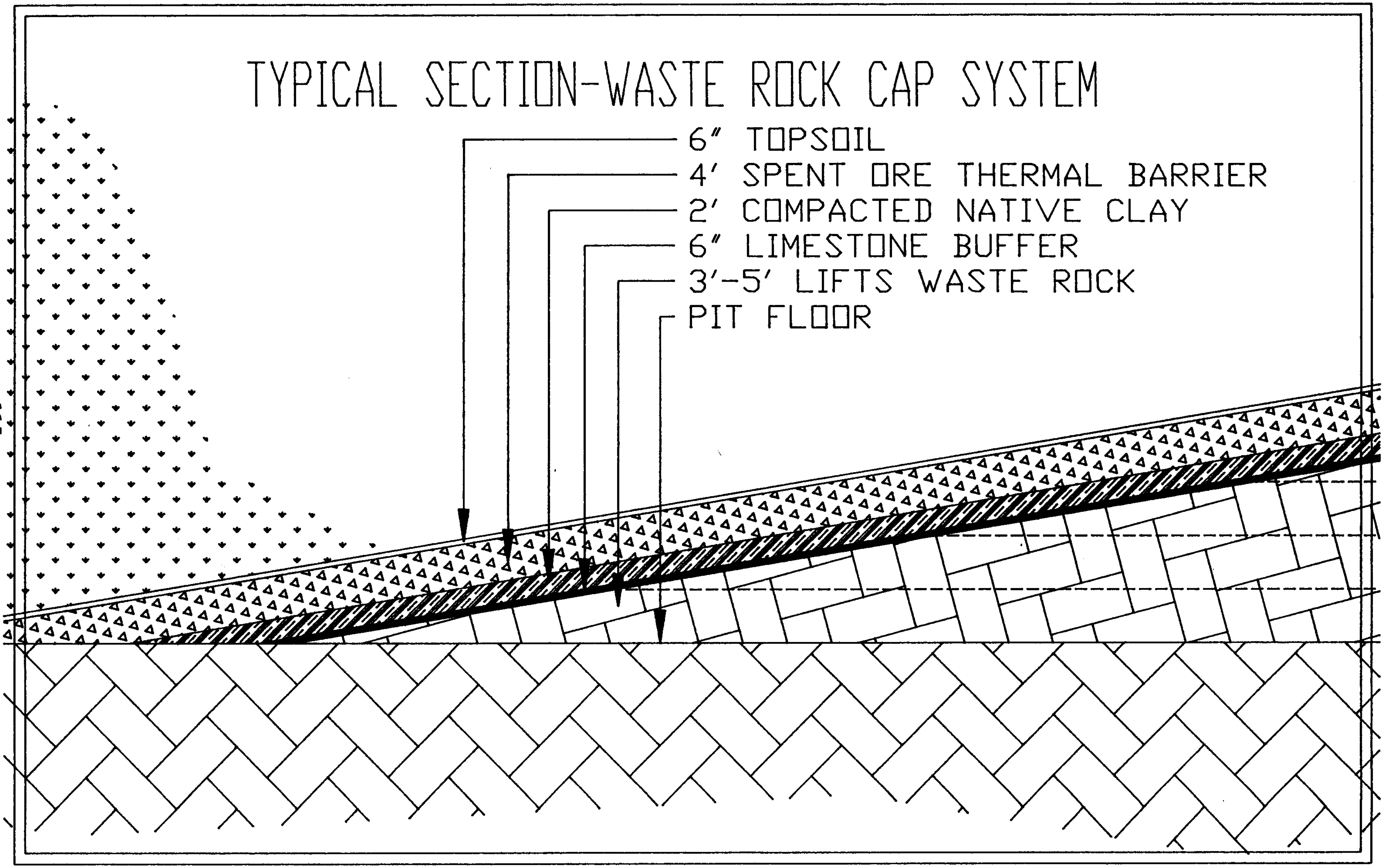
Pit Area

The main feature of the closure plan is to back fill the Richmond Hill pit with the majority of the acid generating material present throughout the mine site. This will include the up to 2.7 million tons determined to be acid generating from the waste dump along with 727,000 tons of primarily sulfide material from leach pad #3.

This back filling accomplishes several key items at one time. Because of its present location in a drainage, the majority of the waste dump is in contact with surface and near surface ground water, and can not be isolated from this hydrologic system. By removing this material to the pit, which is located over 100 feet above the ground water table, it places the material in a "high and dry" location. Sufficient material will be placed in the pit to cover all exposed sulfide high walls, and reducing the acid drainage potential from these areas.

After the selected material is back filled and compacted in the pit, it will be covered by a complex, low permeability liner system to reduce infiltration into the back filled material (Figure 6). The lower most component of this liner system is a 6 inch layer of limestone which will act as a barrier for acid solutions from the back filled material and the rest of the liner system. This layer will also serve as a well prepared base for the remainder of the constructed liner. Overlying the limestone layer will be 2 feet of compacted, low permeability clay, with a minimum permeability in the field of $1x10^{-7}$ cm/sec. This clay will most likely come from a nearby native source which is currently being evaluated. On top of the clay liner will be a minimum four foot layer of benign material which will act as a frost protection layer to prevent freezing of the clay liner. This layer will also protect the clay liner from erosion. The most likely material for this frost protection layer is spent ore from leach pad #1 or #2. As stated above, most of the ore produced early in the mine life has no acid generation potential and will be adequate for this purpose. Lastly, six inches of topsoil will be applied on the frost protection layer to serve as a growth medium.

Figure 6.



TYPICAL SECTION-WASTE ROCK CAP SYSTEM
6" TOPSOIL
4' SPENT ORE THERMAL BARRIER
2' COMPACTED NATIVE CLAY
6" LIMESTONE BUFFER
3'-5' LIFTS WASTE ROCK
PIT FLOOR

Because of the need for long term erosion control and to ensure the integrity of the clay liner, the seed mixture will emphasize the use of grasses and legumes (Figure 7). This will help to preclude tap-rooted species which may penetrate the clay liner and compromise the closure plan. Straw mulch along with hydromulching will be used to enhance revegetation and minimize erosion prior to the establishment of the vegetation.

Waste Dump

As stated above, approximately 2.7 million tons of material will be removed from the waste dump as part of the closure plan. This will leave about 900,000 tons of material in the waste dump area, of which 70,000 tons are sulfide bearing. The majority of the material remaining in the waste dump consists of unaltered country rock, which has significantly lower sulfur values, and therefore lower acid potential, than the majority of the Richmond Hill deposit. This is evident from the results of the static testing which shows a weak positive value for this material. Testing shows that over 90 % of the remaining waste dump material is non-acid forming. The small portion with some acid formation potential will be thoroughly sampled via trenches to determine the size and distribution of this material. If significant quantities of potential acid forming material is found from this sampling program, it will be removed to the pit impoundment area during reclamation.

The residual soil in the waste dump area will be neutralized with limestone and then fertilized prior to the final reclamation of the dump. The remaining material in the waste dump will then be regraded to a 3:1 slope, have topsoil placed on it, and reseeded. Based on our current knowledge, the drainage, if any, from the waste dump area should be of high quality.

Leach Pads

Approximately 728,000 tons of material will be removed from leach pad #3 to the pit impoundment area. This will represent ore produced in the April to October 1992 time frame. This ore is easily accessible and contains some of the higher acid potential present in the leach pad area. While additional quantities of ore could be removed, the capacity of the pit impoundment area will have been met from these quantities. About 2.3 million tons of ore would remain on leach pad #3, still containing 277,000 tons of sulfide bearing material (12 %). Based on the static and kinetic testing, this proportion of sulfide material will most likely generate acid. Therefore, the closure plan includes a limestone amendment of pad #3 material to achieve a minimum 3:1 Neutralization Potential/Acid Potential ratio. Kinetic testing is underway to determine the precise ratio of limestone amendment.

While Pads 1 and 2 have minimal sulfide bearing material, about 2 percent, extensive sampling and testing of this material will be done prior to closure. The main reason for this testing is to determine whether this material is suitable for use in the pit impoundment area as the frost protection layer. Approximately 300,000 tons are needed for this layer and every precaution must be taken to ensure this material has no chance of producing acid. It is anticipated that detailed sampling of the material on pads 1 and 2 will identify small quantities of ore which has acid potential. These will be moved to pad 3 and amended with limestone.

| | lb. PLS/acre |
|---|---|
| Green Needlegrass | 2.4 |
| Sideoats grama | 1. |
| Western Wheatgrass | 4. |
| Slender Wheatgrass | 2. |
| Timothy | .50 |
| Dutch White Cover | *1.00 |
| Kentucky bluegrass | 1.00 |
| Smooth bromegrass | 3.00 |
| Durar hard fescue | 1.00 |
| lb/acre PLS | 15.9 |
| * This legume requires inoculation to insure proper germination. | |

Figure 7: Reclamation Seed Mixture

## SUMMARY

The closure plan to mitigate long term effects of ARD from the Richmond Hill mine is based on several interrelated solutions. The primary feature is a pit impoundment area into which potentially acid forming material will be back filled. This pit impoundment will be covered by a complex liner system to minimize seepage into this material, and thereby limit the release of acid and metals into the environment. In addition, exposed sulfide bearing high walls will be covered by this back filling and liner system. These materials will be removed from both the waste dump and leach pad areas where they are currently in potential contact with surface and near surface ground waters. The remaining material on the leach pads which have moderate acid potential will be amended with limestone to negate acid formation and be placed on leach pad #3.

This closure plan will accomplish the primary goals of LAC Minerals, which are to minimize cost and long term liability from the Richmond Hill mine site. It provides an efficient use of materials at hand and allows for a walk away reclamation plan in the future and provide adequate long term environmental safeguards.

## ACKNOWLEDGEMENTS

The authors would like to thank Lac Minerals for allowing us to give this presentation. We would also like to thank the entire staff at the Richmond Hill mine for their efforts in completing the plan. Finally would thank our consultants, especially Dr. Bill Schafer of Schafer and Associates and Dr. Dirk Van Zyl of Golder and Associates for their contributions.

# DEPTH OF SOIL OVER MOLYBDENUM TAILING AS IT AFFECTS PLANT COVER, PRODUCTION, AND METALS UPTAKE

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ABSTRACT

Molybdenum mill tailing often has high concentrations of soluble salts, heavy metals and other chemicals that make reclamation very difficult. Reclamation of this tailing must be accomplished in such a way as to insure a naturally-functioning plant community that perpetuates itself through time. This study was conducted to determine the depth of soil needed to cover Henderson Mill tailing to maintain a healthy cover of herbaceous vegetation.

Soil that covered tailing became more acidic through time. Lime added to soil at 6 tons/ac reduced the acidification process. However as soil became more acidic, plant uptake of copper increased and helped to improve the copper to molybdenum ratio. Molybdenum concentration in smooth bromegrass (Bromus inermis) on test plots did not differ through time. No heavy metal was concentrated in plants to such a level as to be toxic to plants or to be a hazard to large animals that might graze the reclaimed tailing site. Soil depth of 12- or 18-inches over tailing resulted in better plant growth, but leaching of salts was less than for a soil depth of 6 inches.

Herbaceous vegetation cover, plant species diversity, and production generally increased on the soil-tailing test plots as the depth of soil over the tailing was increased from 6 to 18 inches. Use of only 6 inches of soil over tailing resulted in low production, cover, and diversity. However, few differences existed between measured variables for the 12- and 18-inch depths of soil over tailing. Therefore, after 11 years of growth, it appears that 12-inches of soil over tailing is sufficient to maintain a naturally-functioning, sustainable herbaceous plant community.

## INTRODUCTION

The environment surrounding the Henderson Mine and Mill sites is recognized as being particularly fragile because of the altitude, climate and soils of the areas. Cyprus Climax Metals Company is interested in maintaining a quality environment while conducting mining operations. To assure maintenance of a quality environment, a study was initiated in 1982 to determine what depth of soil would be needed to successfully and permanently revegetate the tailing produced by the milling operation. Another objective was to determine if addition of lime was needed to reduce the acidification process and allow for a healthy cover of herbaceous species to exist on reclaimed tailing. A final objective was to determine whether heavy metals would be concentrated in vegetation present on reclaimed tailing that might be detrimental to plants, or to wildlife or livestock populations that could utilize the area.

Plants vary widely in their uptake and requirements for various macro- and micro-nutrients (Swaine, 1955). Some essential elements can also be taken up in excess and may become toxic to the plant (Lindsay, 1979). Even if an element does not become toxic to plants, it might become toxic to grazing animals that utilize the forage resource (Gupta and Lipsett, 1981). In addition, some toxic elements or compounds can be taken up by plants even though they are not required. Uptake of toxic constituents are often in proportion to their availability in the immediate environment of the plant. In other cases, plants may concentrate certain toxic substances to levels far in excess of their availability (Baker and Walker, 1990). Whether an element or compound is limiting or toxic in many cases depends upon its availability and concentration. We are only now beginning to understand the effects and fate of some potentially-toxic chemicals as they move through food webs in ecosystems.

A number of metals are required by plants in small amounts and are utilized as catalysts in chemical reactions, in enzyme molecules, and in other growth processes. Metals such as iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), aluminum (Al), and molybdenum (Mo) are all essential to plant growth, but can become toxic if uptake is too great.

Iron was shown to be an essential element over a century ago and is required in quantities larger than manganese, zinc, copper, and molybdenum (Wallihan, 1966). Concentrations of iron in foliage are usually $10^{-2}$ to $10^{-4}$ times that in the soil in which the plant grows. As a general rule, other elements known to be essential to plants achieve concentrations in plant tissues that are approximately equal to or greater than that existing in the soil.

Plant leaves that contain less than 20 μg/g of zinc may be deficient in this micro-nutrient. Amounts of zinc in excess of 400 μg/g may indicate zinc excess. Acidification of soils may bring about aluminum, iron, or zinc toxicity in plants.

Plants vary widely in their requirements for molybdenum and in their ability to extract this metal from the soil (Reisenauer et al., 1973). Absorption of molybdate by plant roots is markedly affected by soil pH, amount of sulfate present, soil organic matter content, and soil moisture (Gupta and Lipsett, 1981).

Increased sulfate and soil acidity depresses molybdate uptake. Molybdate is strongly absorbed by soil, minerals and colloids below pH 6.0. Available molybdenum usually increases with soil organic matter content, as does most other nutrient elements. Plant requirements for molybdenum are met at concentrations of 0.3 to 0.5 µg/g in tissues of legumes, and at less than 0.1 µg/g in tissues of most other plants. Forage containing more than 10 to 20 µg/g molybdenum may produce molybdenosis in ruminant animals if the copper concentration is not high. A copper to molybdenum ratio in forage greater than 2:1 is desirable to prevent molybdenosis (hypocuprosis) of ruminants.

## OBJECTIVES AND PURPOSE

The tailing pond that results from the milling of Henderson Mine ore will someday be reclaimed. It is desirable to know how much soil will be needed to cover tailing to establish a naturally-functioning permanent plant community. Lime additions to soil should also reduce the soil acidification process. But, there is concern that salts or other contaminants in the tailing might move upward into the soil and thus adversely affect plants established on the reclaimed tailing. Plant roots might also take up some metals from the tailing to such levels that they could become toxic to the plants or to animals grazing on the reclaimed tailing.

A study was, therefore, designed and initiated in 1982 to address the above concerns. Stockpiled soil and Henderson tailing material were utilized in this experiment. Plots were seeded and plants were allowed to become established. Then sampling of both soil and vegetation from these plots was initiated in 1985 to determine whether chemicals in tailing adversely affected soil and established plants. An additional objective was to determine if heavy metals would be concentrated in forage that could be detrimental to wildlife or livestock populations that might utilize reclaimed tailing.

We also wished to know depth of soil over tailing that would be needed to maintain production, cover and species diversity of the plant community. Sampling of plant species, cover, production, and diversity on these plots was initiated in 1991 to determine if differences existed for the three soil depths over tailing on established herbaceous species. Data for plots of the three depths of soil (6, 12, and 18 inches) over tailing were compared with data collected from a nearby native (control) community. An additional objective was to determine whether the one-time application of varying amounts of lime had affected species cover and production on these plots.

## METHODS AND PROCEDURES

The Henderson Reclamation Plan stated that the final tailing surface would be covered with 6 to 18 inches (12-inch average) of soil and revegetated (Brown, 1977). The State Mined Land Reclamation Board (MLRB) accepted this solution, but the company wanted assurance that a 12-inch depth of soil over tailing would be adequate. Because of the expense to stockpile soil ($2-3 per cubic yard initial expense), it is important to determine plant responses to various depths of soil over tailing so that an appropriate soil depth can be used to cover the tailing prior to reclamation.

An experiment was initiated in September, 1982, near the existing Henderson tailing. The experiment was designed to determine: 1) soil depth needed over tailing to maintain a diverse, functioning, natural plant community, 2) whether addition of lime to soil or tailing would retard the acidification process, and 3) various soil and plant chemical changes through time. The experiment was designed as a randomized complete block with two blocks that served as replications. Three feet of Henderson Mill tailing was first put down. Then four depths of soil were put over tailing. Soil depths were 0, 6, 12, and 18 inches. Lime at 0, 2, 4, or 6 tons/acre was added to the plots. One-half of the lime was placed at the soil-tailing interface, while the remaining lime was added to the surface of the soil. Thus, a factorial experiment was created. Only the plots with 0 or 6 tons/acre of added lime were utilized in the present study of soil and plant chemical characteristics.

A 1% grade was established for the experimental area to reflect the actual grade of the tailing pond. Berms around the experimental area were established to hold the tailing. Six-inch perforated plastic pipes were installed beneath the experimental plots to drain water from the bottom of the tailing. Three feet of tailing was hauled to the experimental area, levelled, and then a 1% grade was established.

Experimental plots of 10-x-10 feet were established on top of the tailing. Large timbers of varying widths were utilized to contain the soil that was to be put on the tailing. A tractor bucket was used to transport stockpiled soil to the appropriate experimental plots that had been assigned at random. Lime was added on top of tailing at 3 tons/acre prior to dumping soil onto the plots for those plots that were to receive the lime treatment. Then an additional 3 tons/acre of lime was top dressed onto plots that were to receive the lime. Thus, these plots received a total of 6 tons/acre of lime.

The soil was then leveled and all plots were seeded in September 1992 with the Climax seed mix at 50 lbs/acre. Species included in this mixture were: smooth bromegrass, orchardgrass, timothy, creeping and meadow foxtail, Kentucky bluegrass, red fescue, hard (sheep) fescue, redtop, crested wheatgrass, white Dutch clover, yellow sweet clover, and cicer milkvetch. All plots were then fertilized with 100 lbs/acre of 20-20-10 (N-P-K) inorganic fertilizer.

Vegetation was allowed to become established from 1983 until 1985 before plots were sampled. In August, 1985, 25 species were found growing on the soil-tailing plots; whereas no plants survived on the tailing-only plots (0 depth of soil), with or without the addition of lime. Of these 25 species, 15 were not present in the seed mixture. In addition, one of the species was a native shrub (Wood's rose). By August, 1989, the stands had thinned out somewhat and species diversity had declined. However, some species lost were weedy species such as peppergrass, thistle and foxtail barley. Only 14 species were found on these plots in 1989. Smooth bromegrass had been dominant in 1985, but hard (sheep) fescue and foxtail were more prevalent in 1989 and 1993.

Soil and Plant Chemistry

Aboveground biomass of smooth bromegrass (Bromus inermis) was collected in August of 1985, 1989, and 1993 from each plot, dried at 60° C and ground to pass through a 1-mm screen. Samples were then analyzed for Cu, Zn, Mn, Fe, Mo, Al, and fluoride (F). It was believed that these chemical constituents might be modified in the plant if roots grew into the tailing or if these chemicals moved from the tailing into the soil above. These chemicals are potentially toxic to both plants and animals if present in excess. Plots that had no soil over the tailing had no plant establishment, so plant samples could not be collected from these plots.

Soil covering the soil-tailing test plots was sampled at three profile depths (top, middle, and bottom) from each of the plots to determine whether salts were moving from the tailing into the soil and whether addition of lime had reduced this movement. These samples were air dried, ground to pass through a 2-mm sieve, and then analyzed for pH, electrical conductivity (E.C.), calcium (Ca), magnesium (Mg), sodium (Na), sodium absorption ratio (SAR), and base saturation percentage (% Sat.) by the CSU Soil Testing Lab. Results of these analyses may help to predict elemental concentrations in vegetation and salinity effects on plant growth. These analyses should also indicate whether the lime addition had been effective in reducing the soil acidification process.

Cover, Production, and Diversity

Cover of vegetation was estimated in the present study as a proportion of ground covered by individual species (Daubenmire, 1959) in each treatment plot and in a native (control) community. The control community was a relatively undisturbed grassland site near the Williams Fork River on Henderson property. Cover of individual species was estimated to the nearest one percent in 20x50-cm quadrats. Five quadrats were located at random within each of the 10x10-ft. study plots. Thus, a total of 20 quadrats within each block was sampled for cover for each of the three soil depths and four lime application treatments. After estimates of individual species cover were recorded, then an estimate of total vegetation cover, litter cover, and percentage of bare ground was made for each quadrat.

Diversity was estimated utilizing individual species cover data. A Shannon-Weiner diversity index was calculated for each soil depth treatment and for the native (control) community (Shannon and Weaver, 1949). This diversity index is an indication of the amount of information content based on the number of individual species present and their respective canopy coverage. The equation is:

$$\text{Diversity Index} = -\sum_{i=1}^{Sp} p_i \ln p_i ,$$

where cover is expressed as a fraction, p, for each (i) species. The summation extends over all species in the treatments being compared. All species do not have to occur in all treatments; they assume values of zero when absent from any one treatment.

Production of vegetation was sampled by a double-sampling procedure (Pechanec and Pickford, 1937) where three individual 20x50-cm quadrats were located at random within each of the soil-tailing treatment plots (Bonham, 1989). Estimates of the total aboveground biomass (production) to the nearest gram were made for each quadrat and one of the three plots was selected at random for clipping. All species were clipped at ground level in the sampled quadrat and the plant material was placed in a paper bag and weighed. Larger samples of vegetation were collected, weighed, returned to the laboratory where they were dried at 60°C. These larger samples were then used to convert wet weight estimates to dry weights. Since no vegetation became established on the tailing plots without any soil, these plots were not sampled.

A nearby undisturbed herbaceous community was selected to serve as a control for comparison with data collected from the soil-tailing test plots. This control area was sampled in a manner similar to that of the treatment plots. Two blocks were established on the control site and each was sampled for cover and production. Vegetation sampling of treatment and control plots was conducted on August 5 and 6, 1991, at about the time of peak standing crop of vegetation.

Data Analysis

Data for soil and vegetation chemical analyses were subjected to a factorial analysis of variance procedure (Steel and Torrie, 1980). When significant ($P<0.05$) differences were detected for years, soil depth, or soil profile level, then Newman-Keul's Range Test was utilized to separate the significant ($P< 0.05$) means.

Otherwise, significant differences ($P< 0.05$) among two means were tested with the F-Test. When meaningful significant interactions were found among variables, these are discussed rather than the main effects.

Because molybdenum concentrations were not significantly different ($P>0.05$) among the three soil depths put on top of tailing or between the two lime treatments (0 or 6 tons/acre), no correlation analyses for soil Mo with plant Mo were conducted.

Data for cover and production of soil-tailing plots and the native community were also subjected to analysis of variance procedures (Steel and Torrie, 1980). When significant ($P<0.05$) differences were detected for soil depth or lime application, then Newman-Keul's Range Test was utilized to separate the three or four significant ($P<0.05$) means. Otherwise, significant differences ($P<0.05$) among two means were tested with the F-test. When meaningful significant interactions were found among variables, these are discussed rather than the main effects.

## RESULTS AND DISCUSSION

### Soil and Tailing Comparison

Soil placed over tailing in the soil-tailing test plots was sampled in August, 1985. Only plots that had not received the supplemental addition of lime in 1982 were included in the sample. Raw tailing from the Henderson tailing pond were sampled at the same time. Chemical analyses of these samples revealed large differences in soluble salts between the soil and tailing (Table 1). The electrical

Table 1. Average chemical characteristics of tailing from the Henderson tailing pond and soil put over tailing on the soil-tailing test plots. All samples were collected in August, 1985.

| Variable (units) | Soil[1] (n=18) | Tailing (n=3) |
|---|---|---|
| pH | 5.3 | 5.0 |
| E.C. (mmhos/cm) | 1.0 | 9.1 |
| Base Sat. (%) | 59.4 | 35.9 |
| Ca (meq/l) | 9.2 | 21.8 |
| Mg (meq/l) | 3.6 | 3.6 |
| Na (meq/l) | 0.4 | 66.1 |
| SAR | 0.2 | 18.5 |

[1]Data for soils were taken from all three soil depth treatments without the addition of lime.

conductivity (E.C.), calcium (Ca), sodium (Na), and sodium absorption ratio (SAR) were all considerably higher in the tailing than in soils. This might indicate future salinity problems in soils placed over tailing if salts migrate upward with soil water evaporation. Salts within the tailing might move with capillary water from tailing into the soil above, thus increasing the salt content of soil (Millar et al., 1965; Brady, 1974).

Soil Chemistry

Soil chemical characteristics were often influenced by the depth of soil (6,12, or 18 inches) put on top of the tailing. Potassium (K), magnesium (Mg), sodium (Na), sodium absorption ratio (SAR), and base saturation percentage (% Sat.) were all significantly affected by the depth of soil put on the tailing. Magnesium (Mg), sodium (Na) and potassium (K) were all less in the 6-inch soil covering tailing than in the 18-inch soil (Table 2). This may reflect greater leaching of neutral soluble salts from the 6-inch depth. Lower sodium absorption ratio (SAR) in the 6-inch soil may also reflect greater leaching of sodium from this soil. The salinity hazard for all three soils at present is low (Millar et al, 1965). It was interesting that molybdenum (Mo) concentration was also slightly higher in the 6-inch and 12-inch soil compared with the 18-inch soil covering the tailing (Table 2).

The addition of lime at 6 tons/acre resulted in a significant increase in soil pH (from 4.9 to 5.9) (Table 2). However, there was a significant interaction between soil depth, profile level and lime treatment. This interaction indicated that lime addition to the 6-inch soil was more effective in raising the pH at the soil profile and tailing interface than when the same amount of lime was added to deeper (12- or 18-inch) soils (Figure 1). This was to be expected as there was more lime per weight of soil in the 6-inch depth. Also, as expected, the pH was lower with increasing depth into the profile. The only other soil variable affected by the lime addition were slight reductions in base saturation percentage (% Sat.) and sodium absorption ratio (SAR) (Table 2).

The electrical conductivity (E.C.) (salts) was significantly influenced by an interaction between lime treatment and level within the profile. When lime had been added, E.C. was greater near the soil surface than when lime was not added (Figure 2). However, E.C. was greater at the soil-tailing interface at the bottom of the profile when lime had not been added compared to when lime was present. This same interaction was also evident for both calcium (Ca) and magnesium (Mg) concentrations (Figures 3 and 4). These two cations (Ca and Mg) probably increased with the lime addition to the soil surface and caused this difference in E.C.

Sodium (Na) and magnesium (Mg) both increased with depth into the soil profile and the increase was most pronounced between 1985 and 1989, and then

Table 2. Chemical characteristics of soil over tailing as influenced by either soil depth or addition of lime.

| Variable (units) | Soil depth | | |
|---|---|---|---|
| | 6 inches | 12 inches | 18 inches |
| pH | 5.5a[1] | 5.4a | 5.5a |
| E.C. (mmhos/cm) | 1.2a | 1.1a | 1.3a |
| Ca (meq/l) | 10.8a | 9.8a | 11.3a |
| Mg (meq/l) | 3.4b | 3.7b | 5.3a |
| Na (meq/l) | 0.5c | 0.6b | 0.8a |
| SAR | 0.23b | 0.27b | 0.32a |
| % Sat. | 57.9b | 59.2b | 60.6a |
| K (meq/l) | 0.27b | 0.31ab | 0.34a |
| Mo (μg/g) | 0.14a | 0.14a | 0.10b |

| | Lime treatment | |
|---|---|---|
| | No lime | Lime added (6 tons/ac) |
| pH | 4.9b[1] | 5.9a |
| E.C. (mmhos/cm) | 1.2a | 1.2a |
| Ca (meq/l) | 10.2a | 11.0a |
| Mg (meq/l) | 4.3a | 4.0a |
| Na (meq/l) | 0.6a | 0.6a |
| SAR | 0.30a | 0.24b |
| % Sat. | 58.5b | 59.9a |
| K (meq/l) | 0.31a | 0.30a |
| Mo (μg/g) | 0.14a | 0.11a |

[1]Means in a row for either soil depth or lime treatment followed by the same letter are not significantly different ($P<0.05$).

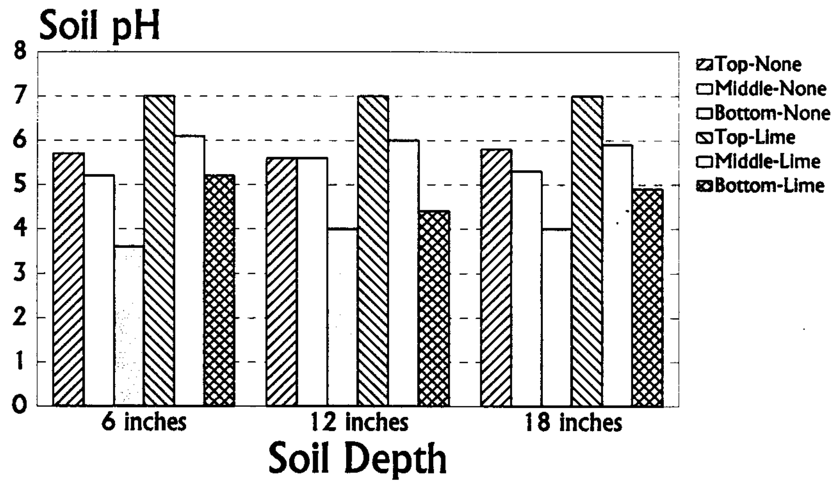


Figure 1. Soil pH as influenced by soil depth, soil profile level, and addition of lime.

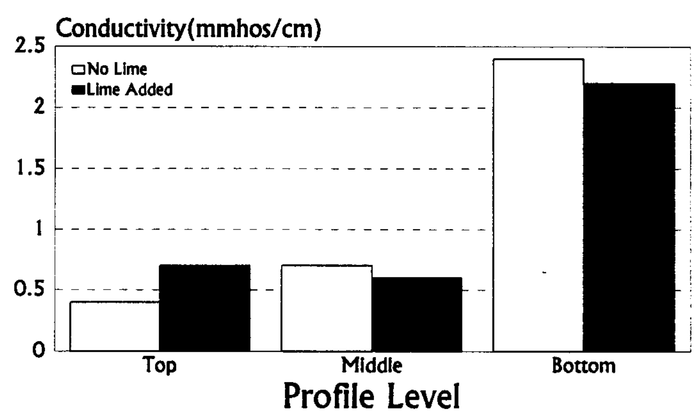


Figure 2. Electrical conductivity (E.C.) in soil over tailing at three levels in the soil profile as influenced by addition of lime.

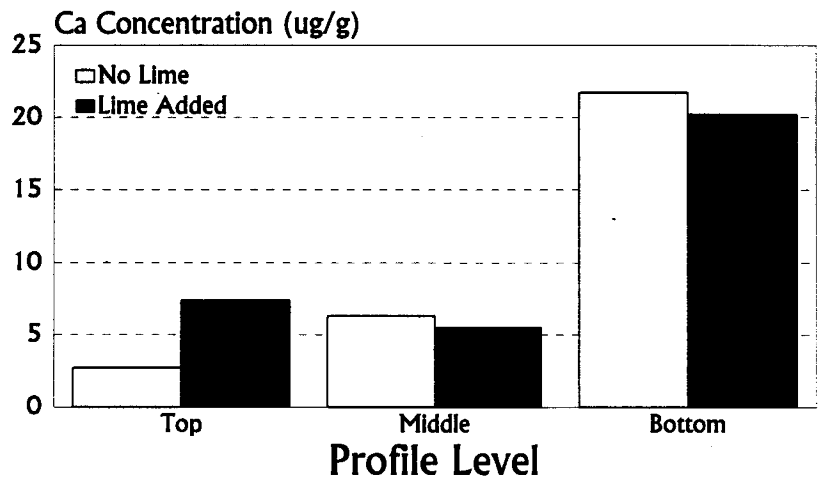


Figure 3. Soil calcium (Ca) concentration in soil over tailing at three levels in the soil profile as influenced by addition of lime.

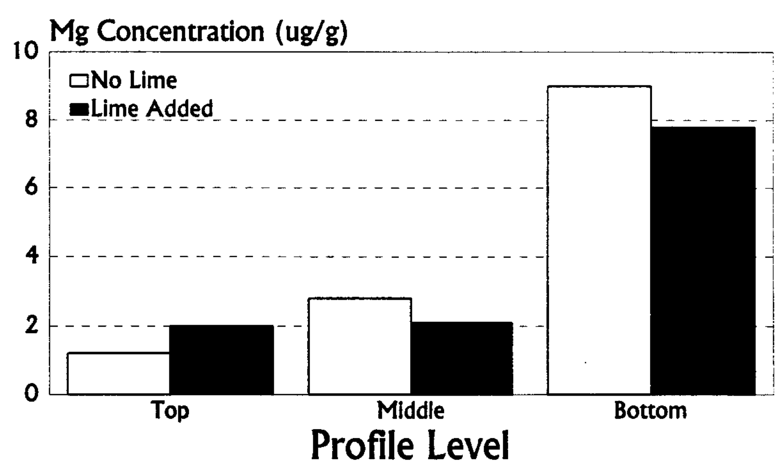


Figure 4. Soil magnesium (Mg) concentration in soil over tailing at three levels in the soil profile as influenced by addition of lime.

declined somewhat in 1993 (Figures 5 and 6). The sodium absorption ratio (SAR) also increased at all three levels in the soil profile between 1985 and 1989, but declined by 1993 (Figure 7). This increase was particularly great at the soil surface. Again, this suggests an increase in salts within the soil and upward salt migration with water that is then evaporated from the soil surface. Possibly more precipitation between 1989 and 1993 caused the decline in SAR that resulted in 1993 values being similar to those in 1985. Base saturation percentage increased between 1985 and 1989 at the 12- and 18-inch soil depths, but decreased at the 6-inch soil depth (Figure 8). Leaching appears to have been effective in removing base cations from the 6-inch soil depth from 1985 through 1993. Upward salt migration predominated in the 12- and 18-inch soils between 1985 and 1989, but leaching predominated between 1989 and 1993. Precipitation at this site may, therefore, not always be adequate for leaching of salts from the 12- or 18-inch soil depths.

Molybdenum (Mo) concentrations were highest at the soil-tailing interface, as would be expected as some mixing probably occurs (Figure 9). Plant root uptake at the soil-tailing interface may be moving Mo upward in the soil profile to some extent. This explanation seems probable as the 6- and 12-inch soils had greater concentrations of Mo than did the 18-inch soil covering the tailing where rooting depth was less restricted (Table 2).

Plant Chemistry

Zinc (Zn) concentrations in aboveground biomass of smooth bromegrass were slightly greater in plants that grew in the 6-inch soil over tailing (Figure 10). The Zn concentration in plants declined somewhat as soil depth increased. This was expected as plant roots in the 6-inch soil probably were greater at the soil-tailing interface and tailing concentration of Zn was much greater than the soil Zn content (Trlica, 1989). Zinc concentrations in smooth bromegrass in 1993 were only about one-half of those found in 1985 and 1989.

There was a significant interaction between years and soil depth that affected plant concentration of iron (Fe) and aluminum (Al). Both metals increased significantly in smooth bromegrass between 1985 and 1989 when plants grew on 6- and 12-inch soil depth treatment plots as compared with the 18-inch soil depth (Figures 11 and 12). However, both metals had declined significantly in the foliage by 1993. The reason for the increase and then decrease is not readily apparent, particularly since Fe concentration is greater in soil than in the tailing (Trlica, 1989).

Fluoride (F) concentrations in plants increased significantly between 1985 and 1993 when plants grew on 12- and 18-inch soils over the tailing (Figure 13). Fluoride content in plants had increased with decreasing soil depth treatments in 1985, which was to be expected as F levels in tailing was much greater than that in

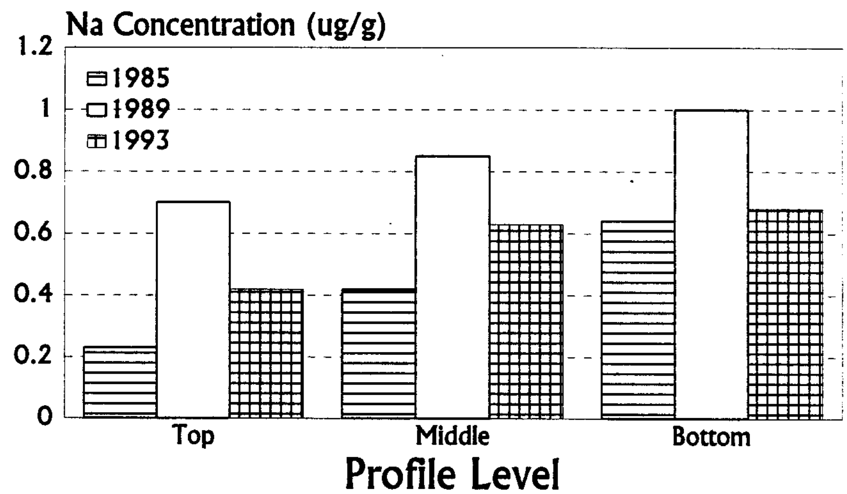


Figure 5. Soil sodium (Na) concentration in soil over tailing at three levels in the profile in 1985, 1989, and 1993.

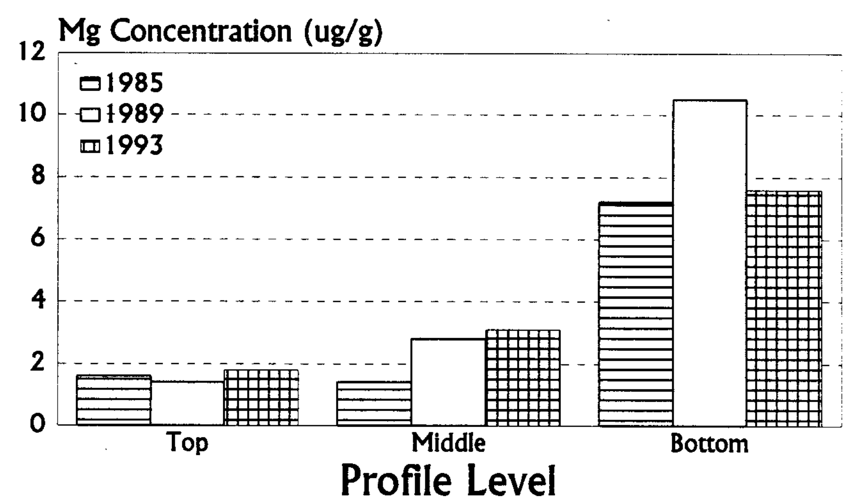


Figure 6. Soil magnesium (Mg) concentration in soil over tailing at three levels in the profile in 1985, 1989, and 1993.

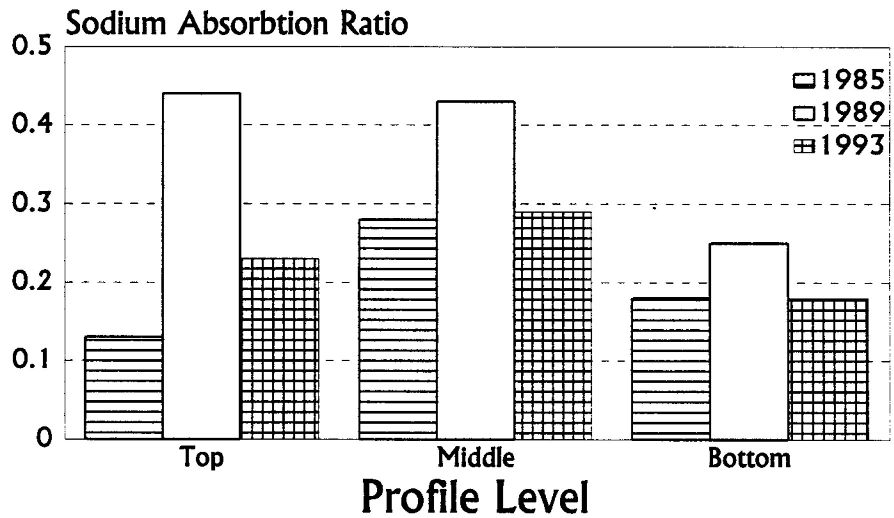


Figure 7. Sodium absorption ratio (SAR) in soil over tailing at three levels in the profile in 1985, 1989, and 1993.

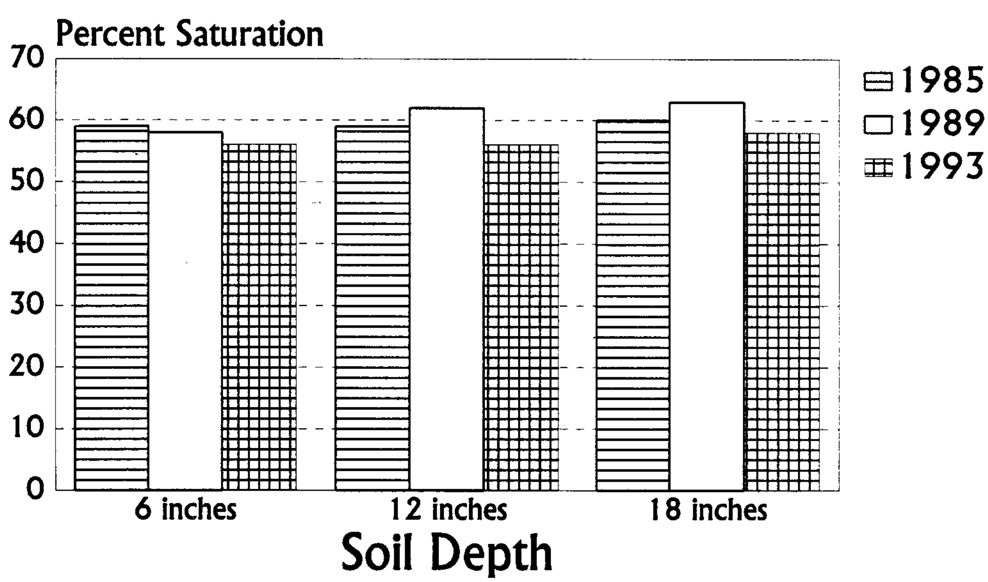


Figure 8. Base saturation percentage at three depths of soil over tailing in 1985, 1989, and 1993.

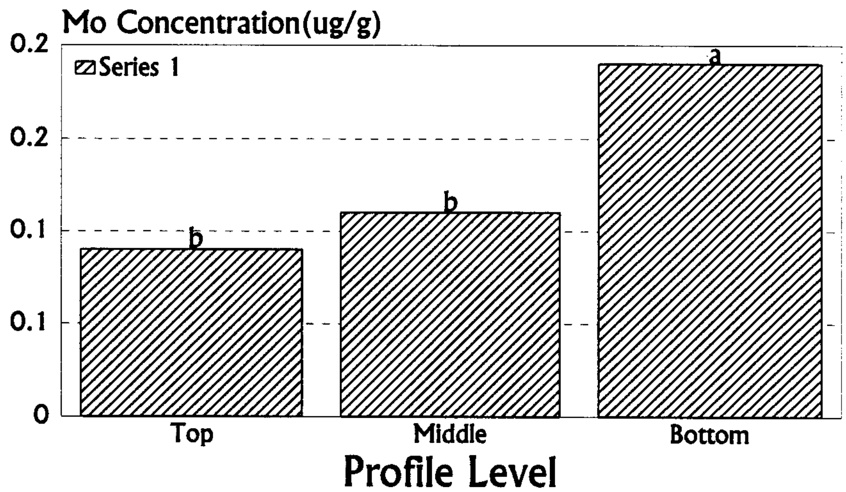


Figure 9. Molybdenum (Mo) concentration in soil over tailing at three levels in the profile in 1989 and 1993.

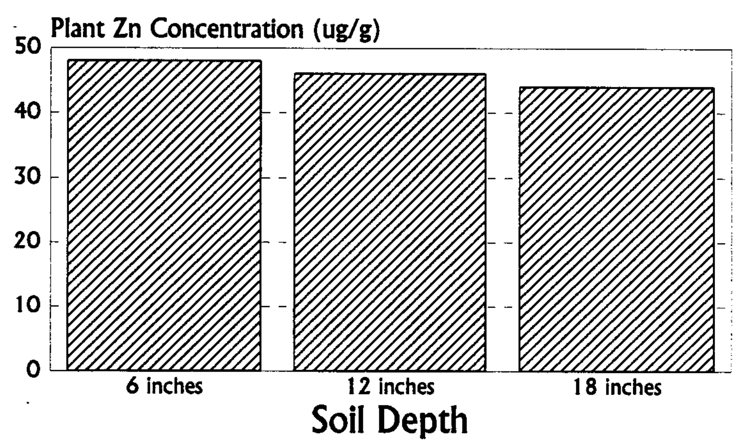


Figure 10. Zinc (Zn) concentration in aboveground biomass of smooth bromegrass as influenced by depth of soil placed over tailing.

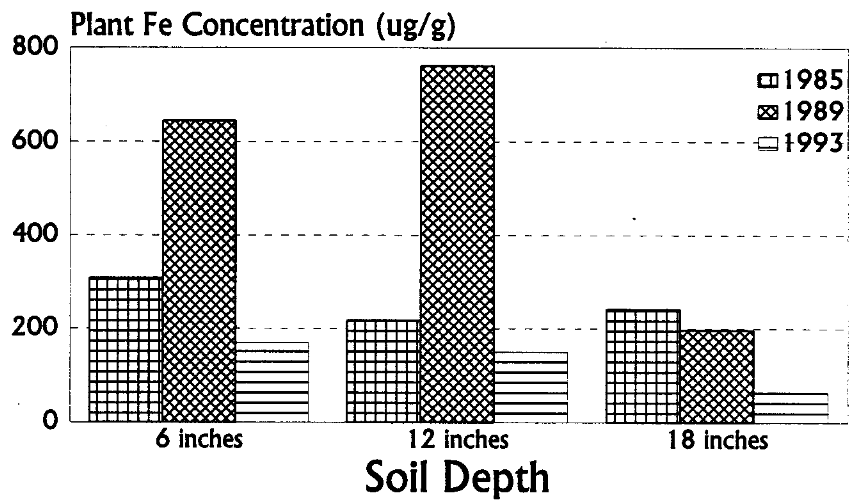


Figure 11. Iron (Fe) concentration in aboveground biomass of smooth bromegrass in 1985, 1989, and 1993 as influenced by depth of soil placed over tailing.

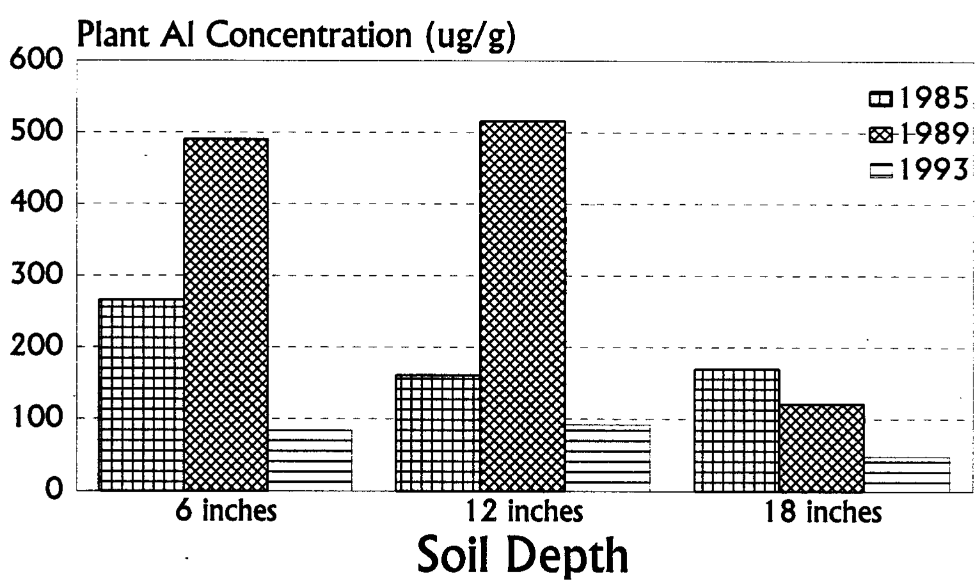


Figure 12. Aluminum (Al) concentration in aboveground biomass of smooth bromegrass in 3 years as influenced by depth of soil covering tailing.

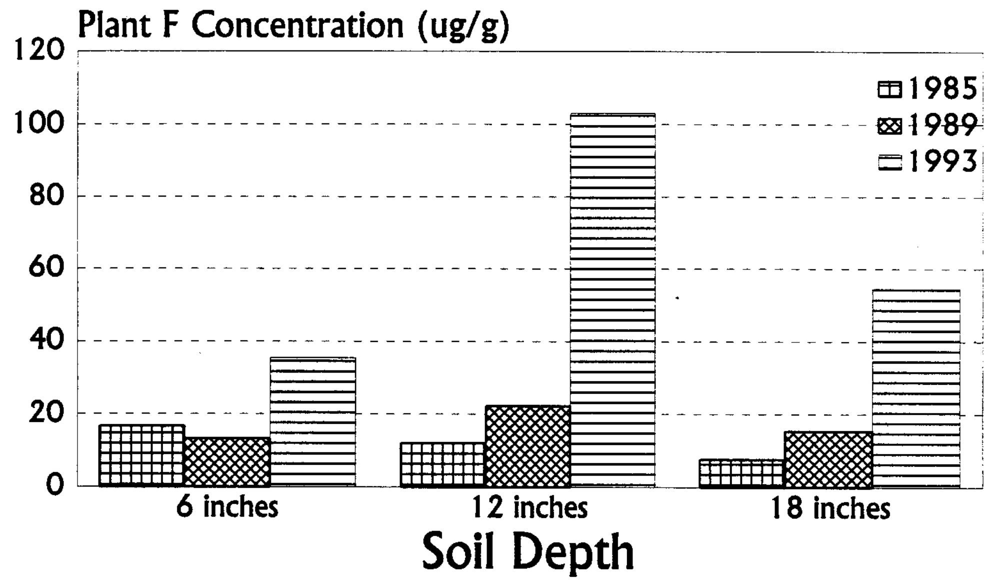


Figure 13. Floride (F) concentration in aboveground biomass of smooth bromegrass in 1985, 1989, and 1993 as influenced by depth of woil placed over tailing.

soil (Trlica, 1989). Thus, the reason for the increase in F for plants on the deeper soils is not known. For some reason the added lime may have interacted with soil F to result in a large increase in plant F concentration on the 12-inch soil covering the tailing.

The plant copper/molybdenum ratio improved considerably between 1985 and 1993, particularly when lime had not been used (Figure 14). The foliage of smooth bromegrass should not cause any copper deficiency or molybdenum toxicity for ruminants that might utilize it.

Chemistry Changes Through Time

Significant differences were noted in many measured soil and plant parameters among samples that were collected in 1985, 1989, and those taken in 1993. Some of these differences might be related to laboratory differences as samples were analyzed at three different times. However, laboratory equipment and procedures remained about the same at the CSU Soil Testing Laboratory between 1985 and 1993. Differences resulting from laboratory procedures in the three different years also may have resulted from different technicians processing and analyzing the samples. But it is believed that errors resulting from technician differences were small. Therefore, most of the differences among the 1985, 1989, and 1993 samples represent true differences among the actual samples.

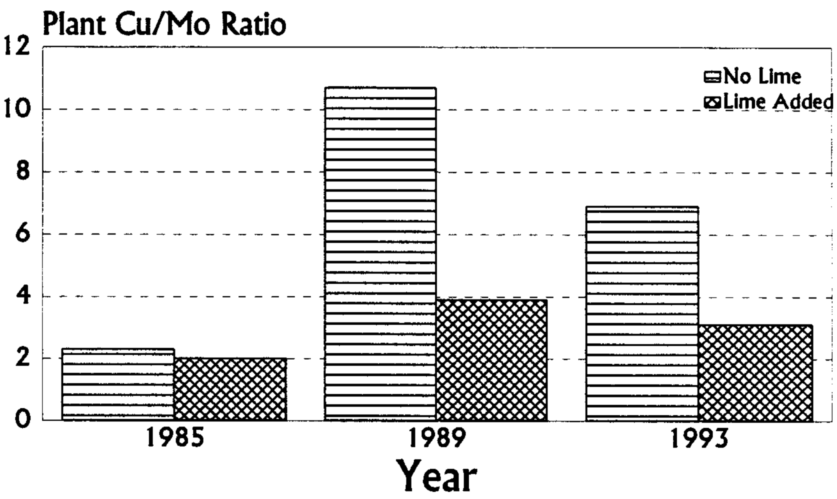


Figure 14. Copper:molybdenum ratio in aboveground biomass of smooth bromegrass in 1985, 1989, and 1993 as influenced by the application of lime.

Soil samples:

Soil pH, electrical conductivity (E.C.), magnesium (Mg), sodium (Na), sodium absorption ratio (SAR) and base saturation percentage (% Sat.) varied significantly between 1985 and 1993. Soil pH became more acidic between 1985 (5.8) and 1993 (5.2). Magnesium in soils increased from 3.4 to 4.2 µg/g between 1985 and 1993 and sodium increased from 0.4 to 0.6 µg/g during this same period. This probably resulted in the higher electrical conductivity in 1993 (1.3 mmhos/cm) than in 1985 (1.0 mmhos/cm). Greater salt concentrations in the soil profile probably affected the sodium absorption ratio and percentage base saturation which were both greater in 1989 and 1993 than in 1985.

It appears that a slight upward migration of salts from the underlying tailing has occurred during the past 11 years. This could result in unfavorable plant growth conditions in the future. However, these salt concentrations are not high at present, but will be affected by the timing and amount of precipitation received through time. Therefore, this should be monitored closely to determine fate of salts in the soil through time.

Plant samples:

Aboveground biomass of smooth bromegrass had significant changes in several of the metals and fluoride between 1985 and 1993 (Table 3). The concentration of iron (Fe), zinc (Zn), manganese (Mn), and aluminum (Al) all

Table 3. Elemental concentrations in aboveground biomass of smooth bromegrass from the soil-tailing test plots in 1985, 1989, and 1993.

| | Chemical constituent (μg/g) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Fe | Zn | Mn | Cu | Al | Mo | F | Cu/Mo |
| 1985 | 225b[1] | 56a | 419a | 4.3a | 199b | 2.7a | 12.1a | 2.2c |
| 1989 | 534a | 55a | 135b | 10.2a | 376a | 1.7a | 16.9a | 7.3a |
| 1993 | 128c | 27b | 71b | 18.0a | 75c | 3.4a | 64.3b | 5.0b |

[1]Means in a column followed by a similar letter are not significantly different ($P<0.05$).

declined in the foliage between 1985 and 1993. Decreased concentrations of these metals in plant tissue might be related to a decrease in soil pH through time. Many metals become more available in soil at acidic pH and could be taken up by plant roots and transported to aboveground plant parts or leached from the soil profile. This decrease in soil pH between 1985 and 1993 (5.8 to 5.2) may have resulted in a net loss of metal cations from the soil. Molybdenum and copper concentrations in smooth bromegrass have shown no significant change through time. However, with a small increase in uptake of copper in 1989 and 1993, the copper/molybdenum ratio in aboveground biomass improved significantly in 1989 and 1993 (Table 3). Since this foliage had copper/molybdenum ratios above 2:1 in all years, the aboveground biomass of smooth bromegrass was safe for ruminant animal consumption (Ward, 1978). Fluoride concentration in foliage was also considered to be in the normal range (Brewer, 1966). Therefore, elemental concentrations in foliage of smooth bromegrass from these test plots were considered to be in the normal range for plant growth and should not create any problems for ruminants utilizing the reclaimed plots at the present time (Stowe et. al., 1983).

## COVER, PRODUCTION, AND DIVERSITY

### Cover

The depth of soil (6, 12, or 18 inches) placed over Henderson Mill tailing had highly significant effects ($P<0.01$) in 1991 on the amount of cover of the dominant grass, hard fescue (Festuca ovina), total plant cover, the amount of litter cover on the soil surface, and the amount of exposed bare soil. The amount of lime (0, 2, 4, or 6 tons/acre) used as an amendment to soil to reduce acidification had insignificant effects on cover values. There was a significant ($P<0.05$) interaction between blocks, soil depth, and amount of lime added for all vegetation cover variables. This indicated that lime applications had varying effects with soil depth in the two blocks. However, an examination of these interaction means showed no meaningful trend in the data.

The highly significant interaction between soil depth and amount of applied lime on cover of hard fescue is diagrammed in Figure 15. It is clear that with the 6-inch soil depth that adding more lime did result in increased cover of hard fescue. However, this effect diminished at the 12-inch soil depth. And, when 18 inches of soil covered tailing, high amounts of added lime (4 or 6 tons/acre) actually resulted in less cover of hard fescue. This indicated that lime may be a desirable amendment to use to improve cover of hard fescue only if the amount of soil covering tailing is minimum.

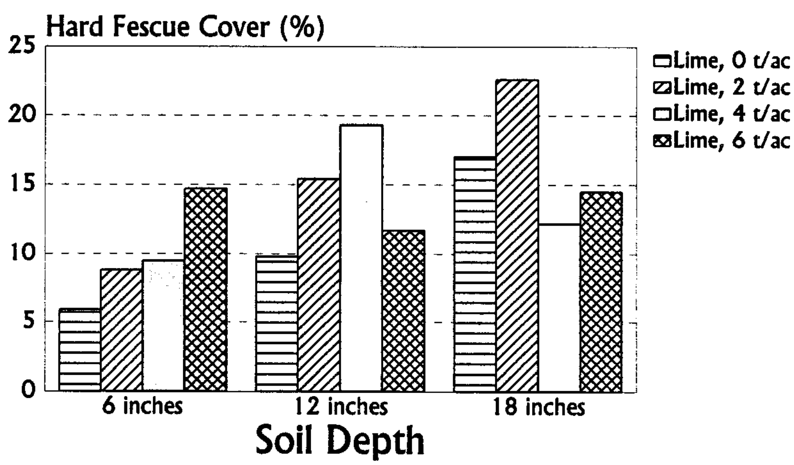


Figure 15. Cover for hard fescue on soil-tailing test plots in 1991 as affected by the interaction between depth of soil over tailing and amount of applied lime.

A comparison of cover on the Henderson soil-tailing plots with cover on a nearby undisturbed herbaceous community (control) was made to determine how closely cover of reclaimed plots resembled that of a native community. Analyses of these data indicated that highly significant ($P<0.01$) differences in all cover categories existed among the three soil depths of the soil-tailing plots and the natural community (control). A Newman-Keul's mean separation test was used to determine significant ($P=0.05$) differences among cover values on the reclaimed plots with three different soil depths compared with the undisturbed plant community. These comparisons showed that cover of the dominant grass, hard fescue on revegetated plots that received a 6-inch cover of soil was similar to that of the undisturbed community (Table 4). However, hard fescue cover (14-17%) on plots that had 12 or 18 inches of soil over tailing was greater than that of the natural community (6%).

Total plant cover on plots with 6 inches of soil over tailing (17%) was significantly less than plots with greater amounts of soil or the native (control) community (23-27%) (Table 4). There was no difference in total plant cover among plots with 12 or 18 inches of soil over tailing and the undisturbed native herbaceous community.

Litter cover on the soil surface increased from 17.6% for plots with 6 inches of soil over tailing to 61.4% on undisturbed plots (Table 4). There were significant differences among all treatments. As soil depth over tailing increased, the amount of litter increased. As expected, an increase in litter cover with increases in soil depth resulted in a significant decrease in the amount of bare soil exposed at the surface (Table 4). Therefore, bare soil was inversely related to the amount of vegetation cover.

Table 4. Average cover (%) in 1991 on the soil-tailing test plots as affected by soil depth over tailing as compared with cover of a nearby undisturbed herbaceous community (control).

| Cover | Soil depth (inches) | | | Undisturbed (control) |
|---|---|---|---|---|
| | 6 | 12 | 18 | |
| Hard fescue | 9.8b[1] | 14.2a | 16.6a | 6.1b |
| Total plant | 16.8b | 22.6a | 27.0a | 27.1a |
| Litter | 17.6d | 33.7c | 53.1b | 61.4a |
| Bare ground | 65.9a | 43.8b | 19.9c | 11.4c |

[1] Means in a row followed by similar letters are not significantly different at P = 0.05.

## Diversity

The number of plant species encountered within quadrats while sampling plant species cover were greatest in the undisturbed (control) community (20), followed by the 6-inch soil depth over tailing (15), and similar species numbered (11) in the 12- and 18-inch soil depths (Table 5). The diversity index indicated that the 12-inch soil depth over tailing resulted in an increase of diversity of only 6% over that of the 6-inch depth (0.585 compared with 0.622). However, an additional 6 more inches of soil over tailing (18-inch soil depth) resulted in an 18%

increase in diversity (0.622 vs 0.691). As expected, the undisturbed natural community was considerably more diverse than the reclaimed plots. The natural (control) community had a diversity index value of 1.027 (Table 5), which is about 50% greater than the 18-inch soil depth treatment and 75% greater than the treatment with only 6 inches of soil over tailing.

There is not an easily-applied statistical procedure to test for differences among values for diversity indices. But, the data showed that little difference (6%) existed between the two soil depths of 6 or 12 inches over tailing (Table 5). On the other hand, the 18-inch soil depth resulted in a biologically-significant diversity increase of 18% over the 6-inch soil depth treatment. It should be noted that four more species were actually present on the 6-inch soil depth than on either the 12- or 18-inch soil depth treatments, but some of these species were weeds or annual species.

Table 5. Number of species encountered in 20x50-cm quadrats and Shannon-Weiner diversity index values as affected by soil depth over tailing and as compared with a nearby undisturbed herbaceous community (control).

| Treatment | Number of species | Diversity index |
|---|---|---|
| 6" soil depth | 15 | 0.585 |
| 12" soil depth | 11 | 0.622 |
| 18" soil depth | 11 | 0.691 |
| Undisturbed (control) | 20 | 1.027 |

Production

The amount of standing biomass (production) on the soil-tailing test plots and a nearby undisturbed natural community was estimated. These data were corrected, based upon actual clipped plot data taken for 1/3 of the estimated plots, and converted to a dry-weight basis. These data were analyzed to determine if significant differences in production existed among plots from the various soil depths and lime treatments, and compared with the undisturbed native community (control). These analyses indicated that highly significant ($P<0.01$) differences in production existed for vegetation in the two blocks and among the three soil depths. Vegetation in the second block had greater production (69 $g/m^2$) than did that in the first block (55 $g/m^2$). The reason for this difference is not known, as both blocks received similar treatments.

Vegetation production increased as the depth of soil over tailing increased (Table 6). Production on these plots was compared with production of a nearby natural community and highly significant differences among the four treatments were detected. It was evident that plant production on the soil-tailing test plots with 18 inches of soil was significantly greater compared with other soil-tailing plots or to the natural community (control) (Table 7). However, production on plots that had either 6 or 12 inches of soil was similar to that found in the natural community. This production varied from 48 to 62 $g/m^2$, but was less than production of 75 $g/m^2$ on the 18-inch soil covering.

Table 6. Average production ($g/m^2$) in 1991 on the soil-tailing test plots as affected by soil depth.

| | Soil depth (inches) | | |
|---|---|---|---|
| Production | 6 | 12 | 18 |
| Total plant ($g/m^2$) | 48c[1] | 62b | 75a |

[1]Means in a row followed by the same letter are not significantly different at P = 0.05.

Table 7. Average production ($g/m^2$) in 1991 on soil-tailing test plots as affected by soil depth as compared with production on an undisturbed herbaceous community (control).

| | Soil depth (inches) | | | Undisturbed (control) |
|---|---|---|---|---|
| Production | 6 | 12 | 18 | |
| Total plant ($g/m^2$) | 48b[1] | 62b | 75a | 63b |

[1]Means in a row followed by the same letter are not significantly different at P = 0.05.

A significant interaction between soil depth and lime additions was noted for aboveground production on the soil-tailing test plots. Production was greatest on plots that received the heaviest application of lime (6 tons/acre) at the shallow (6 inch) soil depth (Figure 16). However, production was greater on plots with 12 or 18 inches of soil when either lighter applications of lime were made or when no lime was used.

There was a positive correlation between total vegetation cover and production on these reclaimed plots. As cover increased, production usually was greater (Tables 4 and 7). Greater soil depth allows plants a greater volume for root exploration for water and nutrients.

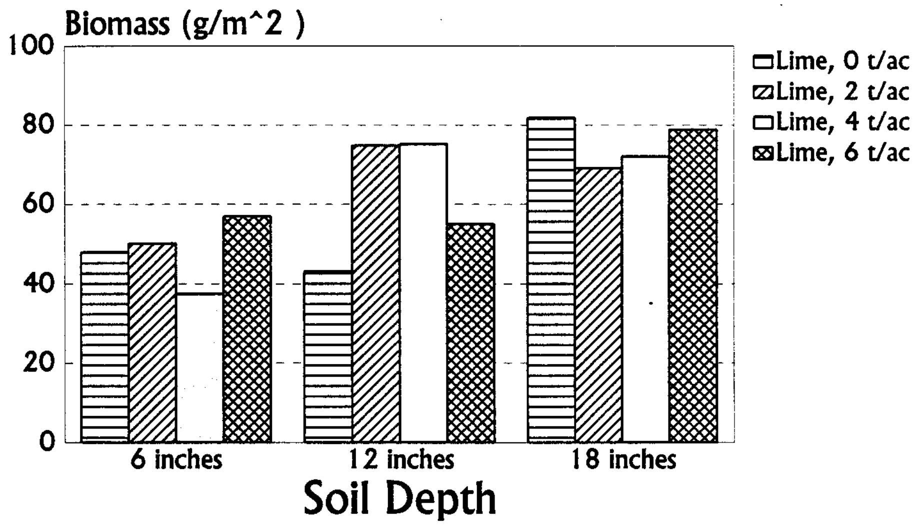


Figure 16. Total plant production in 1991 as affected by soil depth covering tailing and the amount of applied lime.

## CONCLUSIONS AND RECOMMENDATIONS

Mine tailing often has high concentrations of soluble salts, heavy metals, and other potentially-toxic chemicals. Eventual reclamation of these tailings must be accomplished in such a manner as to ensure a naturally-functioning plant community that perpetuates itself through time. Reclamation must be ecologically sound, but should also be done as economically as feasible. Therefore, this study was designed to determine the necessary depth of soil that should be used to cover molybdenum mine tailing that will allow for a naturally-functioning plant community that maintains itself. Plants should also not have concentrations of toxic chemicals in aboveground biomass that could reduce plant growth or be harmful to herbivores utilizing the plants as a forage resource.

Samples of soil taken from soil-tailing test plots in 1985 and 1989 indicated that some soluble salts migrated upward in the soil from the tailing below. This was particularly evident in the 12- and 18-inch soil covering tailing. The 6-inch soil evidently had sufficient leaching from natural precipitation so that there was little net movement of salts from tailing into the soil. And by 1993 some of these salts had been leached from the 6-inch soil by natural precipitation events.

The pH of soil had become more acidic between 1985 (5.8) and 1993 (5.2). Lime added to the soil at 6 tons/acre was effective in reducing the acidification process by about 1 pH unit. As soils became more acidic, several of the metals became more available for plant uptake. Thus, iron (Fe), copper (Cu), and aluminum (Al) were more concentrated in aboveground biomass of smooth bromegrass in 1989 than in 1985. However, concentration of these metals and molybdenum (Mo) at the present time are not excessive and do not represent a hazard for livestock or wildlife that might utilize vegetation on the reclaimed tailing (Stowe et. al., 1983).

Cover and production were not greatly influenced by the amount of lime applied to reduce soil acidification. However, if only 6 inches of soil over tailing is used, then adding lime may be justified. When either 12 or 18 inches of soil over tailing was used, little positive benefit in either cover or production was noted where lime had been added.

Few significant differences were noted in cover and production between the 12- and 18-inch depth of soil over tailing treatments. Production was even greater in the reclaimed plots when 18 inches of soil was used than in the undisturbed native community. The numbers of species were similar in the 12- and 18-inch soil depth treatments, but diversity was greater in the 18-inch soil depth treatment. Thus, the differences noted when soil depth over tailing was increased from 12 to 18 inches may not justify the additional costs associated with stockpiling or handling this volume of soil. If the objective is to maintain a herbaceous plant community that has cover and production similar to that of a nearby undisturbed herbaceous community, then these data would indicate that this could be accomplished by applying 12 inches of soil over tailing. However, when only 6 inches of soil covered tailing, less cover and lower diversity were found as compared with the treatment where 12 inches of soil was used.

It is recommended that these same plots be sampled again in five years to establish whether these relationships change with time. This will also indicate whether succession on these reclaimed plots has slowed and if the herbaceous plant community is at some dynamic equilibrium.

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# TECHNIQUES FOR REHABILITATING LANDS DISTURBED BY OIL DEVELOPMENT IN THE ARCTIC

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## ABSTRACT

To rehabilitate lands that have been disturbed by oil development in the Arctic, numerous techniques are being evaluated by ARCO Alaska, Inc. for developing strategies that are appropriate for a wide range of site characteristics. The rehabilitation techniques are grouped into five categories: site manipulation, surface preparation, soil conditioning, fertilization, and plant cultivation. Site manipulation techniques modify topographic, pedologic, and hydrologic properties and include creation of berms and basins to capture drifting snow, removal of fill to reduce fill or expose tundra soil, removal of fill and excavation of basins to create a mosaic of habitats, removal and replacement of contaminated tundra soil, excavation of basins to impound water, excavation of basins and addition of overburden to bury drilling wastes, and flooding of mine sites to create overwintering habitat for fish. Surface preparation techniques that improve the seedbed properties, aeration, and structure of the soil include compaction, scarifying, tilling, raking, and mulching. Soil conditioning techniques that improve soil properties include application of topsoil, sewage sludge, lime, sulfur for acidification, gypsum, microorganisms, and water absorbents. The number of fertilizer applications is important. Finally, plant cultivation techniques include natural colonization, seeding of native-grass cultivars, seeding of indigenous species, spreading of soil with a seed bank, planting of stem cuttings, sprigging, and transplanting of sod. As of 1993, 74 test plots have been set up within the Prudhoe Bay and Kuparuk oilfields to evaluate various combinations of treatments under different site conditions.

## INTRODUCTION

In northern Alaska, oil exploration has been conducted since the late 1940s, and full-scale oil development in the Prudhoe Bay region has been ongoing since 1973. The extraction of gravel, construction of gravel roads, pads, and reserve pits with drilling waste, and the presence of impoundments, road dust, and occasional spills and washouts associated with this activity have created a wide range of terrain disturbances (Walker et al. 1987). To rehabilitate these disturbances, ARCO Alaska, Inc., began a long-term program in 1984 to develop site-specific techniques for rehabilitating these disturbances. These techniques are directed at creating or restoring productive, diverse, and self-sustaining communities that will be useful to fish and wildlife.

Successful rehabilitation of disturbed lands in the Arctic must overcome many limitations posed by the severe environment (Billings 1987). The growing season on the Arctic Coastal Plain is very short, warm days are infrequent, and frosts can occur anytime during the summer. Low temperatures decrease rates of organic matter decomposition and nutrient cycling, reduce seed production, and retard rates of plant colonization of disturbed areas. In addition, the low precipitation greatly affects raised surfaces such as thick gravel pads, where the soils are very dry and salt crusts may develop at the surface.

Development of rehabilitation techniques for the Arctic began in the early 1970s and focused on planting techniques, development of grass cultivars, evaluation of application rates for nutrients, and transplanting of local vegetation (Mitchell et al. 1974). Based on seeding experiments, a few native grasses have proved successful and have been brought into commercial production (Mitchell 1979). The largest revegetation efforts in the Arctic to date have occurred along the Trans-Alaska Pipeline Corridor (Hubbard 1980, Johnson 1981) and at abandoned drill sites in the National Petroleum Reserve–Alaska (McKendrick 1986). Both efforts relied on seeding and fertilization to provide a quick plant cover and included at least one native-grass cultivar. Unfortunately, such techniques have not been as successful for thick gravel fill on the Arctic Coastal Plain (Johnson 1981, McKendrick 1986, Jorgenson 1988). Efforts also have focused on the evaluation of native and non-native grasses (Wright 1987), nitrogen-fixing legumes and other forbs (Moore 1993), and aquatic grasses (McKendrick 1991, Moore and Wright 1991). This paper contributes to this growing body of knowledge by reviewing the broad range of rehabilitation techniques that we currently are evaluating in the oilfields, in terms of how they modify the physical, chemical, and biological properties of sites, and by providing preliminary judgements on the effectiveness of these various techniques.

## STUDY AREA

The Prudhoe Bay and Kuparuk oilfields encompass what is commonly called an oriented-thaw-lake landscape (Walker et al. 1980) and include the floodplains of the Sagavanirktok and Kuparuk rivers (figure 1). In general, the area is flat and poorly drained and has been influenced by thaw-lake cycles, fluvial and eolian processes along rivers, and the coastal processes of erosion, sediment deposition, and flooding.

On the Arctic Coastal Plain, winters are cold and summers are cool; the thaw period lasts only about 90 days. From 1983 to 1990, the average summer (June-August) temperature in the Kuparuk Oilfield was 2.3°C, and the average thawing-degree-day sum was 618°C (Jorgenson and Cater 1991). Summer precipitation, most of which fell in August, averaged 64 mm during 1983-1992, (based on data from Thoman 1990).

Soil temperatures generally range from 0°C to 10°C during the growing season and soils have a thin layer of seasonally thawed ground that is underlain by permafrost (Walker et al. 1980). The rate of soil development is slowed by low temperature and

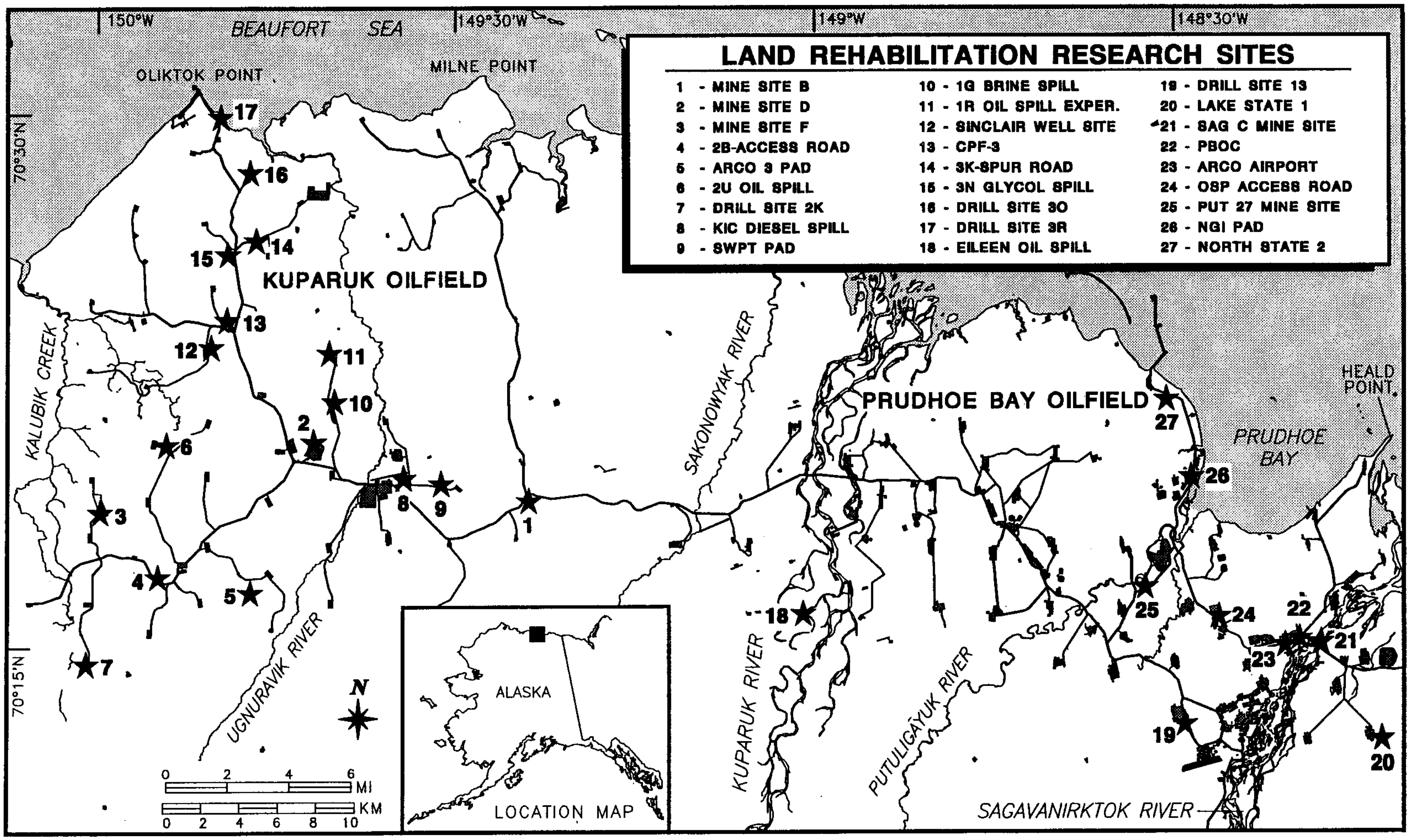


Figure 1. Locations of rehabilitation sites used for researching land rehabilitation techniques in the Prudhoe Bay and Kuparuk oilfiles, northern Alaska.

poor drainage. Vegetative cover, accumulation of organic matter, proximity to the coast, and fluvial processes along major rivers also exert control over these processes. At typical undisturbed sites, a peaty organic mat 10-20 cm thick is found over a silty mineral soil.

The thaw-lake cycle has created a variety of wetland types within the oilfields, including large, wind-oriented thaw lakes, small ponds, seasonally flooded lowland areas, and wetland complexes (Walker et al. 1980). The predominant wetland communities are wet-sedge meadows, moist sedge-dwarf shrub meadows, and *Arctophila fulva* marshes in small ponds and along margins of large lakes. Other plant communities include riparian forb communities along major rivers, dry dwarf-shrub tundra on pingos and along low ridges, and saline-sedge marshes and coastal-graminoid meadows along the coast.

## REHABILITATION TECHNIQUES

The techniques that we have been evaluating for rehabilitating lands have been grouped into five categories site manipulation, surface preparation, soil conditioning, fertilization, and plant cultivation (table 1). As of 1993, 74 test plots have been set up to evaluate various combinations of treatments under different site conditions. Although the techniques are presented below separately, they are being evaluated for inclusion in a comprehensive set of strategies for rehabilitating the wide range of disturbed land in the oilfields (Jorgenson and Joyce, in press).

### Site Manipulation

#### Berm and basin construction:

Thick gravel fill, which is the most extensive type of disturbance in the oilfields, presents a severe environment for plant growth. One of the factors limiting plant growth is soil moisture. Berms can be constructed perpendicular to prevailing winds to capture drifting snow during winter and increase water input during snowmelt, thus compensating for low precipitation in summer and low soil moisture on thick gravel fill (table 2, figure 2). In areas with fine-grained soils, such as overburden stockpiles, meltwater can be impounded permanently to create wetlands. Small berms (~0.5 m high) were constructed on a thick gravel pad at Mine Site D in the Kuparuk Oilfield (Jorgenson et al. 1993). Although these small berms were not efficient at capturing drifting snow, up to 10 cm of meltwater remained impounded within the bermed polygons for 1-2 weeks. In 1989, snowmelt in the bermed treatment added 158 mm of water to the gravel (summer precipitation added 135 mm), whereas only 75 mm was added in the unbermed control. Because water storage in the top 50 cm of gravel ranged from 45 to 60 mm at field capacity, input from snowmelt exceeded storage capacity and was lost as throughflow. Although the experiment showed that small berms were successful at increasing soil moisture, it also showed that increasing the water-holding capacity by adding organic

Table 1. Techniques for rehabilitating lands that have been disturbed by oil development in the Arctic.

| Site Manipulation | Surface Preparation | Soil Conditioning | Fertilization | Plant Cultivation |
|---|---|---|---|---|
| None | None | None | None | Natural colonization |
| Berm and basin construction | Compaction | Topsoil application | One application | Seeding of native-grass cultivars |
| Fill removal | Scarifying | Sludge application | Two applications | Seeding of indigenous species |
| Fill removal and basin excavation | Tilling | Lime application | Three applications | Containerized seedlings |
| Sod removal and replacement | Raking or dragging | Acidification | | Use of seed bank in soil |
| Basin excavation | Mulching | Gypsum application | | Stem cuttings |
| Basin excavation and overburden adition | | Microorganism application | | Sprigging |
| Flooding of mine sites | | Addition of waer asorbents | | Sod transplanting |

matter was more important to the water balance than increasing the input of water.

To expand upon the concept of manipulating the hydrology of thick gravel pads, moderately sized berms (~1 m high) and shallow basins (0.5 m) were created on a thick gravel pad at Drill Site 13 in the Prudhoe Bay Oilfield in 1989 to capture more snow and store larger volumes of meltwater that at Mine Site D (Jorgenson et al. 1993). This design allows water to drain freely off the surface into the basins that potentially can serve to irrigate the pad later in the summer. After snowmelt, water up to 25 cm deep persisted in the basins for up to 2 weeks. Groundwater levels in the flat control and the berm-basin treatment areas were similar after the pad had thawed entirely by late June.

To create wetlands on a previously dry overburden stockpile at Mine Site D in the Kuparuk Oilfield in 1990, large (~4 m) berms were constructed to capture snow and smaller berms (~2 m) were constructed to impound the meltwater (Jorgenson et al. 1992a). Because of the presence of the fine-grained soil and permafrost beneath the shallow active layer (seasonally thawed ground), water levels in the basin have continued to increase from 1990 to 1993 (Jacobs et al. 1994). Transplanting sprigs of *Arctophila fulva* and aquatic invertebrates have made this site attractive to numerous waterbirds.

Table 2. Site manipulation techniques used to modify topographic, pedologic, and hydrologic properties for rehabilitating lands in the Arctic.

| Technique | Purpose | Advantages | Disadvantages |
|---|---|---|---|
| None | To leave site as is | No cost; can avoid further disturbance. | Soil may be poor for plant growth. |
| Berm and basin construction | To capture drifting snow and modify hydrology and microclimate | Increases snowmelt and soil moisture; reduces winter desiccation; and is inexpensive to create. | May cause excessive leaching in coarse soils. |
| Fill removal (gravel or overburden) | To modify hydrologic and pedologic characteristics of the site for plant growth | Improves the growing environment; fill can be reused; initiates thaw settlement that can improve microsite diversity and nutrient availability. | High cost; need a place to put fill; may initiate thaw settlement and alter hydrologic movement; and induce flooding that can reduce planting options. |
| Fill removal and basin excavation | To modify hydrologic and pedologic characteristics to promote aquatic ecosystems | Improves the environment for wetland restoration and creates water bodies for aquatic habitats; less concern for consequences of thaw settlement. | High cost; need a place to put fill. |
| Sod removal and replacement | To replace contaminated tundra soil | Quickly reduces toxicity and liability. | Further damages the ecosystem; organic topsoil may be lost unless it is replaced; may initiate thaw settlement and alter hydrologic properties. |
| Basin excavation | To impound water in basins or troughs | Facilitates the creation of aquatic ecosystems. | May lead to excessive thaw settlement depending on the amount of subsurface ice. |
| Basin excavation and overburden addition | To bury and isolate drilling waste in permafrost | Can isolate wastes and reduce ecological risks. | Effectiveness of isolation and long-term stability unknown; long-term liability may be a problem. |
| Flooding of mine sites | To create overwintering areas for fishes | Provides critical habitat for fish; provides a good use for areas that have few other options. | May alter drainage patterns. |

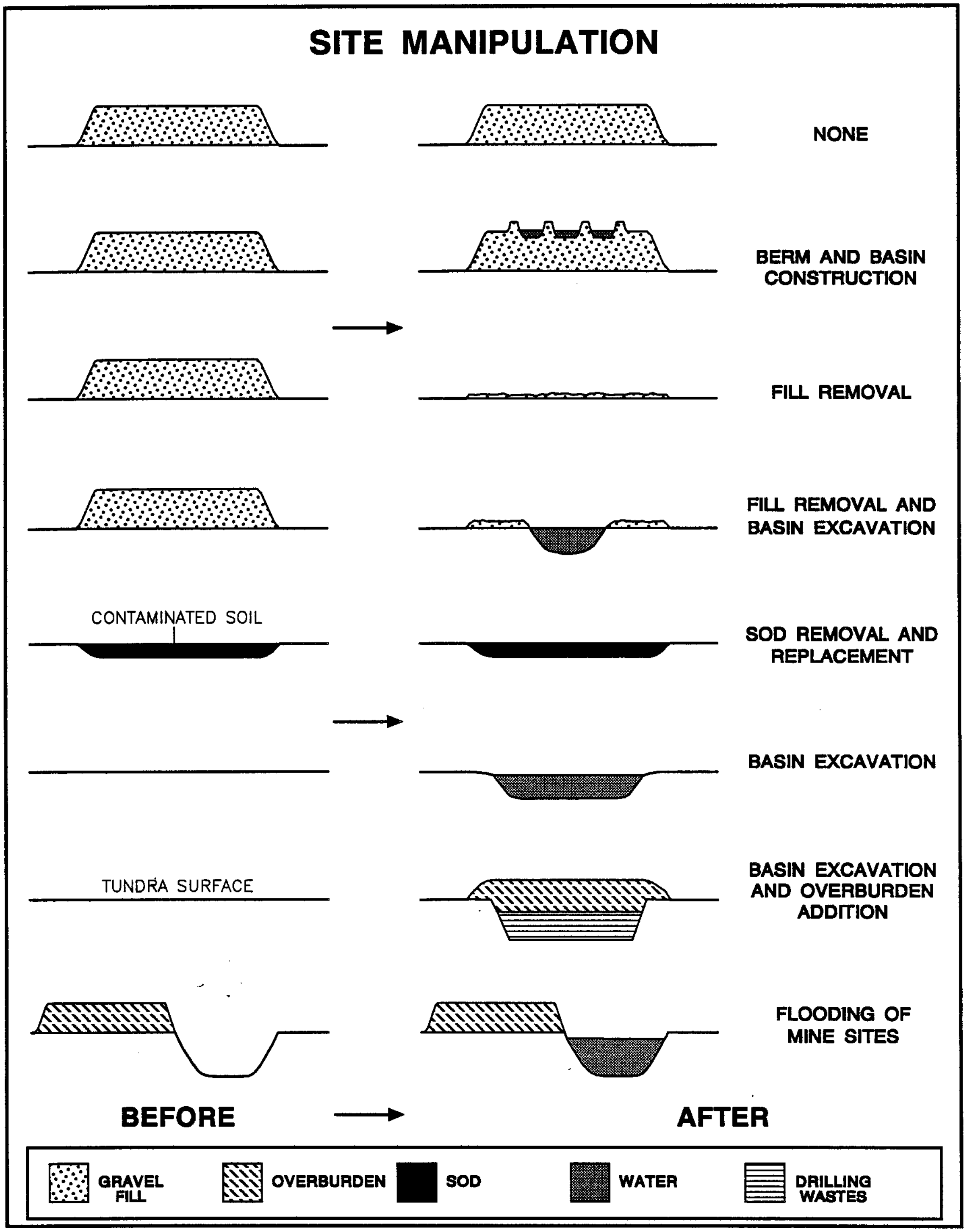


Figure 2. Schematic views of sites before and after various manipulations used for rehabilitating lands disturbed by oil development in the Arctic.

Fill removal:

Removal of gravel fill can make pedologic and hydrologic conditions similar to those found in adjacent undisturbed tundra (table 2, figure 2). Without the removal of gravel and the associated increase in the availability of water and nutrients, the growth of plants on thick gravel fill is poor; Jorgenson (1988) found plant growth to be negligible on gravel thicker than 1 m and attributed the response to the low rate of capillary rise of groundwater as a result of the thickness of the fill.

How much gravel to remove from roads and pads remains problematic. Because tundra soils typically are underlain by ice-rich permafrost, the removal of gravel can initiate thaw settlement as permafrost adjusts to the new thermal regime. Some gravel can be left in place to compensate for thaw settlement, but tundra soil will remain buried. If gravel is removed completely to expose the buried tundra soil, excessive thaw settlement may cause the site to become flooded permanently, and water movement in the adjacent tundra may be altered, such as at the OSP site (Jorgenson and Kidd 1991). The impounded water provides an opportunity to create aquatic habitats, but it also reduces the number of species that can be planted.

The amount of gravel removed to expose tundra soil can have large effects on soil properties. At a wetland restoration experiment at the North State 2 Exploratory Well Site in the Prudhoe Bay Oilfield, a thin layer of gravel was left in place over most of the area, and small patches of tundra soil were exposed after removal of gravel. The organic horizon of tundra soil in the exposed patches was much higher in organic matter (68 vs. 1%), total nitrogen (1.81 vs. 0.02%), exchangeable nitrogen (129 vs. 8 mg/kg), and exchangeable phosphorus (15 vs. 2 mg/kg) than in the thin layer of gravel that remained (Kidd et al. 1994). Similarly, groundwater levels differ greatly between those areas with thick gravel fill and areas where gravel has been removed. At an experiment near Drill Site 13 in the Prudhoe Bay Oilfield, groundwater levels in 1.5-m thick gravel fill ranged from just below the pad's surface (0.20-0.35 m) immediately after breakup to 1.5 m or more during mid-summer (Jorgenson et al. 1993). In contrast, groundwater after gravel was removed at North State 2 occurred near (<20 cm) the surface early and late in the summer (Kidd et al. 1994). During mid-summer, groundwater was absent (precipitation was below average in 1993) but soils remained moist. Preliminary observations indicate that removing gravel is essential to restoring wetland communities, but more information is needed about the long-term surface stability of sites before we can adequately assess how much gravel should be removed to balance concerns over surface stability and restoration of wetland functions.

Fill removal and basin excavation:

Removing gravel fill and excavating basins to create permanent water bodies can facilitate the development of a mosaic of aquatic and terrestrial habitats (table 2, figure 2). At North State 2, an experiment was begun in 1992 to develop a mosaic of wetland communities by removing the gravel pad and excavating several basins to a depth below that of the surrounding tundra (Kidd et al. 1994). Some basins were designed to be shallow (10-30 cm) to support sedge-marsh communities, whereas deeper basins (30-100 cm) were excavated to support grass-marsh (*Arctophila fulva*) communities. After 1 year, these basins have water impounded to depths similar to those in adjacent, natural marshes. Transplanted tundra plugs and *Arctophila* sprigs have survived well, and the newly created marshes have been colonized by at least eight taxa of aquatic invertebrates.

Sod removal and replacement:

Sod removal and replacement (also called cut and fill) has been used to remove tundra soil that has been contaminated by accidental spills of toxic compounds (table 2, figure 2). At a small site near Drill Site 3N in the Kuparuk Oilfield, tundra soil that was contaminated by a glycol spill was excavated during winter and replaced with tundra sod that had been stockpiled at Mine Site F (Jorgenson and Cater 1991). The cut-and-fill approach is useful for sites where the contaminants are highly toxic and degradation rates are slow. The technique completely destroys any surviving vegetation that might have recovered and may result in thermal instability of the site, however.

Basin excavation:

Excavation of basins (0.1-1 m deep) can be used to create shallow water bodies for marsh habitat in tundra areas or to create littoral zones for juvenile fish at flooded mine sites (table 2, figure 2). For tundra, excavation normally is done in conjunction with removal of gravel (see above). To date, excavation of basins has been done primarily at mine sites (e.g., Sag C Mine Site, Mine Site F). Based on a survey of flooded mine sites, Hemming et al. (1989) concluded that mine sites with more extensive littoral habitat had higher rates of algal production and greater densities of zooplankton than did those that contained little littoral habitat.

Basin excavation and overburden addition:

Excavation of basins and addition of overburden recently have been used at numerous drill sites to bury and isolate drilling wastes (table 2, figure 2). This technique is referred to as the "below-grade-freeze-back" technique (Jorgenson and Joyce, in press) because it takes advantage of low ground temperatures to freeze and isolate the wastes in permafrost to prevent migration of contaminants. In practice, a large basin (sump) is excavated below grade, the overburden is stockpiled adjacent to the basin, the wastes are discharged into the basin, and the wastes are covered by the overburden so that the new surface is >1 m above the original level of the tundra. The basins are designed to bury the wastes 0.6-1.2 m below grade, which is well below the active layer. The overburden caps are designed to be above grade to compensate for settling and to prevent impounding of water on the surface. Monitoring has shown that the sites are relatively stable, although some settling of material has led to small impoundments around the perimeter that required backfilling (Cater and Jorgenson 1993).

Flooding of mine sites:

Abandoned gravel mine sites can be flooded with water and connected to nearby drainages to support overwintering fishes (table 2). Natural colonization by fishes has been rapid in mine sites (e.g., Sag Site C, Mine Site D, Mine Site B, Put 27, Kuparuk Deadarm) that have been flooded and connected to adjacent streams with access channels (Hemming 1992). Eleven species of fishes have been found at these sites: arctic cisco (*Coregonus autumnalis*), broad whitefish (*C. nasus*), least cisco (*C. sardinella*), round whitefish (*Prosopium cylindraceum*), burbot (*Lota lota*), ninespine stickleback (*Pungitius pungitius*), rainbow smelt (*Osmerus mordax*), Dolley Varden char (*Salvelinus malma*), arctic grayling (*Thymallus arcticus*), slimy sculpin (*Cottus cognatus*), and fourhorn sculpin (*Myoxocephalus quadricornis*). At two sites (Mine Sites B and D), arctic grayling have been transplanted to increase diversity and the use of available habitat by fishes.

Surface Preparation

Surface preparation techniques tried in the oilfields include compaction, scarifying, tilling, raking or dragging, and mulching (table 3). Because these techniques have not been evaluated as rigorously as other techniques have, they will be discussed only briefly. Compaction was done at the 3K-Spur Road with a large, rubber-balloon-tired vehicle (Rolligon) to improve contact between the applied sod and the underlying thin layer of gravel (Cater and Jorgenson 1993). Scarifying has been done at many sites (gravel pads and overburden stockpiles at Mine Sites D and F, Drill Site 13, and S. E. Eileen Exploratory Well Site) by using a grader equipped with chisel teeth or by pulling a pipe equipped with tines. Plants at scarified sites typically are most abundant in the bottom of furrows, suggesting that scarification increases seed germination by providing favorable microsites. Tilling oil-contaminated soil promotes the biodegradation of hydrocarbons; this technique has been used at S. E. Eileen with a bulldozer equipped with chisel teeth, an agricultural disker, and with a hand-operated rototiller (Jorgenson et al. 1992b). Raking or dragging to improve soil-seed contact has been conducted at S.E. Eileen. Finally, mulching to reduce the rate of evaporation of soil moisture improved seed germination on a gravel pad at Mine Site D (Jorgenson and Cater 1992). Mulched plots, however, had lower soil temperatures and lower soil moisture than unmulched plots because the mulch intercepted solar radiation and precipitation. In summary, scarifying, tilling, and raking appear to be effective treatments that are relatively easy to implement, whereas compacting and mulching do not appear to be beneficial.

Table 3. Surface preparation techniques used to improve seedbed properties, aeration, and soil structure for rehabilitating disturbed lands in the Arctic.

| Technique | Purpose | Advantages | Disadvantages |
|---|---|---|---|
| None | To leave the site as it is | No cost; no disruption of plants that are colonizing naturally. | Surface may provide few microsites for germination. |
| Compaction | To increase bulk density | Useful for areas in which loose fill has been placed. | Requires heavy equipment; may impede root penetration. |
| Scarifying | To loosen soil surface | Useful for creating better microsites for seed germination; improves root penetration; can capture drifting snow. | May disturb existing vegetation; requires heavy equipment. |
| Tilling | To mix and aerate soil | Useful for mixing topsoil into the subsurface and for aerating soil; also see scarifying. | May disturb existing vegetation; requires heavy equipment. |
| Raking or dragging | To improve contact of seeds with soil | Can be done with small equipment. | May disturb existing vegetation. |
| Mulching | To reduce seedling desiccation | Improves germination. | Lowers soil temperature; may introduce weedy species. |

## Soil Conditioning

### Topsoil addition:

Topsoil (a mixture of organic and mineral horizons from tundra soil) has been applied to gravel fill to improve the physical, chemical, and biological properties of the gravel's surface (table 4). On a thick gravel pad at Mine Site D in the Kuparuk Oilfield, topsoil-amended plots were much higher in organic carbon (22.5 vs. 2.9%), total nitrogen (0.55 vs. 0.06%), exchangeable nitrogen (135 vs. 26 mg/kg), and soil moisture (23 vs. 12% vol. in midsummer) 2 years after treatment than did unamended plots after one fertilization, (Jorgenson and Cater 1991). In response to these improvements to the soil, the mean total cover of grasses was much higher in the topsoil-amended plot (68 vs. 29%). Similarly, at an experiment at Mine Site F designed to evaluate various amendments for increasing water-holding capacity on a thick gravel pad, the topsoil-amended treatment was higher in organic carbon (3.8 vs. 0.4%), total nitrogen (0.23 vs. 0.02%), exchangeable nitrogen (48 vs. 1 mg/kg), exchangeable phosphorus (14 vs. 8 mg/kg), and moisture (21.5 vs. 13.3 % volume) than was the unamended treatment. Clearly, the single most important factor for improving soil properties for plant growth on

Table 4. Soil conditioning techniques used to improve soil properties for plant growth when rehabilitating disturbed lands in the Arctic.

| Technique | Purpose | Advantages | Disadvantages |
|---|---|---|---|
| None | To leave the site as it is | No cost. | May not remedy soil chemistry problems. |
| Topsoil application | To improve soil properties by adding organic matter. | Improves soil properties on a long-term basis by improving soil structure, nutrient availability, moisture holding capacity, and the microbial community. | Expensive; availability of topsoil is limited. |
| Sewage sludge application | To improve soil properties by adding organic material and nutrients | May improve soil properties on a long-term basis. | High handling and monitoring costs; may increase alkalinity; may contain contaminants (although domestic sludge from oilfields is relatively clean). |
| Liming | To increase soil pH | Quickly reduces acidity, easy to apply. | Moderate cost of materials and application. |
| Acidification | To reduce soil pH | Elemental sulfur or sulfuric acid can be used to reduce alkalinity. | Moderate cost; acid is a hazardous material. |
| Gypsum application | To reduce the sodium hazard | Useful for mobilizing and replacing sodium in soils. | May modify pH; may add excessive amounts of sulfur. |
| Micro-organism application | To improve a variety of soil properties | Microorganisms can improve acquisition of nutrients, rates of mineralization, degradation of contaminants, reduction of salinity, etc. | Inoculation of indigenous species may be costly; exogenous species may be poorly adapted or incompatible with local environment. |
| Application of water absorbents | To improve water-holding capacity | My improve soil moisture in coarse soils | Effectiveness uncertain; may be effective for only a few years. |

thick gravel fill is the addition of organic matter. Unfortunately, very little topsoil is available for rehabilitation within the oilfields.

Sewage sludge addition:

Domestic sewage sludge from camp facilities has the potential to improve soil properties on thick gravel fill (table 4); because it also is composed primarily of organic matter, it has many of the same beneficial properties as topsoil. Given the lack of topsoil available, sludge could provide an alternative source of organic matter. Potential adverse impacts of pathogens, heavy metals, and nitrates associated with application of sludge on gravel fill within wetlands has been a concern.

In fall 1992, sludge was applied to experimental plots on a thick gravel pad at Mine Site F in the Kuparuk Oilfield (Cater and Jorgenson 1994a). In fall 1993, the plot with the highest application rate (18 mt/ha) had levels of organic carbon (0.31 vs. 0.28%) and total nitrogen (0.03 vs. 0.02%), exchangeable nitrogen (4 vs. 2 mg/kg), and exchangeable phosphorus (9 vs. 3 mg/kg) that were similar to those in unamended gravel (control). Although differences were pronounced immediately after application, soil properties did not appear to be improved substantially on a long-term basis at this relatively low application rate. Factors limiting the application rates of sludge include the low cation-exchange capacity of gravel and concerns over applying excessive amounts of nitrate that can leach into adjacent wetlands. Although groundwater below the plots had concentrations of fecal coliform bacteria and heavy metals that were similar to background levels, nitrate concentrations were three times higher under the sludge-amended plot. Preliminary observations indicate that sewage sludge would have longer lasting effects on soil properties if it could be applied at a heavier rate than we used, but the low cation-exchange capacity of thick gravel fill and concerns over nitrate input into the supra-permafrost groundwater makes heavier application undesirable. In addition, monitoring requirements associated with sludge application increases the cost of the technique.

Other soil conditioners:

Other soil conditioners that have been used in the oilfields include the application of lime to reduce acidity, elemental sulfur and sulfuric acid to reduce alkalinity, gypsum to reduce sodium hazards (toxicity and soil permeability), *Rhizobium* bacteria in a soil-water slurry to inoculate the roots of legumes, and polymer absorbents to increase water retention in gravel fill (table 4). Effects of these treatments are described below.

Although the application of lime usually is not necessary because tundra soil and gravel fill normally are neutral or slightly alkaline, lime was applied (4,500 kg/ha) during bioremediation of a crude oil spill near Drill Site 2U to increase pH after microbial activity had reduced it to <6 (Jorgenson et al. 1992c). Elemental sulfur (200 kg/ha) and sulfuric acid (12% $H_2SO_4$ at 2,300 L/ha) have been added to small plots on an overburden stockpile at Mine Site F to reduce alkalinity of the soil (Jorgenson et al. 1990). These rates appeared to have little effect on soil alkalinity or plant growth, however.

Gypsum has been applied (4,500 kg/ha) to reduce the sodium hazards in tundra that was damaged by fire-extinguishing agents (primarily sodium bicarbonate) used during fire-fighting training at SWPT Pad (Cater and Jorgenson 1994b). After 1 month, the sodium adsorption ratio decreased from 3.1 to 2.5, and germination tests indicated that sodium levels (mean = 290 mg/L) were no longer toxic to plants.

Soil microorganisms have been applied in a soil-water slurry on small germination test plots to inoculate the roots of legumes with nitrogen-fixing *Rhizobium* bacteria (Cater and Jorgenson 1994a). No results are available yet on the effectiveness of this technique.

Finally, a starch-based polymer absorbent has been applied (22 kg/ha) in a test plot at Mine Site F to evaluate its use for increasing soil moisture by retaining additional water during snowmelt (Cater and Jorgenson 1994a). In 1992 and 1993, mean values for soil moisture in the absorbent treatment (8.8% and 13.7%, respectively) were similar to those in the unamended control (6.8% and 13.3%, respectively).

Fertilization

Because most disturbed sites, particularly those containing gravel fill, are deficient in nutrients, fertilization is important for stimulating plant growth (table 1). On thin gravel fill at one of the pads at the Lake State 1 Exploratory Well Site, where plants have been colonizing naturally since 1969, the application of fertilizer in 1986 had a large effect on plant growth. Although, mean cover of vascular plants was 3% after 17 years of colonization, it increased to 15% one season after fertilization (Jorgenson 1988). Similarly, on thin gravel fill with topsoil at the 3K-Spur Road, plants have been colonizing naturally since 1984. After fertilization in 1986, 1988, and 1990, the mean cover in 1991 was 16% on the fertilized treatment in 1991, but only 7% on an unfertilized control (Cater and Jorgenson 1993).

How well fertilization enhances long-term productivity is unclear, particularly for thick gravel fill, which is highly porous and has a low cation-exchange capacity. One strategy is to fertilize sites several times to stimulate root production and the accumulation of carbon and nutrients in the soil for continued nutrient cycling. At the Lake State 1 Exploratory Well Site, plots were fertilized (20-20-10 NPK at 440 kg/ha) and seeded with native-grass cultivars in 1986 and half of the plots were fertilized (200 kg/ha) a second time in 1991. In 1991, the mean cover of grasses was much higher after two applications (42%) than after one application (10%)(Kidd and Jorgenson 1992). How long the effects of fertilizer persists is uncertain, but we suspect that nutrients will be lost gradually and productivity will decline. As a short-term solution, we believe the best strategy is to fertilize lightly (200-300 kg/ha) the first year during seedling establishment and in the third year when roots are well established and can capture most of the nutrients before they are leached away. As a long-term solution, we believe that legumes should be used to capture atmospheric nitrogen and sustain productivity.

Plant Cultivation

Natural colonization:

Natural colonization may be preferable for revegetating disturbed sites where soil properties are favorable because the colonizing species come from adjacent areas and thus should be better adapted to arctic conditions than are cultivated species (tables 5 and 6). To understand better the patterns and rates of natural colonization of disturbed areas, numerous types of sites have been monitored throughout oilfield (Jorgenson et al. 1990).

Although 73 species have been found colonizing disturbed sites, most provide only a trace amount of cover. The most common species are described below.

Based on a survey of 32 sites, six patterns of natural colonization have been identified; these six patterns have different species composition and colonization rates related to soil type and fill thickness (Jorgenson et al. 1990). On thin (<25 cm thick) gravel fill, the dominant colonizers were *Carex aquatilis, Eriophorum angustifolium,* and *E. scheuchzeri*, and the mean annual increment in cover (MAI, where MAI is total cover of all plant species combined, divided by years of natural colonization) was 2.5%. On thick (>25 cm) gravel fill, few species are able to colonize, mostly *Festuca baffinensis, P. langeana, Draba* spp., *Epilobium latifolium, C. officinalis,* and *B. purpurascens.* Colonization rates were very low (MAI of 0.2%) on moderately thick (25-80 cm) and negligible (<0.1%) on thick (>80 cm) fill. The principal colonizers on thin organic-mineral fill, which is typical of small overburden stockpiles, were similar to those found on thin gravel fill but also included *Arctophila fulva.* The MAI on thin organic-mineral fill was 1.8%. On thicker, well-drained organic-mineral fill the dominant colonizers were *Poa alpigena, Braya purpurascens, Puccinellia langeana*, and *Cochlearia officinalis.* Colonization rates were much higher on moderately thick (25-100 cm) fill than on thick (>100 cm) fill (MAI of 3.6 and 1.6%, respectively). These results suggest that natural colonization is adequate for revegetating minor disturbances and sites with only a thin layer of fill, especially fill with a higher content of organic matter, whereas natural colonization is inadequate for thick gravel fill.

Seeding of native-grass cultivars:

The use of native-grass cultivars that are available commercially for use in revegetating thick gravel fill is of interest because (1) large areas of fill eventually need to be revegetated, (2) several of the species are well adapted to arctic conditions, (3) grasses quickly can increase the productivity of a site, and (4) the cultivated seed is inexpensive (tables 5 and 6). Currently, seven native grasses are available commercially for revegetation: *Arctagrostis latifolia, Bechmannia syzigachne, Calamagrostis canadensis, Deschampsia beringensis, Festuca rubra, Poa alpina*, and *P. glauca* (Alaska Plant Materials Center 1993). All of these species have been planted in the oilfields, although *P. alpina, B. syzigachne* and *C. canadensis* have been used in only a few experimental plots. Another species, *Elymus arenarius,* is available commercially from hand collections and has been tried in small test plots (Wright 1987). In our earliest applications (e.g., Lake State 1 in 1986, Mine Site F in 1987), seed mixtures were applied at heavy rates (44 kg/ha) to promote rapid development of a productive cover, whereas the rate has been reduced (10-20 kg/ha) at several recent projects (e.g., S. E. Eileen, N. State 2) to create open grasslands that then are amenable to natural colonization.

Mixtures of native grasses have been used at numerous experimental and full-scale applications in the oilfields and have shown a good ability to develop a productive cover rapidly. Results have been best on thick gravel fill where organic topsoil has been applied; at Mine Site D, for example, mean total vascular cover was 139% (includes overlapping layers) after 3 years (Jorgenson and Cater 1991). Similar results have been found on overburden stockpiles where the soil has a high percentage of fines and where permafrost under the thin active layer prevents leaching of nutrients; mean total vascular cover was 379% after 3 years at Mine Site D (Jacobs et al. 1994) and 28% after 2 years at Mine Site F (Jorgenson et al. 1990). In contrast, growth of grasses on thick gravel fill without any manipulation of the site or topsoil application has been slower; at a gravel storage pad at Mine Site D, mean total vascular cover was 42% after 3 years, even after fertilizer was applied the first and third years (Jorgenson and Cater 1992). On a thick gravel pad at Lake State 1, mean total vascular cover was 10% after 5 years with only one fertilizer application.

Seeding of indigenous species:

The collection and sowing of seeds from hydrophilic plants is being evaluated for restoring wetlands and xerophilic legumes are being evaluated for use on thick gravel fill (tables 5 and 6). Currently, indigenous seeds from hydrophytic species have been applied at six sites (ARCO Airport, PBOC, S. E. Eileen, Drill Site 13, Drill Site 3R, and Mine Site D) where gravel fill has been removed in experiments on wetland restoration. Preliminary observations of seed germination at these sites indicate that the technique is feasible, although germination rates are low, growth rates of seedlings are slow, and availability of seed is dependent on how successful seed production is during any one year. Data have not been collected yet, however, to assess adequately the results of those applications, and much needs to be learned about this technique, including: seed handling and storage techniques for optimizing germination, potential germination rates, annual variability in seed production for harvesting, the feasibility of commercial cultivation, effect of site conditions on germination and growth, and interspecific variation among species.

Since 1991, we have cooperated with the Alaska Plant Materials Center to evaluate the feasibility of using legumes and other forbs for increasing species diversity, forage availability, and nutrient availability (table 6). Legumes are of particular interest for their association with nitrogen-fixing bacteria and potential contribution to long-term productivity. Test plots have been set up in the oilfields, as well as in Interior Alaska, to evaluate feasibility of commercial production (Moore 1993).

Use of soil with a seed bank:

The spreading of topsoil has the potential for introducing propagules from a diversity of well adapted local species stored in soil seed banks (table 5). Our observations in the oilfields indicate that this technique is ineffective on the Arctic Coastal Plain, however. At Mine Site F, where tundra sod was stockpiled separately during mining, natural colonization has been very slow, indicating very little germination of buried seeds (Jorgenson and Cater 1992). After 7 years, there was only a trace cover of forbs (primarily *Cardamine hyperborea, Draba* spp., *Polygonum viviparum*, and *Stellaria* spp.) and graminoids (primarily *Carex aquatilis* and *Eriophorum angustifolium*). Similarly, germination tests of the potential of seed banks along trails created by seismic exploration on the coastal plain of the Arctic National Wildlife Refuge revealed few buried seeds available for germination (Felix and Jorgenson 1984). In contrast, seed banks from soils inland from the coast, where air temperatures are warmer, have been found to have high numbers of viable seed (Gartner et al. 1986, Ebersole 1989).

Stem cuttings:

The use of stem cuttings from willows has the potential to increase species diversity, physical complexity of the plant community, and improve forage availability (tables 5 and 6). Whereas we have planted stem cuttings at only one site (Mine Site D) in the oilfields, large scale plantings of willow stem cuttings were done along the Trans-Alaska Pipeline (Densmore et al. 1987, Wright 1992). At Mine Site D, where stem cuttings (~20 cm long) were planted in topsoil applied to a thick gravel pad, most cuttings of *S. ovalifolia* and *S. pulchra* have survived and expanded, but survival of *Salix arctica* was poor (Jorgenson and Cater 1992). At Material Site 122-4 along the Trans-Alaska Pipeline, 53% of the planted *S. alaxensis* cuttings (33-38 cm long) survived after 9 years (Densmore et al. 1987).

Sprigging:

The use of sprigs (bare roots and stems) for transplanting vegetation has been tried with the aquatic grass *Arctophila fulva* to increase the productivity and physical structure of created wetlands (table 5). Because of its importance as a habitat for birds, *Arctophila* has been the subject of a 5-year study of its life history and ecology (McKendrick 1991) and studies of transplanting techniques (McKendrick 1991, Moore and Wright 1991). In full-scale applications of the sprigging technique at Mine Site D and N. State 2, transplanting worked best when sprigs were planted horizontally in wet sediments above the waterline with a small portion of the leaves protruding. This method allowed rapid resprouting from multiple nodes on the rhizomes, avoided uprooting from wave action and ice movement, and resisted removal by grazing. At Mine Site D, stem density increased from 3 stems/m$^2$ to 12 stems/m$^2$ after 3 years (Jacobs et al. 1994), and at N. State 2, stem density increased from 4 stems/m$^2$ to 11 stems/m$^2$ after 2 years (Kidd et al. 1994).

Sod transplanting:

Transplanting of sod (vegetated layer of soil, including roots) in various sizes, such as plugs (~15 cm across), chunks (20-50 cm across), or mats (50-200 cm across), has the potential to introduce a larger diversity of locally adapted plants along with the chemical and biological properties of the native soil (table 5). This technique is most appropriate for restoring wetland vegetation and areas with permanent shallow water, where seeding is ineffective. In most of our experiments, plugs were taken from wet tundra for use in areas where gravel fill has been removed; plugs from moist sedge-dwarf shrub tundra also have been transplanted into topsoil on a thick gravel pad at Mine Site D. Generally, plugs have been transplanted at a spacing of 0.6-1.5 m to balance the

Table 5. Plant cultivation techniques for rehabilitating disturbed lands in the Arctic.

| Technique | Purpose | Advantages | Disadvantages |
|---|---|---|---|
| Natural colonization | To allow natural colonization | Colonizing species may be well adapted; lack of planting other species improves colonization rates. | Colonization may be slow and unpredictable. |
| Seeding of native-grass cultivars | To establish well-adapted species quickly | A variety of species are available for large applications; can create a productive community quickly. | Species diversity is limited; may impede natural colonization; appropriate cultivars may not be available; may introduce genes from remote populations. |
| Seeding indigenous species | To introduce a low density of indigenous species | Can increase species diversity; plants may be better adapted to site conditions than cultivars; genetic resources are from the same area, seeding provides more propagules than other planting methods. | Seed production is sporadic, depending on the weather; seed viability may be low; techniques for handling seeds are poorly understood; cost is higher than for cultivar seeds. |
| Use of soil with a seed bank | To introduce a diversity of local, well adapted species | Can increase species diversity; plants may be well adapted to site conditions; genetic resources are from same area. | Appears to be ineffective on the Arctic Coastal Plain. |
| Containerized seedlings | To introduce plants that already have a good start | Plants are past critical the germination stage; technique has not been tried in the oilfields. | Labor intensive; requires months of handling. |
| Stem cuttings | To introduce woody plants | Plants may grow more rapidly than seedlings. | Labor intensive, limited period when it can be done. |
| Sprigging | To introducing herbaceous and woody plants. | Plant may grow more rapidly than seedlings; part of the root system and mycorrhizal association may be preserved. | Labor intensive; limited period when it can be done. |
| Sod transplanting | Useful for introducing a diversity of species and microorganisms, along with the topsoil. | Can be used for a wide diversity of species; native soil microbiota are introduced; less disruption to individual plants than sprigging; chunks and mats are more amenable to mechanized equipment. | Transplanting of plugs is labor intensive; damages source area; limited period when it can be done. |

Table 6. Plant species that have been planted by various methods for rehabilitating disturbed lands in the Arctic.

| Species | Natural Colonization | Native-Grass Cultivars | Indigenous Seeds | Stem Cuttings | Sprigging | Sod Transplanting |
|---|---|---|---|---|---|---|
| GRAMINOIDS | | | | | | |
| *Alopecurus alpinus* | - | | - | | | |
| *Arctagrostis latifolia* | * | * | * | | | |
| *Arctophila fulva* | * | | - | | * | |
| *Bechmannia syzigachne* | | - | | | | |
| *Carex aquatilis* | * | | * | | | * |
| *Calamagrostis canadensis* | | - | | | | |
| *Deschampsia caespitosa* | * | ? | - | | | |
| *D. beringensis* | | * | | | | |
| *Dupontia fisheri* | - | | * | | | - |
| *Eriophorum angustifolium* | * | | * | | | * |
| *E. scheuchzeri* | * | | * | | | * |
| *Festuca baffinensis* | * | | | | | |
| *F. rubra* | * | * | | | | |
| *Poa alpigena* | * | | | | | |
| *Poa arctica* | - | | | | | |
| *P. glauca* | - | * | | | | |
| *Puccinellia langeana* | * | ? | - | | | - |
| *Trisetum spicatum* | - | | | | | |
| FORBS | | | | | | |
| *Artemisia arctica* | * | ? | * | | | |
| *Astragalus alpinus* | - | ? | * | | | |
| *Braya purpurascens* | * | | | | | |
| *Cerastium beeringianum* | - | | | | | |
| *Cochlearia officinalis* | * | | | | | |
| *Descurania sophioides* | - | | | | | |
| *Draba* spp. | * | | | | | |
| *Epilobium latifolium* | - | ? | - | | | |
| *Hedysarum alpinum* | * | ? | * | | | |
| *H. mackenzii* | * | ? | * | | | |
| *Oxytropis borealis* | * | ? | * | | | |
| *O. campestris* | - | ? | - | | | |
| *O. deflexa* | * | ? | * | | | |
| *O. nigrescens* | - | | - | | | |
| *O. viscida* | * | ? | * | | | |
| *Sagina intermedia* | - | | | | | |
| SHRUBS | | | | | | |
| *Dryas integrifolia* | - | | | | | - |
| *Salix arctica* | - | | | - | | - |
| *S. ovalifolia* | | | | | | |
| *S. planifolia* | - | | | - | | - |

* Commonly found or used, - uncommon, ? under evaluation.

objectives of increasing plant cover in the treated area while minimizing damage to the donor area. Plugs are a good size for use with hand tools and can be obtained during the summer, when the ground has thawed. Preliminary observations of plug transplants at Mine Site D, Airport, PBOC, OSP, Drill Site 3R, and N. State 2 indicate that survival of the plugs is high and that sedges and willows have started sprouting into adjacent soil. Data have not been collected yet on expansion rates into adjacent areas, however.

Sod chunks have been used at a large below-ground disposal site created for drilling wastes near Lake State 1 (pers. obs.). During the development of that site, we experimented with techniques for extracting large mats from the frozen tundra during excavation of the pit, with the idea of trying to reestablish the original tundra's surface; however, the frozen mats shattered into small chunks during excavation. Sod chunks can be easily transplanted during the winter with heavy equipment but can be taken only from areas where disturbance or burial of the tundra is planned.

## CONCLUSIONS

Numerous techniques for site manipulation, surface preparation, soil conditioning, fertilization, and plant cultivation are being evaluated for use in rehabilitating the wide range of disturbances associated with oil development in the Arctic. Of particular interest is the development of techniques for gravel roads, pads, and gravel mine sites, which compose most of the disturbed land. Preliminary results indicate that a productive and diverse vegetative cover can be established even on sites with severe ecological limitations, such as thick gravel pads, through the construction of berms and basins, application of topsoil, and use of various plant cultivation techniques. However, only a very limited amount of topsoil, which probably is the most important factor for improving the growth of plants on thick gravel fill, has been stockpiled for future use in the oilfields. Without topsoil, long-term productivity and the variety of species that can survive is diminished. Accordingly, the use of sewage sludge as an alternative source of organic material and the use of legumes for their nitrogen-fixing ability warrant further evaluation.

Removal of gravel fill as a technique for restoring wetlands has received increased interest because most of the fill has been placed under wetland development permits. Preliminary evidence indicates that numerous plant cultivation techniques can be effective for creating a mosaic of habitats, although data on the rates and patterns of community development and on their similarity to natural reference sites are still being collected. There also are serious disadvantages to the removal of fill, however, such as high cost, finding an acceptable location for the fill, and increased surface instability.

Research at mine sites has shown that flooding of pits can provide good overwintering habitat for fish and that establishment of both mesic grasslands and aquatic emergent wetlands on overburden stockpiles is feasible. Monitoring of these relatively new sites, however, has shown that most indicators of ecosystem development continue to change and have not yet stabilized.

As more is known about the long-term ecological response to these techniques, they can be organized into a set of comprehensive strategies that can be used to rehabilitate the entire range of disturbances in these arctic oilfields. An important factor that we have not included in this evaluation, however, is the relative cost of applying these techniques. How best to balance the relative costs and benefits associated the wide variety of techniques that are available for rehabilitating disturbed land in the oilfield will be a difficult issue for government and industry.


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# REMINING AND ENVIRONMENTAL RESTORATION AT THE DRUID MINE

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## ABSTRACT

The Druid Mine Project demonstrated that "remining" can be a viable environmental restoration technology as well as a profitable business venture. Before the project activities began in 1990, the South Willis Gulch location was considered to be one of the most severely impacted acid mine drainage and erosional soil loss areas in the state by the Colorado Inactive Mines Program.

The project focused on removing piles of dump rock and mill tailings from their historic locations, relocating them to a central heap leach processing area, recovering precious metals, stabilizing and reclaiming the processed material and performing reclamation at the dump removal sites. The company's restoration efforts were enhanced by an EPA 319 Nonpoint Source Grant. Overall, the project reclaimed approximated 80 acres of previously disturbed and environmentally impacted mine and milling sites, and processed approximately 250,000 ton of dump rock and mill tailings.

The remining process and facility were approved by Region 8 EPA to serve as an acceptable alternative technology for the scheduled Superfund Clean-up of listed mine and mill sites in the nearby communities of Black Hawk and Central City. Regulating the site operations and defining closure protocol and long term monitoring became a three-way agreement of the Colorado Department of Health, the Colorado Division of Minerals and Geology, and the EPA.

## INTRODUCTION

The Druid Mine is a small precious metals heap leach operation as well as an Off-site Repository for reprocessing historic mine wastes. Located near Central City, in Gilpin County, Colorado, the company is owned and operated by Solution Gold, Ltd.,(SGL) of Golden, Colorado. The company finished leaching operations in 1993, and continues to serve as a mine waste repository. SGL did not do any new mining, but engaged only in "remining" historic mine dumps and mill tailings and performing environmental restoration of previously disturbed sites.

The project, by mining industry standards, wasn't large enough to be considered even a small mine, and was properly considered to be a large demonstration project, processing about 250,000 total tons of ore in its four year operating history. By comparison, the Summitville Mine in southern Colorado processed about 12,000,000 tons of ore, and the proposed expansion of the Cresson Mine will bring its capacity to 50,000,000 tons.

SGL maintained primary permits with the Division of Minerals and Geology - Mined Land Reclamation Office (DMG-MLRO), and other agencies commonly requiring permits from a mining operation: such as NPDES, Air Quality, and County Special Use. However, permitting to perform the function of an Off-Site Repository to receive historic mining wastes, and CERCLA related mining wastes, provided both testing grounds and battlegrounds for the operator and regulators.

## ELEMENTS OF A REMINING PROJECT

The Central City and Black Hawk area had many of the key elements necessary to conduct a remining and environmental restoration project:

- a need or pressure to clean up sites: in this case both Superfund requirements and local development pressure to build gambling establishments and support facilities.
- an incentive for property owners to reclaim inactive mine sites to protect themselves from future personal liability for un-managed historic mine sites with respect to Stormwater Regulations and potential impacts to ground and surface waters.
- severely impacted area from historic mine waste and acid mine drainage, that can be re-habilitated by removal of wastes and reclamation of sites.
- suitable location for sighting a remining and processing facility, away from water resources and population.
- mine waste as either dump rock or mill tailings, with gold and silver values sufficient to support a remining project.
- favorable metallurgy for recovery of metals
- sufficient tonnages to support the capital expense of the operation
- local understanding and support for the project
- regulatory framework for operating flexibility

Whereas most of these key elements were in place, this case study focuses on finding a "regulatory fit", that would allow for remining and reclamation, but would also address the protocols and requirements necessary for remedial activities involving Superfund Sites. It covers the high and low points of that process, and discusses future changes in permitting philosophy that may be inevitable for heap leach mining or reprocessing operations.

## FINDING A REGULATORY FIT

Finding a way to permit an existing heap leach mining operation as a Superfund Off-site Repository involved cooperation and joint reviews by the EPA, Colorado Department of Health (CDH) and the Colorado Division of Minerals and Geology (DMG). It resulted in a Memorandum of Understanding (MOU) among the three agencies that gave oversight and enforcement authority to DMG through its reclamation permitting process. It also left the door open for ongoing dialogue and scrutiny from the three parties with respect to permit changes, monitoring, post closure procedures, long term liability, bonding requirements, oversight and enforcement authority.

In this particular situation, it also provided the operator with some assurance that it had addressed the concerns of the individual state and federal regulatory agencies, while allowing the operator to remain directly accountable to a single agency engaged in permitting mining and reclamation activities, the DMG.

SGL recognized the opportunities for remining in this area in 1988. They began gathering baseline information and acquiring necessary permits to remine a series of highly pyritic dumps in South Willis Gulch, approximately 4 miles south of Central City, and at an elevation of 9,000 feet. Permits were granted in 1990, and the Druid Mine commenced operation as a remining project.

Later in 1990, SGL began a dialogue with EPA and the Colorado Department of Health (CDH), to expand the activities at the Druid Mine, and serve as an Off-Site Repository for excavated mining waste that was being disturbed or removed as part of local development activities. The material, identical to that being processed from dumps by the Druid Mine, was determined to be chemically unsuitable to be used as landfill or dumped indiscriminately in the County. This material, although not characterized as a hazardous waste, exhibited low pH's, in the range of 2 to 5, and was often high in metals, with values in the range of: arsenic > 150 ppm, lead > 500 ppm, zinc > 1000 ppm, and mercury > 1 ppm. In some cases, the material was part of a Superfund site.

In 1990, SGL requested that the Druid Mine be given joint approval by the CDH and EPA to serve as an Off-Site Repository for Mining Related Solid Wastes. After a period of negotiating, permit modifications, and voluntary adoption of many Sub-Title D landfill requirements, approval was granted in January of 1993.

## PERMITTING AN OFF-SITE REPOSITORY

In late 1990, SGL submitted a preliminary request for approval of a plan to perform a privatized clean-up for the owner of a historic mining related Superfund Site in Black Hawk, Colorado. The owner was unable and unwilling to conform to the CERCLA requirements necessary to carry out his plan, and withdrew his offer in April of 1991.

However, SGL continued to believe that the idea of treating the CERCLA mine waste materials in the same manner that old dumps and mill tailings from the Russell Gulch area were being treated at the Druid Mine, made a lot of sense and would provide a cost effective clean-up alternative for Superfund sites with dump rock and mill tailings. Therefore, SGL sought approval for the Druid Mine to provide a nearby location for the operation of an "Off-site Repository for Superfund Mining Waste".

In January of 1992, SGL was granted conditional approval for such a facility by Region 8 EPA. The approval allowed for the immediate receipt of non-CERCLA geologic material excavated from building foundations or from the removal of dumps and mill tailings as part of an excavation or building permit issued by a local government. The approval for receipt of CERCLA site material was granted as a conditional approval, based on the satisfactory resolution of several issues. Final approval was received in January of 1993.

SGL also sought interpretative rulings from the Mined Land Reclamation Board and the Colorado Department of Health (CDH) - Solid and Hazardous Waste Divisions. The Division of Minerals and Geology (DMG) initiated a Memorandum of Understanding between CDH and DMG with respect to the management and disposal of mining related wastes.

EPA viewed the "Off-Site Repository" activity as closely related to the operation of a Sub-Title D Landfill for industrial waste. In order to receive approval to receive Superfund mining waste, the Sub-Title D requirements became the criteria for construction of the pad, pond, leak detection and monitoring systems. SGL also committed to specific ground and surface water protection programs, 30 year post closure bonding and monitoring program, and ongoing involvement of EPA, and CDH.

## DESCRIPTION OF REPOSITORY AND REMINED MATERIALS

Repository and remined materials consisted of naturally occurring geological materials and were generally described by the following categories:

Dump Rock - Historic surface piles, consisting of waste rock or low grade ore; the material has not been processed, only dumped aside, hence the name "dump rock".

Mill Tailings - The solid waste product from the minerals processing plant; the material has been crushed to a fine sand consistency, and the metals of interest removed by gravity or flotation separation.

Repository Materials - Repository materials in the Central City - Black Hawk area were generally a mix of soils, dump rock and mill tailings, but because of their location near waterways or populated areas, they were regulated as:

1. CERCLA or Superfund Site materials, where removal and off-site treatment were ordered as part of an approved remedial action.

2. Non-CERCLA sites, where removal and off-site treatment were allowed by local excavation and building permits and where acceptance at the Druid Mine was allowed by Mined Land Reclamation Permits and MOU's between CDH and DMG-MLRO.

## WATER SAMPLING AND MONITORING PLANS

The surface and ground water monitoring programs at the Druid Mine have been in effect since 1988, when initial pre-mining baseline studies began. As mining and reclamation activities grew and expanded, the program was modified and amplified to address changes as they occurred. New legislation has either been promised or promulgated in areas of ground water and storm water, and the Druid Mine's plan has instituted early characterization and prevention programs to be prepared to accommodate the new legislative requirements as they become effective.

In August, 1992, SGL hired Dr. Catherine Kraeger-Rovey and her firm W&EST, Inc. to perform a hydrologic audit at the Druid Mine. The purpose of this audit was to have a professional hydrologist assess the existing quantity and quality of water occurrences at the Druid Mine, and to evaluate the current and proposed measures taken by Solution Gold for the protection of both ground and surface waters. Among the tasks to be evaluated by Dr. Kraeger-Rovey were:

- Perform a water balance model to evaluate the engineering design of the capped leach pads over a 30-year period,

- Evaluate permeability of on-site clay bearing materials for use in subsurface liners and as capping material for heaps,

- Examine the adoption of the french drain and leak detection systems as part of the long term monitoring program,

- Consider the site geomorphology, catchment basin, and effects of a 100 year storm event,

- Review existing data on attempts to characterize the ground water potential and occurrence,

- Recommend other ground water monitoring well locations and propose "Points of Compliance" for the upcoming ground water regulations,

- Review protective measures taken for storm water prevention and control.

## NONPOINT SOURCE PREVENTION AND CONTROL

In 1991, Solution Gold was awarded a 319 Non-Point Source Grant from EPA and the Colorado Department of Health to perform a prevention and mitigation project to address the impacts of acid mine drainage on 37 acres of land adjacent to, up-gradient of, and blended into the active operations at the Druid Mine. Project implementation began in the fall of 1991 and was completed by December of 1992. The blending of reclamation and mitigation measures from the 319 Program and from the Druid Mine's reclamation activities has already shown dramatic improvement in controlling erosion and abatement of acid mine drainage impacts in South Willis Gulch.

Water quality sampling for the 319 Grant is performed in conjunction with SGL's routine sampling at the Druid Mine. These data are taken to measure progress of the 319 activities, and are reported to the CDH 319 Program and to the Division of Minerals and Geology - Mined Land Reclamation Office.

## PROJECT LOCATION CONSIDERATIONS

The Druid Mine is located approximately 4 miles south of Central City in Gilpin County, Colorado. The mine site is in South Willis Gulch, a small drainage area at about 9,000 ft, in elevation. The mine site is on the north slope of Pewabic Mountain, and consists of the remining of pyritic mine dumps remnant from the mining activities in the district in the 1860-1905 period.

Modest ephemeral drainage occurs in the lower portion of the Druid Mine permit area during spring run-off and during some of the heavier storm events. The ARGO tunnel passes directly under the Druid property, approximately 1500 feet below the surface. Rarely are surface flows seen in this area. The nearest perennial drainage is North Clear Creek, approximately 5 miles away. It is considered the receiving stream for the Druid Mine. Several mining related Superfund sites are situated along this stream reach, and it does not support aquatic species.

The terrain in this area is steep and the slopes have been void of any vegetation for more than 100 years due to historic mining and acid mine drainage impacts. Large piles of pyritic dump material from the immediate area totaling 170,000 tons, were processed on Pad #1 at the Druid Mine during 1990 - 1992. The combined removal of the acid producing dumps and site reclamation has already had a favorable impact on mitigating the environmental impacts of these historic dumps in the small

Willis Gulch Watershed.

## ON-GOING PREVENTION AND CONTROL EFFORTS

Through the combined efforts of the 319 Project and the on-going reclamation activities at the Druid Mine, visual and erosional impacts of rilled channels and wash out gullies have been mitigated. Diversion ditches, dozer basins and silt dams have been constructed to break up sheet flow areas and provide storm water control.

These measures have been successful to the degree that surface flows are nearly non-existent. The area has only scant ephemeral drainage, usually peaking in May or early June from a result of snow melt. The check dam system has provided a stair step series of small basins in the steepest part of Crest Gully. These have been successful in catching and absorbing most of the surface runoff long before it leaves the permit area.

The primary down gradient surface sampling point in Crest Gully, at the lower permit area boundary, did not have any measurable surface flow throughout the 1992 season. Storm water samples were obtained in July and October of 1992, however, quarterly samples could not be taken because of lack of continual measurable flow at the sampling point. It appears that the up-land storm water management practices are having a positive impact on controlling run-off and erosion in South Willis Gulch.

## BASELINE AND PRE-EXISTING CONDITIONS

During the baseline gathering portion of the mining and reclamation permitting process, a total of 69 analytical parameters were evaluated, with 16 of these representing the Acid Semi-volatile Organic Fraction, EPA Method 8278. None of these organics were ever detected. Solution Gold asked to drop this part of the analytical program, and it was granted to do so, based on the reports of "not detected" and the fact that none of these chemicals were represented in any part of the processing to occur on site.

The remaining 53 parameters represented those requested by the DMG-MLRO and others added to make the data collected compatible with other sampling going on in the Clear Creek Drainage Basin as part of the Superfund Area Study. It was thought that these data would be a useful reference for showing the mitigation success of remining as an environmental restoration technique. In May 1992, SGL requested and was granted permission to delete other parameters from the suite of analyses to be determined based on non-occurrence or other factors.

Solution Gold hoped to demonstrate to EPA and CDH that the removal and treatment of pyritic dumps was the first and most important step in restoring both ground and surface water quality in this historic mining district.

## CLOSURE AND POST CLOSURE

Once the repository operation activities have been completed, SGL will follow the DMG-MLRO approved plan for detoxification, grading and slope configuration. The capping of the heap will follow, with all possible measures taken to minimize infiltration and run-on of storm water.

The cap configuration and modeling of water balance scenarios are as recommended by Dr. Krager-Rovey. After grading to specified slopes, the cap will be put in place consisting of:

- 18 inches of low permeability clay
- 6 inch rock drainage layer
- 18 inches of topsoil
- native grass vegetative cover

The largest area to be covered will be approximately 2 acres. SGL has stockpiled clay and topsoil for the purpose of capping and final reclamation. Other clay and topsoil resources are available on the property for long term care and maintenance.

Permanent survey markers will be installed at various locations on the capped heap to serve as reference points in determining settling and subsidence.

## IMPLEMENTATION OF CARE PLANS

Care plans will be instituted immediately following capping and reclamation, and will continue for a period of 30 years as required by RCRA Sub-title D Sub-Part F 258.61. Leachate collection systems and all leak detection systems will be preserved and maintained throughout this period.

## MONITORING, SAMPLING, REPORTING & MAINTENANCE

During routine monitoring inspections the inspector will look for signs of loss of capping integrity. These will include:

- indications of erosion
- establishment of suitable and protective vegetative cover
- areas of cracking or subsidence
- condition of sampling points
- integrity of storm water control structures
- indications of water collected in leak detection systems
- damages caused by vandalism or inappropriate land use.

A report of the sight visit, observations, and need for corrective actions will be submitted to DMG-MLRO, CDH and EPA. Maintenance will be performed as necessary to insure continual cap integrity. In the event of a failure that has the potential to impact ground or surface water, SGL's corrective action programs would be immediately implemented.

## RECORDATION ON PROPERTY DEEDS OF ACTIVITIES AND LAND USE RESTRICTIONS

After active operations have ceased and closure has been accomplished, SGL shall have recorded on its property deeds for the Druid Mine and Repository, proper notification of the following:

- that mining and repository activities were conducted on this site

- dates of the periods of activities

- reference to a map that locates the areas where the heaps were located, and where permanent survey markers can be found

- any land use restrictions that may be appropriate, such as no excavation or surface disturbance on or within a specified distance from the capped heaps

- where additional information may be obtained (DMG-MLRO, CDH, EPA, Solution Gold, Ltd.)

The intent of SGL is to notify potential future property owners of the condition and potential use of this property. SGL's reclamation plans specify "Wildlife Habitat" as a post closure land use.

## COOPERATIVE PROGRAMS WITH STATE AND FEDERAL AGENCIES

SGL has maintained an active involvement in local communities and with state and federal agencies. SGL's close proximity to the Denver metropolitan area allows the mine to serve as a working laboratory for many study and demonstration projects related to mining and long term behavior of cyanide in the environment.

The Druid Mine is often a site visit for foreign visitors and dignitaries interested in remining and environmental restoration. It also serves as a training ground to acquaint new reclamation specialists and regulators with heap leaching technology and the concept of remining.

## CONCLUSION

Solution Gold, Ltd. has been dedicated to balancing environmental restoration and mining through the concept of remining in previously disturbed areas. They have demonstrated a willpower and way to incorporate the concerns of state and federal regulatory agencies into an enforceable yet flexible permitting process that allows for the utilization of natural resources in the form of extracted metals, while insuring environmental protection and multiple beneficial land uses.

# CRYSTAL HILL MINE: A RECLAMATION CASE HISTORY

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## ABSTRACT

The Crystal Hill Mine is located in the foothills of the San Luis Valley in Saguache County, Colorado, 9 miles north-northwest of LaGarita. The operation consisted of a small 3 acre open cut pit, 24 acres of waste rock dumps, a 30 acre heap leach pad, 10 acres of ponds and plant site, and 6 acres of miscellaneous disturbances. Although small by most precious metal heap leach standards, Crystal Hill was a modern operation which was run by Draco Mines in the mid-80's. In 1989 Crystal Hill was purchased by Amax Gold Inc. (AGI) as part of a larger land package. AGI never intended to operate Crystal Hill as a gold producer; only to reclaim it for bond release. The majority of the operation is located on Bureau of Land Management (BLM) administered lands and was permitted and bonded under the then prevailing rules of the Colorado Mined Land Reclamation Act. Reclamation of the site began on the ground in May 1991 and was completed in November 1991 at a cost of about $4000 per acre. The operation was bonded at approximately $1900 per acre. Bond release inspection is scheduled for 1994.

## INTRODUCTION

### History

Underground mining at Crystal Hill, located 9 miles north-northwest of LaGarita, Saguache County, Colorado, dates to the 1880's. Open pit mining operated in 1950 with 578 ounces of gold recovered. Draco Mines of Tucson reopened the surface mine in June 1984 and operated it until September 1986. During the Draco management of Crystal Hill Mine approximately 27,000 ounces of gold and 40,000 ounces of silver were produced. As part of a multi-state, multiple property acquisition in 1989, AGI obtained responsibility for the reclamation of the minesite, including 60 acres of open pit, haul roads, heap leach pads, plant site, and ponds. Working with the Canon City District and the San Luis Resource Area of the Bureau of Land Management, AGI, through the assistance of AMAX Resource Conservation Company (AMAX) renegotiated the Colorado Mined Land Reclamation Permit to develop a comprehensive reclamation plan for the site. Reclamation field work commenced on site in May 1991 and was completed in November 1991. Groundwater and vegetation monitoring is ongoing with the goal of bond release set for mid-1994.

## Geology and Mining Operations

The Crystal Hill ore body is a typical breccia pipe complex characterized by an average grade of 0.043 ounces of gold per ton of ore. During the years 1984-86 Draco developed an open pit measuring 500' X 200' in plan view and about 300' high to recover ore. Waste rock was deposited in 40-50' lifts at the angle of repose (37 degrees) west, northwest of the pit. Ore was crushed to minus 1.5" on site by two portable crushers. Crushed ore was loaded by CAT 988 loaders into Terex 50-ton trucks and transported 0.7 miles, one-way, to the heap leach pads. Over the life of mine, approximately 825,000 cubic yards of leach grade material were treated with a weak cyanide solution on the 30 acre hypalon-lined pad. Gold laden solutions flowed by gravity in hypalon-lined ditches to the pregnant pond. These solutions were then pumped into the metals precipitation facility (southeast of the leach pads) which employed the zinc cementation method known as the Merrill-Crowe Process. Concentrates were smelted onsite to produce mixed metals dore' bars. Facilities also associated with the mining operations were: (1) shop building at the saddle (present day observation loop road), (2) barren pond southeast of the metals plant and office building, and (3) a make-up water pond and small storage building southeast of the barren pond. During Draco's management of the Crystal Hill Mine approximately 35 workers were employed.

## RECLAMATION

Reclamation of the Crystal Hill Mine began in May 1991 and major earthmoving and seeding were completed in November 1991. The heap leach pad was the largest single area of reclamation effort. The 30 acre pad area was graded to a 3H to 1V slope by utilizing a track-mounted CAT backhoe, rough grading with dozers, followed by topsoiling to a depth of 8 inches with a Terex elevating scraper, construction of erosion control diversion ditches, rock drains, and revegetation. The exposed perimeter portion of the hypalon liner was ripped and pushed back beneath the heap leach material and covered over on the perimeter of the pad. No attempt was made to puncture or tear the liner directly beneath the majority of the pad site. Revegetation consisted of disking with a heavy duty disk, tractor-pulled spreader wagon broadcasting fertilizer and polyacrylamide, and conventional seed drilling with a John Deere seed drill and small tractor. Some isolated steep and remote areas too small for equipment were hand-seeded with a cyclone seeder.

Fertilizer, polyacrylamide, and seeding rates were as follows:

(1) Fertilizer: 200 lbs/acre 16N-16P-16K-20S
(2) Polyacrylamide: 10 lbs/acre Hydrosource
(3) Seeding heaps, office/shop at the saddle, and heap launder:
10 lbs/acre Pure Live Seed drilled May 24-25, 1991

| | |
|---|---|
| Western Wheatgrass, Arriba | 20.6% |
| Indian Ricegrass, Nespar | 18.6 |

| | | |
|---|---|---|
| Smooth Brome, Lincoln | 15.1 | |
| Orchardgrass, Paiute | 14.1 | |
| Timothy | 9.6 | |
| Russian Wildrye, Vinall | 9.4 | |
| Red Top | 4.9 | |
| Yellow Blossom Sweet Clover | 4.8 | |
| Other (inert matter, crops, weeds) | 2.9 | |
| | 100.0% | Total |

(4) Seeding plant site, reclaimed ponds, and ditches consisted of 10 lbs/acre PLS drilled November 12, 1991 using same mix as above.

(5) Seeding terraces, scallop areas of waste rock dumps, ditches from saddle to plant site, access road outslope involved hand seeding with the "Climax Mix":

| | | |
|---|---|---|
| Smooth Brome | 17.8% | |
| Timothy | 12.9 | |
| Red Top | 12.3 | |
| Balboa Rye | 9.9 | |
| White Dutch Clover | 9.0 | |
| Red Fescue | 8.8 | |
| Hard Fescue | 8.8 | |
| Orchardgrass | 8.5 | |
| Meadow Foxtail | 6.8 | |
| Other (inert matter, crops, weeds) | 5.2 | |
| | 100.0% | Total |

(6) Road sideditches from the plant site east to the fenceline were hand seeded November 13, 1992 with 25 lbs of Ephraim Crested Wheatgrass.

At the request of the BLM, reclamation work was also performed on the access road and the waste rock dumps. For visual effects, a 900 foot outslope of the mine access road was reconfigured by eliminating a safety berm and "pulling back" angle of reposed rock materials. Also, for visual effects, a previously reclaimed waste rock bench was "scalloped" by grading out "saucer-shaped" sections fo the sharp outslope edge on the benches. Both of these special areas were hand-seeded as described above.

Although the originally approved reclamation permit did not require any reclamation in the pit area, AMAX did perform some grading with dozers on the pit's base and lower benches to produce a stable, bowl-shaped configuration. Because this pit material consisted entirely of broken rocks, no seeding was attempted.

**Bonding and Reclamation Costs**

The Colorado Division of Minerals and Geology holds a $137,000 bond on Crystal Hill's reclamation. Using mine maps and aerial photos, the total area affected by mining operations was 73 acres, of which 61 acres are now considered revegetated (pit and waste rock dump angle of repose rock slopes are not revegetated). Calculating the bonded amount per acre from the above figures yields a value of $1,877. This compares with approximately $4,000 per acre incurred by AMAX in reclaiming Crystal Hill Mine.

**Monitoring and Bond Release**

The BLM has established several vegetation transects on the reclaimed areas at Crystal Hill, as well as on surrounding undisturbed land. Recently, the BLM has utilized the Crystal Hill reclamation effort in training classes for "Holistic Resource Management (HRM)," a concept in range resource management beyond the scope of this paper. Utilizing one of the evaluation procedures of HRM, an extensive one-day field class was conducted at Crystal Hill on June 30, 1993. The field class consisted of several groups of ranchers, government range scientists, reclamation specialists, and one of the present authors. Each group monitored the condition of the soil and vegetation on a given transect using the HRM method. Briefly, the method involved using a sampling dart thrown in a random fashion on a pre-determined permanent transect which will be used in future evaluations. The randomly thrown dart defines a point of measurement where soil/plant/ecosystem conditions are evaluated. For purposes of this paper, one can examine the ground cover and species present on three reclaimed transects compared to an undisturbed (control) transect in order to evaluate the reclamation success. Please note that transect measurements occurred only 7.5 months after seeding transect #1, barely 13 months after seeding transect #4, and approximately 6 years after seeding transect #2. Transect #3 is located on the undisturbed site. Table 1 provides the basic data from each of the transects.

**TABLE 1**

**TRANSECT MEASUREMENTS AT CRYSTAL HILL MINE, JUNE 30, 1993, USING METHODS OF HOLISTIC RESOURCE MANAGEMENT**

| PARAMETER | | TRANSECT NUMBER | | | |
|---|---|---|---|---|---|
| | | 1 Plant site Nov 91 | 2 Saddle area 1987 | 3 Undisturbed | 4 Heap leach May 91 |
| Cover; | Bare | 61% | 14% | 46% | 6% |
| | Litter 1 | 28 | 43 | 14 | 65 |
| | Litter 2 | 0 | 41 | 17 | 0 |
| | Rocks | 0 | 1 | 2 | 12 |
| | Basal Plant | 11 | 1 | 21 | 15 |
| Species Present | | W. Wheat<br>Sm. Brome<br>SIHY<br>Orch Grass<br>Wild Rye<br>Kochia<br>Thistle | W. Wheat<br>Cr. Wheat<br>Ryegrass<br>Wormwood<br>Sm. Brome<br>Int. Wheat | Slim Muhly<br>Locoweed<br>Sage<br>Buckwheat<br>Junegrass<br>Hymenoxis<br>Bl. Gramma<br>Lichen<br>Pkly. Pear<br>Daisy<br>Bluebells | Cr. Wheat<br>Sm. Brome<br>Wild Rye<br>Ind. Ricegr<br>SIHY<br>Kochia<br>Thistle |
| Distance Between Perennial Plants | | 8.05" | 3.3" | 1.46" | 3.25" |
| Predominant Age; | | | | | |
| | Seedling | 6% | 0% | 14% | 0% |
| | Young | 94 | 100 | 8 | 0 |
| | Mature | 0 | 0 | 78 | 91 |
| | Decadent | 0 | 0 | 0 | 3 |
| | Resprout | 0 | 0 | 0 | 0 |
| Capping of Soil; | | | | | |
| | Mature | 0% | 0% | 2% | 0% |
| | Immature | 78 | 50 | 0 | 0 |
| | Recent | 0 | 0 | 37 | 9 |
| | Broken | 0 | 0 | 26 | 0 |
| | Covered | 22 | 50 | 35 | 91 |

Notes: Litter 1 is a new, undecayed layer of litter (leaves, sticks, and dung). Litter 2 indicates deeper litter that is decaying and being incorporated into the soil. Basal refers to basal plant cover-the area actually covered by the root crowns or stems of perennial plants (ref: Bingham and Savory, 1990, p. 109). Plants identified by common name for simplicity. SIHY = bottlebrush squirreltail.

Utilizing the information from Table 1, combining it with additional monitoring in June and visual inspections of the site, the Crystal Hill Mine reclaimed areas should be ready for bond release in the summer of 1994. After the Colorado Division of Minerals and Geology releases the bond, most of the site can be managed for wildlife or grazing by the Bureau of Land Management.

## OTHER ENVIRONMENTAL CONCERNS

A variety of liquid and solid materials stored onsite at Crystal Hill presented a disposal problem, which was handled as follows. Flue dust residues, slag, and laboratory cupels were shipped to AGI's Sleeper Mine in Nevada for precious metals recovery. Fourteen barrels (55 gallons each) of unused Nalco flocculants and dispersants were shipped to USPCI's Grassy Mountain, Utah disposal facility at a cost of about $10,000. About 2.5 million gallons of water in the process ponds were used as irrigation water and sprayed on the revegetated heap leach pad.

One ground water monitoring well exists down-gradient from the reclaimed heap and plant site. This well has been monitored by AMAX since October 1990. Only on four occasions since 1990 has there been enough water in the well to sample. Metals content and cyanide concentrations are within the acceptable range according to Colorado Agricultural Standards. No acid rock drainage has been observed onsite, and in fact, the pH of water in the shallow well ranges between 7 - 7.9.

## FUTURE PLANS

In addition to wildlife habitat and grazing, the Crystal Hill Mine reclamation has benefit to the BLM as part of its Backcountry Byway Program. Realizing this additional recreational land use potential, AMAX and the BLM entered into a Memorandum of Understanding in June of 1991 to showcase Crystal Hill as an example of successful reclamation and cooperation between industry and government. As soon as bond release is achieved, the site can be developed for inclusion in the Backcountry Byways Program, and more formal site tours and public visits may begin.

## SUMMARY

The Crystal Hill Mine Reclamation Project has demonstrated that heap leach gold operations at high altitudes can be returned to viable land uses, and that environmentally sound reclamation goals can be achieved through cooperation between the mining industry, federal land management agencies, and state regulatory agencies.

## ACKNOWLEDGEMENTS

Although not directly mentioned in the paper, several agencies, personnel, and contractors have been referenced. Foremost in the accomplishment of the reclamation at Crystal Hill are Mr. Ken Goodrow of the Alamosa Office of BLM and Mr. Doug Kaess of Kaess Contracting of Salida. These men worked diligently with AMAX personnel to solve problems in the field as needed. Additionally, during the field phase and subsequent monitoring, the former Colorado Mined Land Reclamation Division and the present Colorado Division of Minerals and Geology provided the following individuals who have given constructive suggestions and advice: Steve Renner, Allen Sorenson, James Dillie, and Bob Oswald.

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# DEVELOPMENT OF PLANT MATERIALS FOR NATIONAL PARKS

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## Introduction

The National Park System of the United States comprises 356 areas covering almost 80 million acres in 49 states, the District of Columbia, America Samoa, Guam, Puerto Rico, Saipan, and the Virgin Islands. These areas are of such national significance as to be afforded protection by various acts of Congress.

After the establishment of Yellowstone National Park on March 18, 1872, a movement began that has resulted in the preservation of natural, cultural, or historical resources for public enjoyment.

The diversity of the National Park system is reflected in the variety of the park unit titles. These titles are usually descriptive: seashore, lakeshore, historic site, battlefield, and recreation area, for example. The designations have not always been used consistently, but they reflect certain precedents that have been followed by Congress and different management policies. The parks have traditionally been reserved for unique spectacular natural areas with a wide variety of feature.

All these areas are managed by the National Park Service in accordance to specific legislative mandates set forth by Congress. Key management requirements for all park units are that they must provide for the public use in such a way that will leave their resources "unimpaired for the enjoyment of future generations."

Achieving this management objective of preserving resources while providing for public enjoyment is a delicate balancing act for the park administrator. Revegetation and reclamation activities present special problems when trying to maintain native plant populations in areas impacted by visitor facilities.

The National Park Service policy seeks to perpetuate native plant life as part of the natural ecosystems. Preservation of native plant genetic resources with their natural ecosystem is a high priority in the National Park Service. The National Parks recognize that historical and cultural landscapes are important and worth protecting.

To the extent possible, plantings in park units consist of species that are native to the park or that are historically appropriate for the event commemorated.

## Cooperative Program

To this end a cooperative agreement between the National Park Service and the Soil Conservation Service was developed in 1989. This cooperative Plant Materials Program seeks to draw upon the strengths of the two federal agencies in the development, testing, and establishment of native species for disturbed sites within National Park Service units.

The National Park Service and Soil Conservation Service plant materials program is a nationwide program that can help provide genetic strains of plant materials that are native to individual parks. By working with plant material centers located in the most appropriate climate and topographic region, each park has a cost-effective means for evaluating plant materials and meeting vegetation resource management needs.

The plant materials program between the two agencies initial focused on development of native plants for the revegetation of areas disturbed by road construction. Reconstruction of park roads is handled through monies allocated the National Park Service from the National Highway Trust Fund. The National Park Service is allocated funds for construction or repair of approximately 200 miles of road out of the 4800 miles of paved roads contained within the park system.

The park roads program between the National Park Service and the Federal Highway Administration is the ideal starting point for the plant material program. Since advanced scheduling and funding appropriations are critical to the timely success of this program, the park roads program assures that all plant materials projects will be adequately funded and that sufficient lead time will be available to complete plant production schedules.

Park Service native plant needs range from cool to warm season grasses, to a variety of shrubs and half shrubs, to trees extending from the Pacific Northwest to the forests of the deep south. Basic information about the development and growth habits of these plants is presently lacking. Specialized propagation and revegetation techniques that are needed are not always available.

## Soil Conservation Service Plant Material Centers

The Soil Conservation Service has established 27 Plant Materials Centers throughout the United States to develop plants and technology. Networking together, centers accomplish national and local objectives. They are ecologically located to provide service to a given region.

Each center has facilities and specialized equipment to handle a variety of native seed and plants operations needed in plant propagation and testing.

The centers cooperate and use expertise developed by Agricultural Research Service, Forest Service, State Experiment Stations, and other research institutions. The Soil Conservation Service Plant Materials program maintains a close working relation with seed growers and the commercial seed industry across the United States.

## Program Activities

The National Park Service and Soil Conservation Service cooperative plant materials program can generally be grouped into four main activities:

1. Seeds are collected within the parks to preserve the unique characteristics of the original plant genetic diversity.

2. Seed and plants are grown and reproduced at centers located with approximately the same topography and climatic conditions.

3. New technology is often needed to reproduce and grow these plants. New techniques are also tested to successfully use the new species.

4. And finally quality seed of known genetics along with the needed technology for establishment are returned to the park for use by resource managers.

## Summary

Presently, the National Park Service and the Soil Conservation Service have developed plant materials agreements for 42 park projects with an estimated 400 new park indigenous ecotype. The majority of these plants are not be available to the National Park Service through other sources. Basic information about the development and growth habits of these plants is presently lacking. The plant program and information generated over the coming years will add to the information base and will help develop park indigenous species that are locally adaptive. In addition, this program will provide the needed reclamation technologies to develop successful revegetation techniques in reestablishing these native park species. The National Park Service feels that its association with the Soil Conservation Service will be most helpful in the understanding and development of native plants.

# *KIWI GREEN:* SOIL MOISTURE RETENTION VIA USE OF A SEMIPERMEABLE MEMBRANE TO ENHANCE PLANT GROWTH

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## ABSTRACT

A key limiting factor in efforts to establish or sustain healthy growth of young plants is the absence of continuously available moisture. While mature plants are better able to withstand periods without water, absence of moisture still causes stress, which in turn raises the plant's susceptibility to disease and negatively impacts crop yields.

To alleviate this problem, Quattro Environmental in conjunction with American Colloid Company is utilizing the properties of a semipermeable membrane to inhibit evaporation of moisture from the soil surface. By effectively increasing the volume of water available to the plant root structure, we are able to minimize the degree of moisture stress experienced by plants in arid and semi-arid climates. A corollary benefit would be to sustain any given prior level of plant growth or crop yield with less water.

## INTRODUCTION

Lack of sufficient moisture is a key limiting factor in efforts to establish vegetation on disturbed sites. Throughout the Rocky Mountain States region, the problem is not to receive sufficient moisture to trigger germination of the native shrubs and grasses seeded pursuant to permit mandates. At some stage, whether it be spring snow melt or spring rain showers, sufficient moisture will be available to germinate seeds planted in the fall and early spring. Instead, the problem lies in not receiving sufficient subsequent moisture to nurse the young seedlings to a level of maturity where they can withstand the heat and/or dry conditions of summer. This problem is compounded for those undertaking reclamation seeding in late spring.

## THE *KIWI GREEN* Moisture Membrane

The function of the 2-component ***KIWI GREEN*** ***moisture membrane*** formulation is to facilitate plant growth by:

(1) minimizing stress from lack of moisture
(2) facilitating access to nutrients in the soil, and
(3) stabilizing the soil surface to counter wind and water erosion.

**Moisture Retention:**

At the heart of the ***Kiwi Green*** ***moisture membrane*** formulation lies a water-retaining, evaporation-suppressing inorganic semipermeable membrane. This semipermeable membrane operates to cause minimal interference with the infiltration rate of rainfall/irrigation *into* the soil while the disordered membrane "bridging" between soil particles presents a vapor barrier to moisture *leaving* the soil surface. The semipermeable membrane is non-phytotoxic to plant life, non-UV sensitive and biodegrades to plant food over a lifetime of three to five years.

By effectively increasing the volume of water available to the plant root structure, we can minimize the degree of stress experienced by plants in arid and semi-arid climates. The corollary benefit is to sustain any given prior level of plant growth or crop yield with less water.

The ***Kiwi Green*** ***moisture membrane*** is not a polymer, a surfactant or a fertilizer. It contains the following minimum elements:

| | | | |
|---|---|---|---|
| Organic Matter | 59.0% | Organic Nitrogen | 1.9% |
| Sulphate | 20.3% | Iron | 9.0% |
| Potassium | 3.8% | Chloride | 1.3% |
| Ammonium | 0.7% | | |

Unlike the action of a polymer, the ***Kiwi Green*** ***moisture membrane*** does not rely on absorbing water (which subsequently requires the plant to expend energy in an effort to retrieve that same water.) The water molecules attach themselves in and about the membrane. The crystal structure of the membrane forms a molecular cage.(Figure 1) The repulsion of the metals in the molecule allows this cube-shaped structure to move water in and out, but it does not allow ions to be transported in and out, i.e., semi-permeable membrane. Statistically there is a missing metal in the center of the cube which forms a hydrogen bonding structure and allows a water molecule to be stored there which is the key to the water retention.

There's a lattice work formed by these crystalline molecules with the soil particles that makes this membrane so effective. The crystals bridge (see Figure 2) some of the gaps between the soil particles providing an evaporation barrier in the top inch of soil. This traps the moisture deep below the membranes surface, yet, when water does become available it can penetrate the barrier since the membrane is not continuous and, infiltrate for later use. This deep moisture retention encourages a deep and healthy root system.

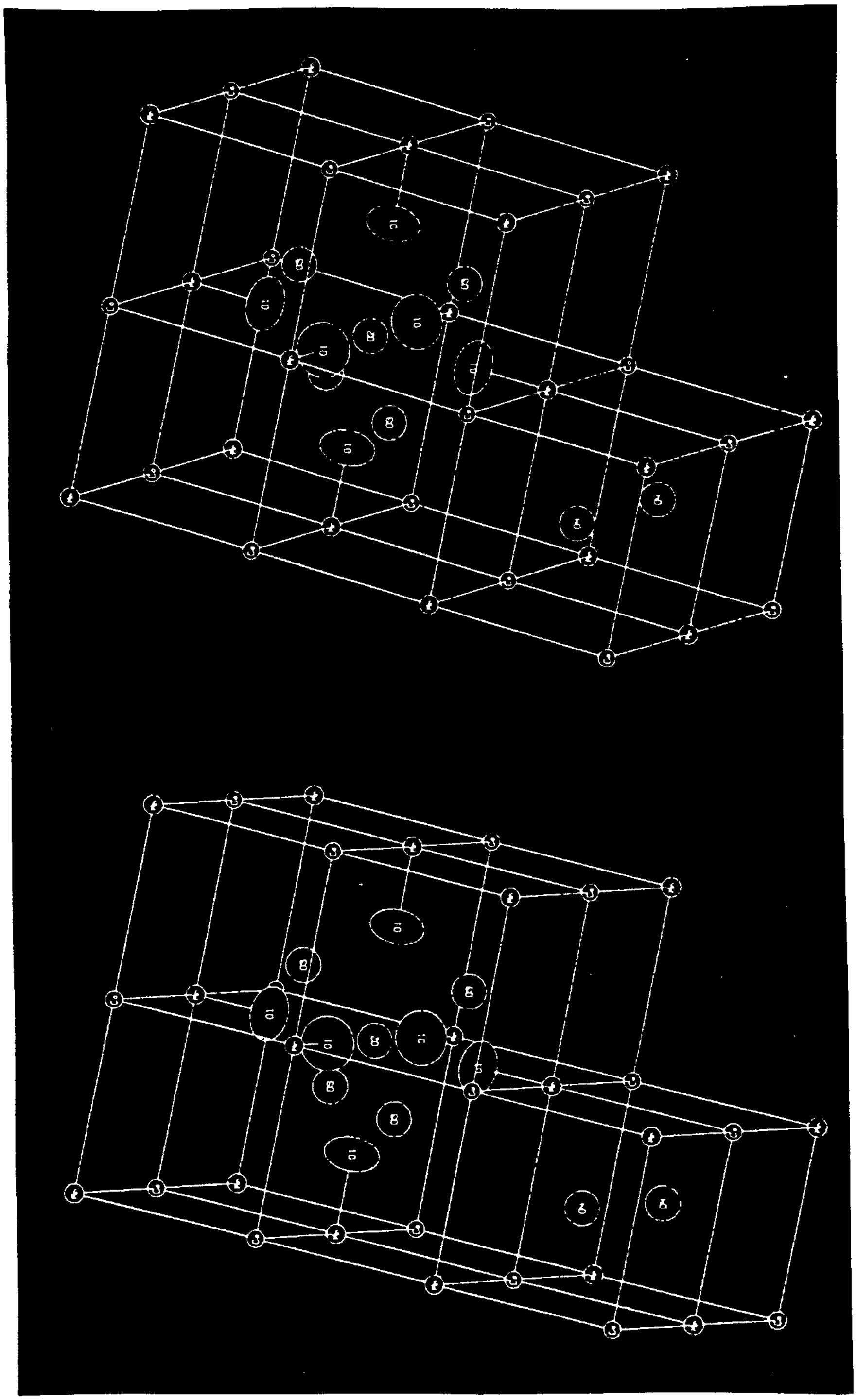

FIGURE 1: Crystalline Molecular Structure of Membrane

# Semi-Permeable Membrane

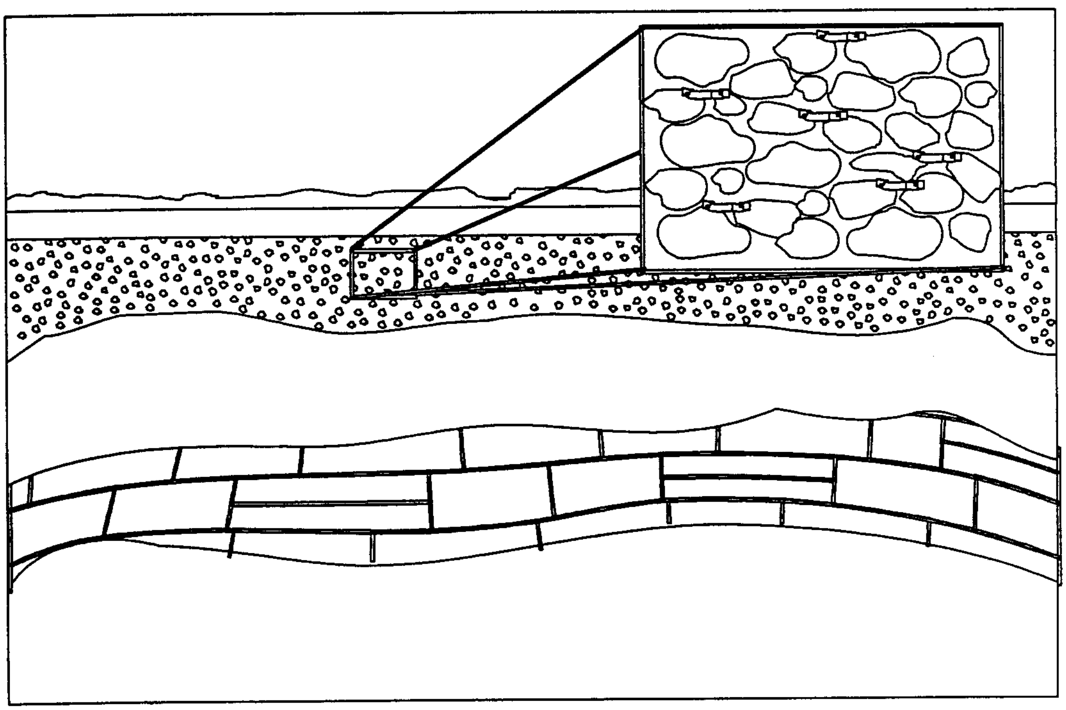

FIGURE 2: Membrane Crystals Bridge Gaps Between Soil Particles

Field trials supported by laboratory research are being conducted to test the moisture retaining performance of the "moisture membrane" in at least three representative climate zones of the western United States. These climate zones encompassing regions influenced by the Pacific Ocean, by the continental air mass and by elevation. Consequently, the test sites will be subjected to a broad spectrum of temperature, levels of rainfall and soil conditions. A number of test sites will benefit from controlled irrigation.

This research will expand our understanding of the membrane's operation, and conceivably will identify under what conditions the membrane does not effectively "stretch out" available moisture to the plant. While an emphasis has been placed on reclamation seeding applications, turf and agricultural applications also are being pursued.

**Nutrient Uptake Enhancement:**

The second component in the ***Kiwi Green*** **moisture membrane** formulation is a humic acid biostimulant derived from leonardite shale. Humic acid has demonstrated a direct positive effect on nutrient uptake, root length and mass, turf quality and color. It is responsible for several chemical activities in the soil including the increased uptake of micronutrients or the stimulation of plant growth through its effect on metabolism and the improvement of basic soil properties such as aggregation, aeration, permeability and water holding capacity.

Figure 3 is an idealized structure of humic acid. This material has a large number of carboxylic functional groups that act as chelating agents for metals. Humic acid's chelating activities can take excess metal cations out of solution and store them for later use by plants. Because of this, it prevents buildup of micronutrients in the soil and at the same time releases them in suitable amounts to the plants. Figure 4 demonstrates the ability of humic acid to improve uptake of micronutrients in slash pine callus culture. Data from Figure 4 is also tabulated in Table 1.

Table 1. Radiation Counts of P, K, Ca and S in Callus Cells in the Third Subculture as Determined by EDAX (Average of six cells).

| Treatment | **Phosphorus** ---Counts/100s--- | **Potassium** ---Counts/100s--- | **Calcium** ---Counts/100s--- | **Sulfur** ---Counts/100s--- |
|---|---|---|---|---|
| Control | 52 | 113 | 48 | 47 |
| 160 μg/ml | 307 | 1280 | 768 | 384 |

The ability of humic acid to complex metals also can have a very positive secondary effect upon phosphate availability by complexing calcium that tends to hold phosphate in a very insoluble form in the soil. Figure 5 illustrates how humic acid increases phosphate release from a Bauxite soil as well as common chemical chelating agents.

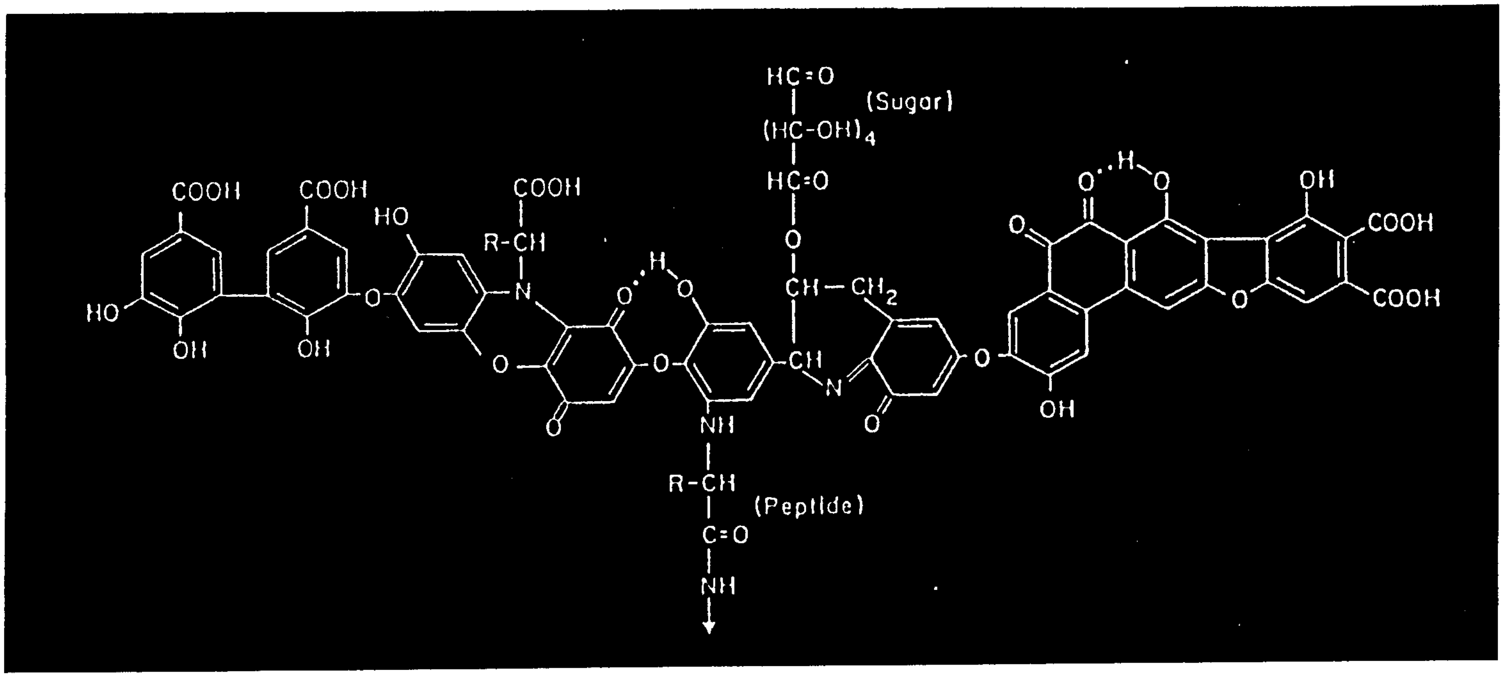


FIGURE 3: Idealized Molecular Structure of Humic Acid

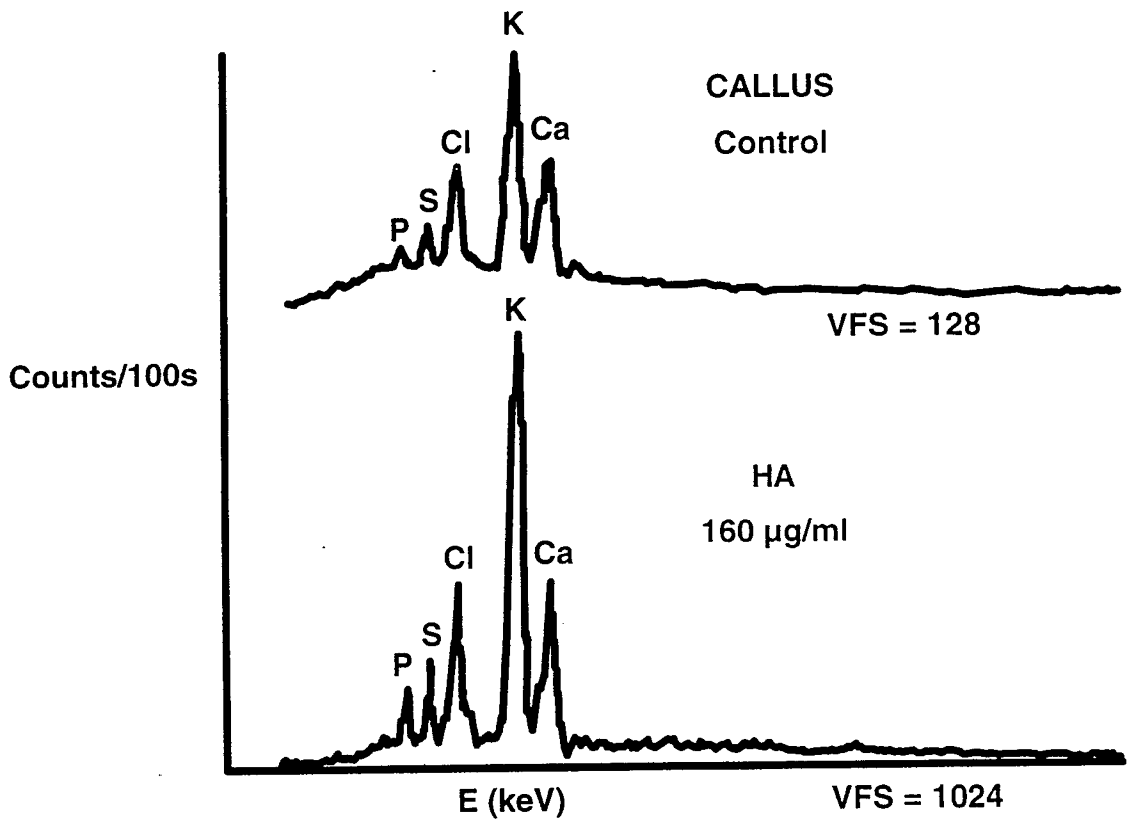


FIGURE 4: Improved Uptake of Micronutrients in Slash Pine Callus Culture

## Cumulative Release of Phosphate from the Brown Bauxite Soil by the Action of Various Organic Reagents

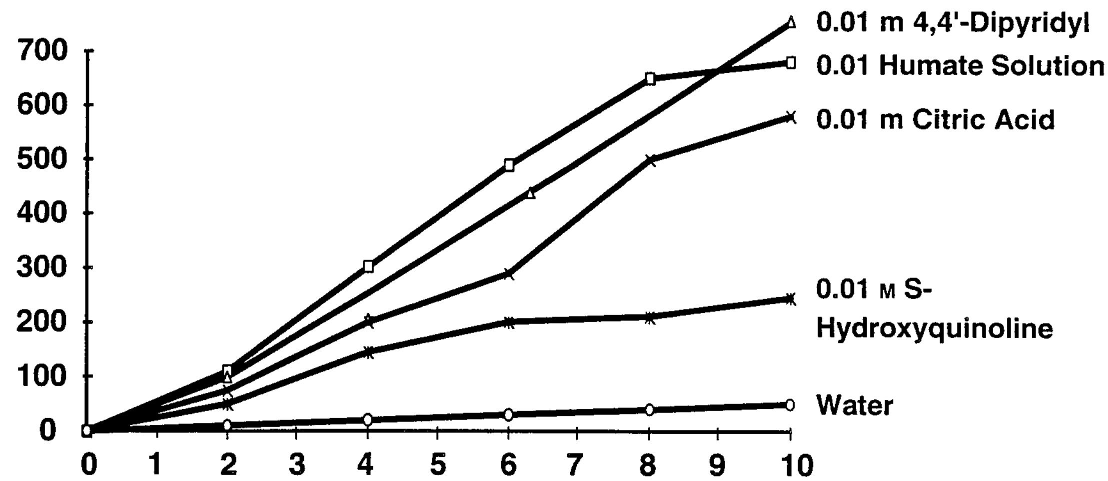


FIGURE 5: Humic Acid Increases Phosphate Release

**Soil Stabilization:**

The lattice-like, cubic structure of the ***Kiwi Green*** **moisture membrane** was first observed to have the capability to stabilize soil in the course of a reclamation seeding trial on drainage channel slopes at Denver International Airport. This capability of the membrane to bind soil grains together has since been enhanced by the optional addition of a montmorillonite clay third component to the ***Kiwi Green*** **moisture membrane**. Available under the tradename ***Kiwi Green Plus Tack***, this 3-component alternate formulation is currently being utilized to tackify seeds to the soil surface and provide immediate erosion control protection on slopes until such time as the moisture and nutrient-assisted plant growth is sufficiently established to provide long term soil stabilization. This tackifier component is not subject to biodegradation or ultraviolet light destruction.

## SUMMARY

Quattro Environmental, Inc. in conjunction with American Colloid Company are utilizing the properties of a semi-permeable membrane to inhibit evaporation of moisture from the soil in the product ***Kiwi Green*** **moisture membrane** and then adding a tackifier to ***Kiwi Green Plus Tack*** to aid in soil stabilization. These products are designed for arid and semi-arid climates to:

a) minimize stress from lack of moisture on young seedlings and mature plants via a water-retaining, evaporation-suppressing inorganic semipermeable membrane formed by unique crystalline molecules;
b) facilitate access to nutrients in the soil with the addition of humic acid which demonstrates a direct positive effect on nutrient uptake, root length and mass, turf quality and color as well as improvement of basic soil properties; tests have proven humic acid's chelating activities are valuable in micronutrient uptake and storage;
c) stabilize the soil surface with the lattice-like cubic structure of the ***Kiwi Green*** **moisture membrane** by binding soil grains and by the addition of montmorillonite clay to counter wind and water erosion.

Most of the emphasis has been placed on ***Kiwi Green*** **moisture membrane's** reclamation seeding applications, yet, turf and agricultural applications are also being pursued. Field trials now in progress at various Western locations are testing the moisture retention performance of the membrane and are displaying promising results.

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# A QUANTUM JUMP IN MONITORING SOIL CHEMISTRY

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## ABSTRACT

Techniques for monitoring soil chemistry are labor intensive and laboratory extraction methods do not mimic the mechanisms of ion bioavailability. First, all updates require either a new soil sample or enough soil water to extract a sample from a well. Then, soil testing chemical-extraction procedures provide only a rough "index" of elemental bioavailability. Furthermore, the utility of these indices varies for each element and soil thus presenting a risk of not detecting a deficient plant nutrient or pollutant overloads for some soils.

A new resin capsule methodology provides an ion extraction process that more closely simulates elemental availability to plants. Repeated in situ sampling of the same point in a soil allows capsules to respond to the same soil variables of temperature, moisture, nutrient solubility, and transport that regulate how much of each element plants can take up. A quantitative analysis for most ions of interest is obtained from a single extraction procedure. This resin capsule also works on a saturated paste made from soil samples taken to a laboratory for analysis. An added benefit is that field and laboratory monitoring costs are lower with resin methods than for traditional soil testing methods.

## INTRODUCTION

Sometimes it is useful for a land manager to use soil tests to evaluate the adequacy of essential nutrients for plant growth or to detect toxic concentrations of other elements. Also as part of a long term soil monitoring program, these tests provide a way to follow the movement and concentration of chemical elements. Monitoring soil chemistry has two steps 1) sample collection and 2) laboratory analysis with less than ideal methods and results for each.

Traditionally, sample collection has relied on 1) hard, time consuming work to obtain soil for a laboratory analysis, which destroys the site for the next follow-up, or 2) wells that provide repeat samples but only work when there is adequate soil moisture. Also, wells are expensive to install and it takes a lot of time to ensure that a representative sample is collected

In the laboratory, the best chemical-extraction procedures can only provide an "index" of elemental bioavailability. This is because nutrient availability under natural conditions, varies among soils due to interacting chemical, physical, and biological processes (Binkley and Vitousek 1989, Trlica and Brown 1992). The result is that traditional soil testing methods create an uncertainty about whether the elements are available in amounts that will benefit--or at least not harm--biosphere organisms.

An ideal soil monitoring and laboratory analysis process would integrate the effects of natural processes without destroying the very site that is being investigated. Using resin capsules for repeated in situ sampling of the same point in the soil coupled with a relatively inexpensive laboratory analytical process goes a long way toward meeting the criteria for an ideal process.

## THE SOIL ANALYSIS CONUNDRUM

Trying to find a satisfactory soil analysis technique has been discussed in laboratories and publications for decades. Skogley (in press) observed that a debate about the accuracy and standardization of soil testing for agronomic purposes was going on at the Soil Science Society of America (SSSA) meetings in 1954 and continued to be addressed at the 1993 meetings.

A major problem is that analytical procedures do not adequately represent the availability of elements to biosphere organisms. Recently, Kelly (1993) refreshed observations made by Barber (1984) and Bartlett and James (1980) that laboratory conditions do not represent conditions for plant nutrient uptake in a natural setting such as forests.

Natural resource managers need a kinder, gentler soil testing method that will better emulate natural environmental process. This is important because the basis for standards of adequacy or toxicity of soil elements is their availability for uptake by, and subsequent effects on, biosphere organisms.

**The Ideal Soil Test**

Skogley (in press) lists the following criteria for an ideal soil test:

1. Extract all nutrients simultaneously (universal).
2. Work on all kinds of soils (standardizable).
3. Be accurate.
4. Be simple.
5. Be cost-effective.
6. Be rapid.
7. Be sensitive to mechanisms that control plant nutrient availability (ion diffusion).

**Resin Extraction**

Ion-exchange resins have been available since the 1940's and offer a way to meet most of the ideal soil test requirements.

Mechanistic relationship to nutrient availability is inherent in encapsulated ion exchange resins. Each capsule is spherical, with a rigid, porous surface that has a uniform surface area. These properties provide a system where there is a known contact area between the soil and adsorber and that remains constant during the extraction period. The capsule contains enough resin to act as an infinite ion "sink" for long periods in most media.

Universal extraction occurs because the mixture of cation and anion resins is initially saturated with $H^+$ and $OH^-$ ions. This ensures that the resins have a greater affinity for other ions in the surrounding medium and will function as an extractant during the testing period.

Standardization tests indicate that this technology will function in virtually all kinds of soils. There is no need to change the laboratory extraction process when testing different kinds of soils.

Accuracy is based on a sensitivity to mechanisms that control nutrient availability. Several sample handling steps (for example, drying and grinding) that alter nutrient extractability are eliminated.

Simplicity is inherent by the very few steps needed to obtain analytical results.

Cost-effectiveness is achieved by eliminating many labor-, chemical-, space-, labware-, and energy-intensive steps in the analytical process.

Rapidity may be compromised for some because an extraction period requires several days. This one exception is due to being sensitive to the same mechanisms that control plant nutrient availability which does compromise the ideal of being rapid.

## RESIN CAPSULES

A UNIBEST resin capsule adsorbs soil chemical elements from a laboratory saturated paste or in situ under field conditions. The amount of each ion accumulated by the resin capsule during a specific time depends on; 1) the initial soil solution concentration of each ion, 2) the diffusion rate of each ion through the soil, and 3) the capsule surface area in contact with the soil. Thus, at the end of an accumulation period the amount of each ion in a resin capsule is a measure of its "bioavailability" for the conditions during that period.

### Capsule Processes

Each resin capsule has thousands of resin beads charged with $H^+$ and $OH^-$ ions (deionized water) within a porous fabric membrane. The 2-cm diameter capsules are precisely made and have a constant surface area. In a soil the capsule adsorbs chemical elements through an ion exchange process as illustrated in Figure 1. Ion exchange occurs very close to the capsule surface in physical terms but on a chemical scale the distances are very large.

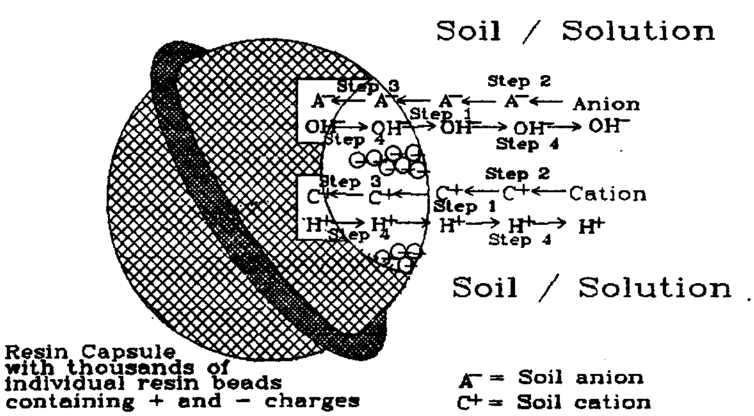


Figure 1. Drawing of a resin capsule illustrating how it works in the soil.

**Step 1** takes place across the capsule membrane when a capsule first comes contacts the soil. The resins adsorb both + and - ions from the soil solution in exchange for $H^+$ or $OH^-$ ions from the capsule. This step in the process is relatively rapid and occurs because the resins have a greater affinity for all other ions than those originally present on the resin. In chemical terms, the resins act as a "strong acid" and "strong base," thus giving up their $H^+$ or $OH^-$ ions in favor of other ions in the soil solution.

Because exchange reactions occur independently for each soil solution ion, the resin will simultaneously adsorb all types of available ions. The quantity of each ion adsorbed by the resin during the first phase of accumulation depends on the soil solution concentration of each ion when the capsule is placed in the soil.

This initial ion exchange reaction sets the stage for the following steps. The soil solution concentration of each ion at the resin-soil interface decreases relative to concentrations in the bulk soil solution creating a "diffusion gradient".

**Step 2** occurs because a diffusion gradient causes soil solution ions to move toward the resin capsule from ever-increasing distances in the soil. When these ions reach the resin surface they are also exchanged for $H^+$ or $OH^-$ ions. In this way, the resin capsule continues to function as a "sink," similar to a plant root taking up nutrient ions.

Soil properties regulate the rate of ion diffusion through a soil. These properties are different for each soil and each ion. This is the slowest part of the process, or the "rate-limiting" step. Thus, soil properties that regulate ion diffusion influence the amount of each ion accumulated by the resin during a given time.

For the capsule to provide accurate results, it must be in place long enough for the effects of diffusion to be expressed. This will usually require one to four or more days, depending on conditions for diffusion.

**Step 3** occurs within the capsule. Accumulation of specific soil ions in the resin at the capsule-soil interface creates a diffusion gradient within the resin capsule. These ions then diffuse toward the center of the capsule where the specific ion concentration is low, essentially zero, initially. The rate of ion diffusion through the resin capsule is much faster than ion diffusion through the soil, so this step in the process is not rate-limiting.

**Step 4** is a continuous process because electrical neutrality must be maintained in all parts of the system, as required by Mother Nature. The resin counterions, $H^+$ and $OH^-$, diffuse outward as other ions diffuse inward. Because most soils have more cations than anions that can diffuse to a sink, more $H^+$ than $OH^-$ ends up in the soil surrounding a resin capsule. This causes a decrease in soil pH near the capsule, which can also increase the solubility of some elements. Again, this is like a plant root function.

**Predicting Plant Nutrient Uptake**

Comparing resin capsule soil analysis with standard soil testing shows that the results, as expressed by the shape of the graph curves, are very similar. For example, in a greenhouse study with Sordan grass (Bauder, et al. 1992), fertilizer response to added phosphorus on three low-P soils was compared using resin capsule soil analysis and Olsen-P extraction.

The following graphs are from the original regression equations for each soil. They show the relationships between plant P uptake and plant dry weights for each testing method. Resin capsules were in the soil for four days before analysis. Analytical results for resin capsules are reported as micrograms per capsule. This is because the lab analysis is performed on capsules that have previously adsorbed ions from a surrounding soil. In figure 2, the combined resin capsule family of curves are closer together ($R^2$=0.82) than the combined curves in figure 3 ($R^2$=0.76) for the Olsen-P soil test. This indicates that the capsules may be better than the Olsen-P test at predicting P uptake from different soils by Sordan.

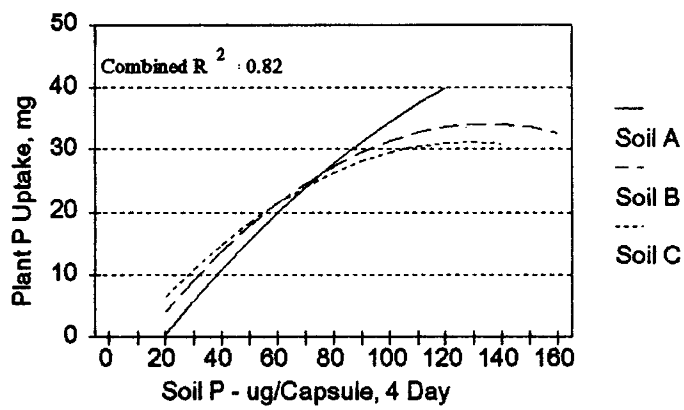


Figure 2. Plant P uptake by Sordan compared to a resin capsule soil analysis.

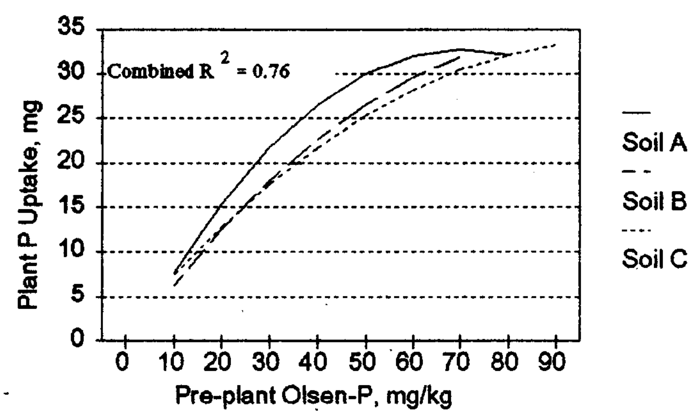


Figure 3. Plant P uptake by Sordan compared to an Olsen-P soil test.

Figures 4 and 5 show the relationship between Sordan dry weight and each soil testing method. The combined $R^2 = 0.72$ for the capsule family of curves is lower than the $R^2 = 0.76$ from the Olsen-P soil test.

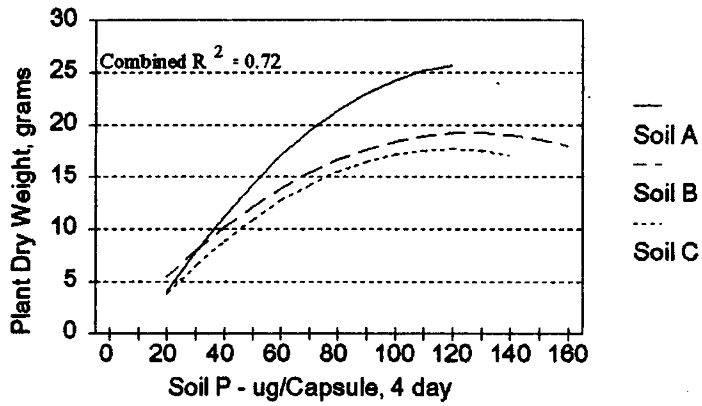


Figure 4. Sordan dry weight compared to a resin capsule soil analysis.

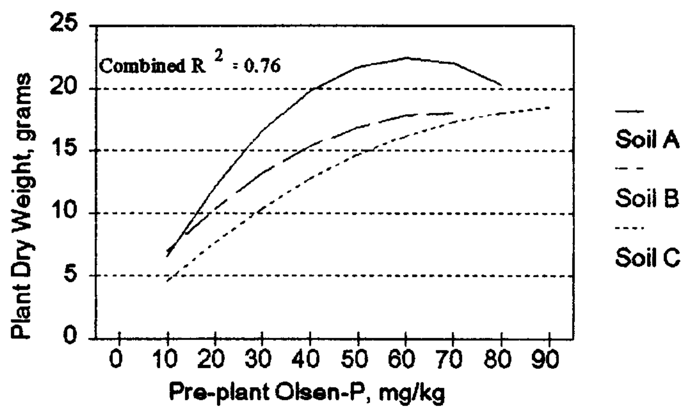


Figure 5. Sordan dry weight compared to an Olsen-P soil test.

Perhaps, with additional correlation work, individual plant species and communities could be indexed with capsules for nutrients or tolerance to toxic elements. If successful, this could provide another relatively inexpensive analytical tool for characterizing land capability.

## IN SITU MONITORING

Several studies have demonstrated that resin capsules provide a good way to evaluate plant availability of soil elements. The modified "solid-state-extraction" process closely simulates elemental availability to plants (Skogley 1992, Binkley and Matson 1983, Binkley 1984). When placed in situ (Montagne, et al. 1992), showed that capsules responded to the same soil variables of temperature (Yang, et al. 1991a, 1992), moisture (Li, et al. 1993), nutrient solubility (Yang and Skogley 1992), and transport (Li, et al. 1993) that regulate (Yang, et al. 1990a, 1990b, 1991a, 1991b) how much of each element plants can take up.

**In Situ Response**

Monitoring solute movement traditionally requires porous ceramic cups in the soil at various depths. These are periodically vacuum pumped, often for several hours, to extract a soil solution sample for laboratory analysis. With a soil access tube, resin capsules can be used to monitor inorganic and organic solute movement over time.

Figure 6 (Skogley 1992) shows the results of a laboratory column study to compare the resin capsule methods with vacuum extraction to detect Br leaching under unsaturated water flow. Detailed information about the breakthrough curve was obtained by frequent capsule changes. These curves illustrate that using capsules in situ provides a good monitoring system for transient events.

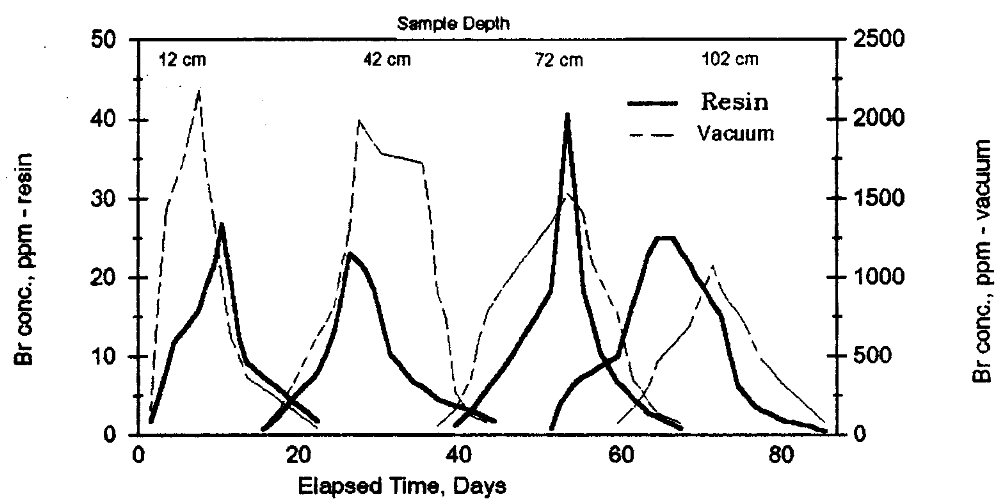


Figure 6. Comparison of Br leaching under unsaturated water flow as measured by resin capsule methodology and vacuum extraction.

**Soil Access**

Soil access tubes are designed for long-term monitoring. These tubes (Figure 7) have a casing with a cap and a capsule carrier assembly that fits inside the casing. Except for the stainless steel spring, all components are made from PVC plastic to minimize possible capsule contamination when sampling for inorganic elements and most organic materials.

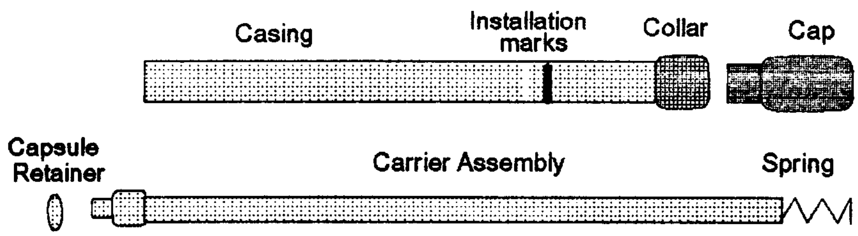


Figure 7. Soil access tube components.

The resin capsule is firmly held by a retainer so that one-half of the capsule surface is in contact with the soil. The retainer is easily removed for replacing the capsules for continuous monitoring. At the top of the carrier assembly a stainless steel spring provides a constant pressure to keep the capsule in contact with the soil. Installing the access tube at a $60^0$ angle to the soil surface places a capsule at the vertical depth marked on the tube.

## Access Tube Installation

Soil access tubes are installed at a $60^0$ angle to the soil surface (a $30^0$ angle from vertical). The reasons for installing tubes at an angle (Figure 8) are:

1. A vertical column of soil can be sampled at several places below a surface point.
2. Water that might run down a vertical tube will wick into the soil along the underside of an angled tube. If water moved along the tube to the capsule:
   A) The capsule could pick up a different chemistry than found in the bulk soil.
   B) An "un-natural" condition would occur if the sample site became wetter than the surrounding soil.
3. Roots will grow vertically into the soil instead of along the access tube.

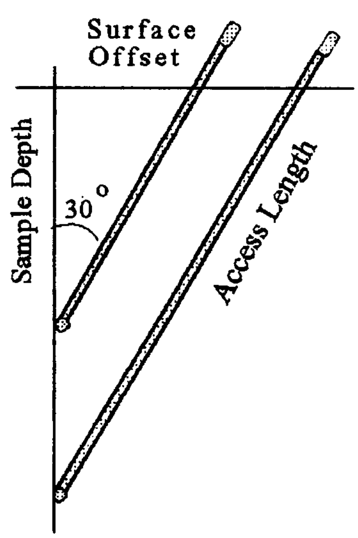


Figure 8. Diagram of soil access tube installation.

## SUMMARY

Resin capsules provide a tool that solves important soil testing problems because the ion adsorption process is like the process that plants use to take up nutrients. From a single extraction procedure, an individual capsule can be quantitatively analyzed for most ions of interest. This resin capsule method also works on a saturated paste made from soil samples taken to a laboratory for analysis. An added benefit is that field and laboratory costs of monitoring with resin methods are lower than for traditional soil testing methods.

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## "MORE RECIPES FROM THE GALLOPING FORESTER - SEEDLING SURVIVAL PRODUCTS (1): YEA, NAY OR GO TO..."

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Success in establishing woody plants on revegetation projects can be difficult, particularly in the western United States. Many elements impede the survival of trees and shrubs. Disturbed soils, steep slopes and harsh light surfaces are just a few of the man-made conditions that may exist on the planting site -- then the natural environmental conditions must be added to the mix. These can range from wild swings in temperature and precipitation, to increasing light intensities versus elevation and strong wind events.

Finally, the transfer of the plant materials from the favorable growing conditions at the nursery to the subsistence, or even sterile conditions at the revegetation site, adds a certain amount of transplant shock. All these factors, when combined together, may present enough stress to cause severe mortality or entire failure of the planting project.

While there are a number of reasons for tree and shrub loss, an entire industry has arisen that caters to the tree planting community. These are a large number of survival accessories that can be utilized on sites and more are being touted daily.

This paper will define the conditions that cause these survival enhancement products to be used, how to properly utilize them, and where a little ingenuity may provide that best solution.

First, a quick look at transplant shock. These are changes that occur immediately that affect the overall metabolism of a plant. The most obvious change that occurs from being removed from the nursery is the interruption of normal water and nutrient uptake by the roots. This is due to the removal of the plant from the soil and subsequent damage to the roots themselves, and the fine root hairs which are responsible for most of the uptake of water and nutrients.

The degree of transplant shock depends on the soil and atmospheric conditions, and the overall vigor and growth stage of the plant. So even though the latest technological survival products are used, the plant may still wilt and subsequently die if not properly handled prior to placement at the planting site. It has also been found that the mistakes made during the physical planting operation are the "most serious technical blunders committed (Zon, 1951)."

(1) Mention of any products by either common or trade name does not constitute endorsement by the Colorado State Forest Service, nor does it imply discrimination against materials not expressly listed.

So a lot of care needs to be given to seedlings as they make the trip from the nursery to the hole they will be planted in. If the level of transplant shock has not exceeded the plant tolerance, survival enhancing products may then benefit and improve the chances of that plants' long term survival.

Probably the most critical factor to long term survival is water, or the absence of it. But the delivery of supplemental water to most revegetation sites is impractical due to their relative isolation. However, the development and use of synthetic polymers help to somewhat overcome this obstacle.

**Polymers**

Synthetic polymers come in different forms ranging from single strand starch based, to multi-stranded petro based products. The basic premise is that once individual grains of polymer have been hydrated, these crystals will provide a source of water during periods of short term drought. If an individual root hair comes in contact with a hydrated crystal, it will penetrate the crystal and extract the moisture from that crystal for use by the plant.

It should be noted that the water is tied up in the polymer itself, and is not free water. Hence, the danger of increasing the susceptibility of roots to fungi and other disease does not apparently exist. In addition, the polymer can only hold a finite amount of water. So the plant can only sustain itself over a drought of short duration. The hope is that a rainfall event will occur prior to the plant reaching its permanent wilting point.

So does this work you ask? My personal experience is such that I feel it does. Since 1985, polymers have been available for purchase through the Trees for Conservation Program; the response has been very positive and it appears that the polymers do add significantly to initial survival.

However, hard research results are hard to come by. A study in Sudan (Callaghan, 1986) showed a fivefold increase in survival with polymers over control plantings. In 1990, a non-technical report by the Bureau of Reclamation in Arizona expressed increased survival rates in excess of 50%. Finally, a field trial in South Dakota showed a species specificity to the results. Overall there was a 20% increase in survival using the polymers. So it would appear for the relative nominal cost for polymers and their application, it is worth the expense.

Another spinoff benefit that has not been looked at is the reduction of transplant shock from field handling. This would apply to bare root planting stock. Polymers appear to be a superior holding slurry over plain water or mud solutions.

An alternative to supplemental water is the technique of water harvesting. This concept basically eliminates all competition for naturally occurring moisture and captures and stores the better part of that moisture.

The first step is to physically or chemically remove all grass and forb competition. This allows the planted seedling access to all moisture that occurs. Then mulches, typically wood chips, are laid down to prevent evaporative losses. The problem with wood chip mulches is they may not be readily available, costs involved in transportation and installation are high, and the mulches must be saturated before moisture can reach the soil.

### Geotextile Fabrics

The recent introduction of woven geotextile fabrics have solved this dilemma. Light weight, easily transported, this product may be the largest boon to tree plantings in the semi-arid west. The product is composed of a woven polyethylene black plastic, 14 mils thick. Bonders are added to protect against degradation by ultra-violet light, and also provide a 5-year warranty. I personally know of a site in southeast Colorado that has had weed barrier exposed for 10 years and is just now showing signs of significant degradation.

The fabric is 99.8% opaque to sunlight, hence eliminates weed seed germination and growth under the fabric. Finally, the fabric acts as a mulch, reducing the loss of moisture from evaporation.

In a field trial in southeast El Paso County in Colorado, survival ranged from 74% to 100% with six different tree and shrub species. Average height of Eastern Red Cedar after three growing seasons was 39.6 inches (Spaulding, unpublished).

In 1990, a soil moisture retention was initiated in Laramie County, Wyoming. It was found that geotextile fabrics maintained a field capacity of 90%, where non-treated controls had field capacity values that fell as low as 10% for extended periods (USDA-ARS, unpublished).

A high altitude planting (8,800 ft.) was performed using 3 foot squares of fabric in the spring of 1993. In September of that year, 99.9% survival was experienced without the necessity of having supplemental moisture. This technology appears to be a major step forward in providing means of harvesting naturally occurring precipitation.

The next major factor as it applies to survival is wind and heat. Evapotranspiration is a common and important metabolic process in all plants. However, this process is speeded up by heat or air temperature and wind. As temperatures rise, plants increase their rate of transpiration and lose more moisture. Wind movement further exacerbates this situation as it moves dry air past plants and further accelerates this moisture loss process. When there is adequate and available soil moisture, this is not an issue. But in the semi-arid west, this moisture loss can be fatal, either in the summer or winter.

### Shelter

The easiest solution to this problem is to protect a seedling by placing a wind or sunlight barrier around it. This can be something a simple as straw bales or wood shingles. Another solution is the use of tree shades. The shade is composed of a photodegradable polyolefin plastic that is sewn into a mesh envelope. The envelope then slips over a wire wicket, which is set into the ground. The mesh provides a shade factor of 80%.

This product appears, again, to be easily transported into isolated areas. In most cases, the wicket and openings in the mesh provide enough strength and air passage to remain upright. They will be knocked down in situations where drifting snow occurs. What is not communicated about this product is that the wind will vibrate the mesh envelope off the wicket. This is easily remedied by using 24 gauge florist wire to secure the top of the mesh envelope to the steel wicket.

A higher technological advancement against wind and heat damage hails from Europe. Tree shelters are intended to provide a mini-greenhouse, or growth chamber, around each plant. They are usually made of polypropylene which is extruded into a twin walled tube similar in appearance to cardboard.

The concept is to protect the plant from heat, having about a 75% shade factor. In addition, the shelter protects the seedling from wind and provides a favorable micro-climate to accelerate growth -- which the tree shelter definitely does. Results from Michigan, Ohio and Wisconsin indicate that overall height doubles when using the tree shelters versus control plots without the shelters. This occurs with deciduous trees and shrubs only; conifers, in my experience, have not responded at all.

A word of caution when using this product. Due to the increased height production achieved, stem caliper often lags behind. Once the protection of the tree shelter is removed, the elongated tree quickly blows over in the next wind storm.

Also, plants in the shelters may not harden off quickly enough and mortality has been reported from fall frosts. In the Rocky Mountain west, it would not be surprising to see damage in early spring. The shelters may cause the tree to break dormancy before the last of the killing frosts have passed. Both of these situations may be alleviated by using the shorter length of tree shelters, staying in the 18 - 24 inch range.

A final frustration I have gone through is trying to keep the shelters erect in high winds. Due to the large wind profile of the tube, I have had to use steel rebar to keep the tube from being wind thrown.

## Fertilizers

Another question is to fertilize or not to fertilize? This is a question not readily answered as the scientific community is really at odds over woody plant fertilization, particularly in time release formulations, such as Agriform, Gromax or Woodace. My only recommendation is to watch the nitrogen level of the product you use; it should be a 20 or less. The fertilizer should also not contain a herbicide; you may accidentally kill your plants.

Research has shown, repeatedly, definite responses to early fertilizer applications. After initial establishment, fertilization response varies among all woody plants.

## Repellents

Repellents are intended to reduce damage to plants, either through taste or smell. Taste repellents need to be, obviously, ingested by the target critter. So this involves some damage to the plant you are trying to protect. The concept here is that the noxious taste of the repellent will be imprinted on the animal, and it will then tend to shy away from continued feeding. Odor repellents follow this same idea, with the scent being the deterrent to the animal.

Research has shown a broad spectrum of success among a wide variety of repellent brands. A study performed by the Colorado Division of Wildlife and Cooperative Extension Service showed tame Mule Deer consumed 15 - 20% of rations treated with Big Game Repellent, coyote urine and a chicken egg solution. Additional products tested with percent of ration consumed were Thiram (42%), Hinder (45%), Lifebuoy soap (62%), and Ropel (80%). A Connecticut study (Swihart and Conover) used Big Repellent and Ropel as taste repellents also. Again, the results were pretty much the same, with Big Game Repellent out performing Ropel.

This study also looked at using soap as an odor repellent. When used to protect apple trees, Cashmere Bouquet, Coast, Ivory, Shield and Dial were quite effective. Soap bars of Safeguard and Irish Spring were less effective and Jergens showed no level of control. The soap bars were hung from the apple trees approximately 1 meter apart. As the distance between soap bars grew, the less effective this treatment became.

The major drawbacks of repellents are price and frequency of application. Big Game Repellant retails for as much as $20 per gallon, with an effective life of 90 - 120 days under normal conditions. The question begs, what are normal conditions? Ropel can cost $38.90 per gallon, and Hinder $18.25 per gallon. And then the animal must ingest a part, or in the case of seedlings, all of the plant you are trying to protect. The only product I have found that works consistently are the vexar tree guards.

## Tree Guards

The tree guard is made of a combination of polyethylene and polypropylene that is extruded into a tube with a diamond mesh pattern. Ultra-violet light inhibitors are added to allow the guard to photodegrade slowly. The concept here is to provide protection to the plant until it can establish itself and grow to a degree where it can tolerate some feeding by animals.

The key benefit here is that your planting won't get wiped out overnight. Deer and elk cannot put their muzzles down the tube. Small rodents will not climb over the tube, nor gnaw through the vexar tubing itself. Where tree stakes are used to keep the guard secure in an upright position, deer and elk have a difficult time knocking the guard off. One initial draw-back to this product can be the expense. The guard with stakes can run as high as 25 - 30 cents each, plus installation. But one application does the trick!

Large game animals will mow the top off any trees or shrubs that grow out the top of the guard. However, in my experience on the U.S. Air Force Academy with their deer populations, the guards allowed the plants to establish and escape heavy feeding by the deer. The planting site does experience damage, but no mortality has occurred.

Another problem that can occur using the vexar tree guards happened on a project on the Snowy Range Road in Wyoming. Due to the highly visible yellow color of the guards, the seedlings were being dug up and taken home by passersby.

**Fencing**

Another option to tree guards, provided a small area needs protection, is portable photo-voltaic electric fences -- a car battery with a solar charger and T-tape electric fence. The fence is baited with a mixture of vegetable oil and peanut butter, which appears to be a favorite late night snack with the ungulate bunch. The deer or elk really learn quickly to avoid the planting site.

The Nebraska State Forest Service has used this technique in protecting research plots and have been greatly impressed with the results. They have protected areas up to three acres in size and feel the fence could be used on even larger areas. The big benefit here is that the fence charger is portable and easy to use. Nebraska's experience has shown that the fence needs to be charged once every 2 -3 months after the initial exposure to the animals.

Now it is not necessary to use all the products mentioned in order to obtain acceptable survival of your plantings. It may only be necessary to use the appropriate survival accessory that combats the worst factor you encounter. It is best to spend your dollars on whatever single item gives you the most benefit. Trying to improve survival an additional 10 - 15% over what you are currently experiencing may not be worth the cost. Other mitigating factors, such as the importance of the planting itself, may require that additional steps be taken.

But in any event, look closely at what a survival enhancing product tries to do in relationship to environmental factors you have on your planting site. For every day, it seems a new product hits the market place. For example, a new repellent using garlic is available. Does this mean the tree needs to use a mouthwash before it pollinates?

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# Alpine dwarf willow and its ectomycorrhizal partners: a potential system for alpine ski slope restoration !

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From 1988 to 1990, mycosociological and mycoecological research has been carried out during the vegetation period (July to October) in acidic alpine snowbeds with *Salix herbacea* L. and *Polytrichum sexangulare* (Flörke ex Hoppe) Brid. in the Valley of Radönt (Grisons), Switzerland, in 13 permanent plots of 50 $m^2$ each. Interests have been focused on macromycete taxonomy resulting in a check-list of 80 recorded species of which 63 grew in the 6 pure Salicetum herbaceae Br.-Bl. plots. Of them, 42 (67%) were ectomycorrhizal fungi associated with *S. herbacea.* Numerous isolations of different ectomycorrhizal partners resulted in pure cultures of *Hebeloma repandum* Bruchet, *Cortinarius (Myxacium) favrei* Mos. ex Henderson and *Hymenogaster saliciphilus* Graf & Horak. So far, synthesis experiments were successful with *H. repandum* and *S. herbacea.* Syntheses were performed with seedlings grown from seeds in sterile Erlenmeyer flasks containing a Vermiculite-peat moss mixture. Synthesized ectomycorrhizae had a two layered mantle and a mostly paraepidermal Hartig net. Naturally grown ectomycorrhizae of these two partners had a similar mantle and Hartig net structure. Different cultivation methods of the willow (seeds, cuttings) and successful formation of ectomycorrhizae under sterile and non-sterile conditions have turned this plant-fungus-system (PFS) into a potential and powerful tool for the restoration of destroyed acidic alpine environments, especially ski slopes above timberline in the Swiss Alps.

## INTRODUCTION

The main objective of this study was to gain information about *Salix herbacea* and its ectomycorrhizal partners with the prospect of laying the foundations for restoration projects in the alpine zones with this plant-fungus-system (PFS). In this context ecology and sociology of the macromycetes in snowbed communities with *S. herbacea* and closely related associations were investigated during a three year period. From 1988 to 1990 during the snow-free vegetation periods, all observed macromycetes in 13 permanent investigation plots of 50 $m^2$ each were protocolled on excursions in weekly intervals whenever possible. Besides the list of the registered taxa, the main goal of this work was to record abundance, frequency and periodicity of the macromycetes. Furthermore, relationships between carpophore productivity of selected taxa and the course of climatical parameters (microclimate) and soil properties were subjects of this study. The mapping of the carpophores and the snow melting zones (isochiones) in 11 of the 13 permanent plots was carried out to better understand distribution patterns and association behaviour, especially between ectomycorrhizal taxa accommodated by the dwarf willow. It was further attempted to cultivate typical ectomycorrhizal macromycetes from fungal tissue (auxenic cultures) and from the host plant *S. herbacea* from seeds as well as from cuttings. With these materials it was predicted to carry out ectomycorrhizal synthesis experiments and to produce inoculum and host plants for future restoration projects.

## MATERIAL AND METHODS

### Investigation area

The research area is located between Davos (1560 m) in the Landwasser Valley and Susch (1426 m) in the Lower Engadin, south-east of the Flüela Pass (2383 m) in the Valley of Radönt between 2400 and 2500 m, in the Canton of Grisons, Switzerland.

The bedrock of the research area belongs to the Silvretta formation which is dominated in the Valley of Radönt by ortho- and paragneiss ($pH_{H2O}$ 3.5-4.2) occassionally intermixed with alluvial soil originating from moraine deposits ($pH_{H2O}$ 4.9-5.5) of the glacier of Radönt (Quaternary glaciation).

### Collecting and mapping of macromycetes

In this work only macromycetes i.e. carpophores (cp) visible with naked eye (cp > 1 mm diam.) are treated. Concerning Basidiomycetes the main attention was focused on Agaricales, although a few conspicuous representatives of Aphyllophorales and Gastromycetes are included also. Ascomycetes were collected likewise and with *Didymium squamulosum* (Alb. et Schw.) Fr. even one Myxomycete is reported.

During the vegetation period (July to October) between 1988 and 1990 totally 47 excursions in weekly intervals, whenever possible, took place to record ecology and sociology of macromycetes in the 13 permanent plots of 50 $m^2$ each. In 11 of them (6 belong to the Salicetum herbaceae Br.-Bl. association) all observed carpophores were mapped. Each collection (i.e. a group of basidiomata of the same taxa within a basal area of 5 cm diameter) has been protocolled with its relative position and number of individuals. These observations were complemented by reading weekly data (taken at soil surface level) on precipitation (using rain guages) and maximum-minimum air temperatures. Furthermore, from mid-May to July weekly investigation took place to map and document the snow melting process (isochiones).

### Ectomycorrhizal synthesis experiments and natural ectomycorrhizae

Small tramal pieces of *Hebeloma repandum, Cortinarius favrei* and *Hymenogaster saliciphilus* were cut and placed on Petri dishes on modified Melin Norkrans (MMN) agar (Marx & Bryan 1975). After several weeks of incubation small pieces of the mycelium were transferred into sterilized 500 ml Erlenmeyer flasks containing a liquid MMN solution. After 10 weeks these liquid cultures were homogenized and injected into autoclaved Erlenmeyer flasks containing a Vermiculite-peat moss mixture. The fungal inocula were allowed to grow 1 to 2 months prior to seedling introduction.

Seeds of *Salix herbacea* were collected from the investigation plots. After surface sterilization for 3-5 minutes with $H_2O_2$ (30%) they were placed on water agar in Petri dishes for germination and incubated at room temperature and in daylight. After the development of the cotyledones the seedlings were transferred and maintained on MMN agar plates. After 2

to 3 weeks the plantlets were ready for synthesis experiments, i.e. were added to the Vermiculite-peat moss Erlenmeyer flasks.
Synthesis experiments were carried out in a growth chamber with a 16 hour day period at 20°C and 70% humidity. The duration of the syntheses of *H. repandum* were 11 months. Ectomycorrhizal rootlets were then harvested and cleaned with sterile water, fixed, dehydrated in alcohol, embedded in glycol-metacrylate, longitudinally sectioned (1.5 μm) and stained with Giemsa for chitinoid material (BRUNNER *et al.* 1992).
For comparison reasons, naturally grown *S. herbacea* rootlets were examined for ectomycorrhizae. Based upon mapping data, spots of carpophore monocultures were chosen from different ectomycorrhiza forming taxa, viz. *H. repandum, C. favrei, Laccaria montana, Entoloma alpicola,* and *Russula norvegica.* In addition structures of *Cenococcum geophilum* Fr. ectomycorrhiza were also considered.

### Cuttings

Cuttings of *Salix herbacea* were made from plants grown under sterile conditions from surface sterilized seeds and naturally grown plants, respectively, both collected in the permanent plots.
Each cutting, consisting of at least 3 leaves and with a minimal height of 15 mm, was put into a pot filled with a well watered Vermiculite-peat moss mixture to which 150 ml $MMN_{anorg.}$ solution was added. These systems were maintained under non-sterile conditions at 20°C and daylight in a greenhouse and weekly supplied with water and 30 ml $MMN_{anorg.}$.
After $2^1/_2$ months 100 ml of homogenized mycelia of *H. repandum* were injected into one of the pots. Ten and fifteen months later, respectively, some of the rootlets were harvested for investigation of ectomycorrhizal structures.

## RESULTS

### Collecting and mapping of carpophores

During the 3 year research period more than 26'000 carpophores, belonging to 80 different taxa, were counted within the 13 permanent plots. In the 6 Salicetum herbaceae plots the share constitutes about 17'000 basidiomata resulting from more than 7'500 mapped collections. From the 63 distinguished taxa of these Salicetum records 42 (67%) represented about 16'000 carpophores (97%) belong to the ectomycorrhiza forming partners of the willow. Among them the most frequent species are shown in Table 1:

**Table 1:** The most frequent ectomycorrhizal partners of *Salix herbacea* with corresponding numbers of colletions and carpophores. Bold species are considered in Figure 1.

| | collections | carpophores |
|---|---|---|
| ***Laccaria montana*** | 1854 | 4100 |
| *Cortinarius stenospermus* | 662 | 1894 |
| *Cortinarius rufostriatus* | 611 | 1692 |
| *Russula norvegica* | 892 | 1087 |
| ***Cortinarius favrei*** | 543 | 842 |
| ***Hebeloma repandum*** | 282 | 443 |
| *Hebeloma marginatulum* | 210 | 314 |
| ***Inocybe lacera*** | 187 | 290 |
| *Inocybe peronatella* | 161 | 212 |

The graphic data evaluation of the 3 year mapping cycle allows demonstration of different growing patterns and strategies among the 42 distinguished mycorrhizal forming taxa all related to *S. herbacea* (Fig. 1).

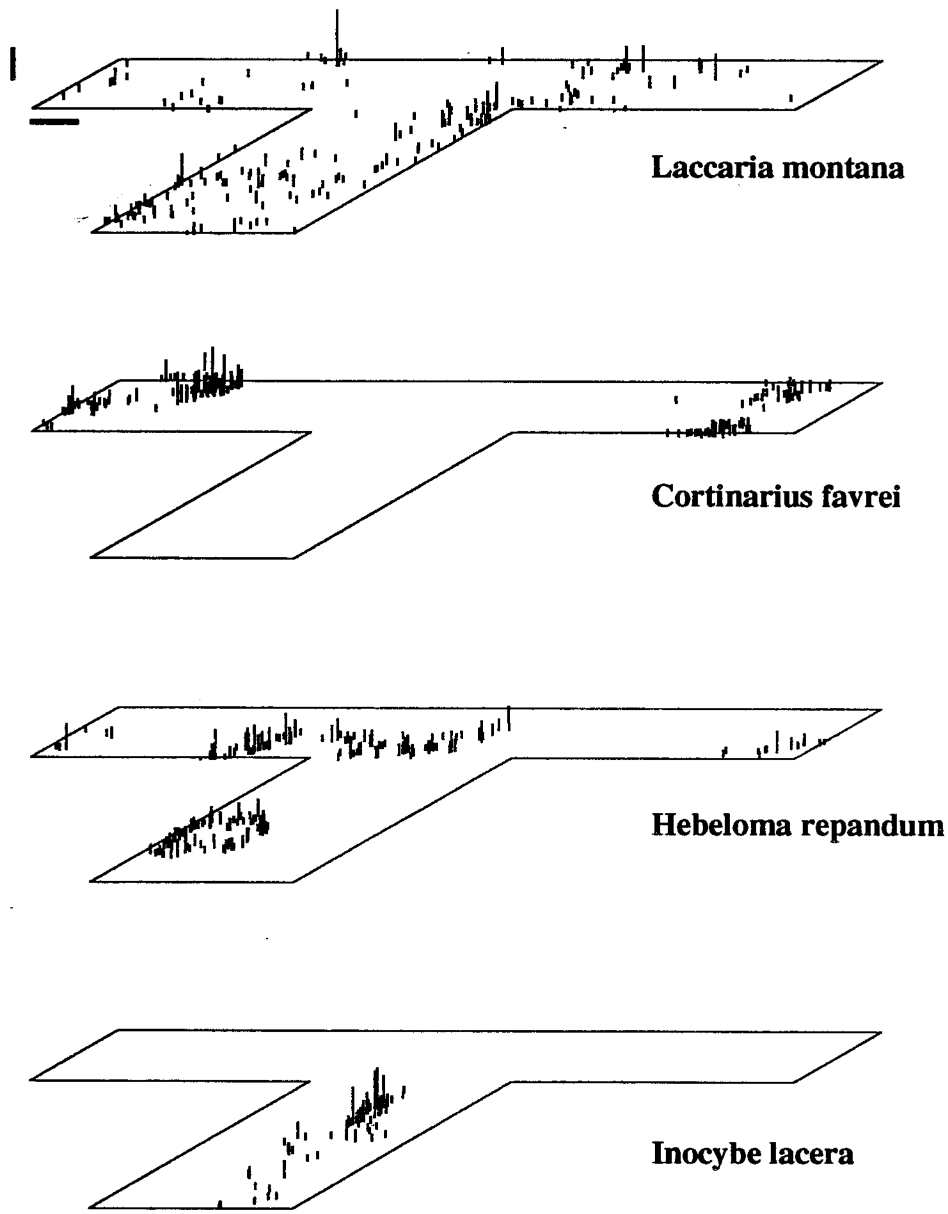


**Figure 1:** Abundance, frequency and distribution patterns of selected ectomycorrhizal macromycetes in plot 7 (Salicetum herbaceae) from 1988-90. Horizontal scale bar = 1 m, vertical scale bar = 5 carpophores.

**Ectomycorrhiza**
The *Salix herbacea-Hebeloma repandum* system had typical ectomycorrhizal rootlets, after 11 months under sterile conditions in the Erlenmeyer flasks and after 15 months in the pot, maintained in a greenhouse. The two layered mantle structure and the paraepidermal Hartig net (Fig. 2) were more or less identical in both synthesized samples corresponding to the examined natural ectomycorrhiza. Concerning *Hymenogaster saliciphilus* no synthesis experiments were carried out because of lack of sufficient inoculum material (extremely low growth rate, see GRAF & HORAK 1993). Furthermore, *Cortinarius favrei* did not develop ectomycorrhizal structures neither in the Erlenmeyer flasks under sterile conditions nor in the pots maintained in the greenhouse within 15 months of synthesis duration. More results about ectomycorrhizal synthesis experiments and producing of cuttings are subject of a further publication (GRAF & BRUNNER in prep.)

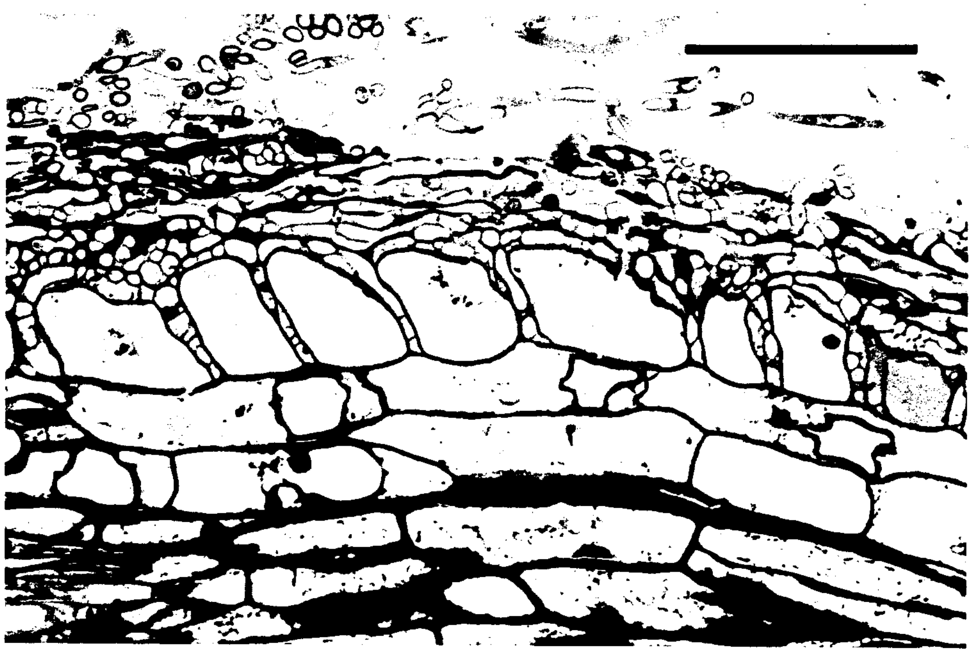

**Figure 2:** Light micrograph of a longitudinal section of synthesized ectomycorrhiza of *Salix herbacea* with *Hebeloma repandum*. Fungal hyphae form a two layered mantle and a paraepidermal Hartig net. Scale bar = 50 µm.

Examined natural ectomycorrhiza types confirm that the structure of the above mentioned *Hebeloma* synthesis is probably developed by most of the fungal partners of *S. herbacea*. It seems obvious to assume that the ectomycorrhizal structures are mainly dependent on the host plant. This is in accordance with observations of ANTIBUS *et al.* (1981) who examined synthesized and natural ectomycorrhizae of *Salix rotundifolia*. Synthesis experiments with aspen resulted in comparable assumptions (GODBOUT & FORTIN 1985).
The examined natural ectomycorrhizae of *S. herbacea* with *H. repandum*, *C. favrei*, *Dermocybe crocea*, *Laccaria montana*, *Entoloma alpicola* and *Cenococcum geophilum* showed similar structures as the synthesis with *H. repandum* i.e. a two-layered mantle and a paraepidermal Hartig net.

**Cuttings**
Cuttings from naturally grown as well as from sterile maintained plants grew well. Ten months after inoculation of *H. repandum* no ectomycorrhizal structures have been formed. However, after 15 months typical ectomycorrhizal structures were present as described for the synthesis under sterile conditions. Several generations of leaves have been developed since in both systems, with and without inoculation of *H. repandum*. There was a distinct higher production of third generation leaves in the pot where *H. repandum* inoculum was added.
During the first and second generation the plantlets grew all in vertical direction. Only at the end of the second and then with the developing of the third leaf generation the plants did start to creep horizontally as it is known in nature (Fig.3).

**Figure 3:** Cuttings of *Salix herbacea* at the age of 12 months with the third leaf generation showing typical leathery context. Most plantlets demonstrate their characteristic creepy growth habit. Scale bar = 1 cm.

**Snow melting zones (isochiones)**
The mapping of isochiones is helpful to detect relationships between the snow-melting-zones (isochiones) and the distribution patterns especially of the ectomycorrhizal macromycetes. Throughout the Salicetum plots it was registered that symbiotic partners occurred predominantly either at places where snow melted early or late in the season (Fig. 4, [**I-IV**]). Beside others, *Cortinarius favrei* is an example of the former group (**I**), whereas *Inocybe lacera* and *I. peronatella* belong to the latter (**II**). The fact that *S. herbacea* shows particular differences in the composition of ectomycorrhizal species in connection with isochiones raises the assumption that certain symbiotic partners of the dwarf willow are more competitive under the condition of long snow cover. Differences in time of thaw are correlated with the time available for the development of the ectomycorrhizal host plant *Salix herbacea*. Plants which start their vegetation period later in the season find a

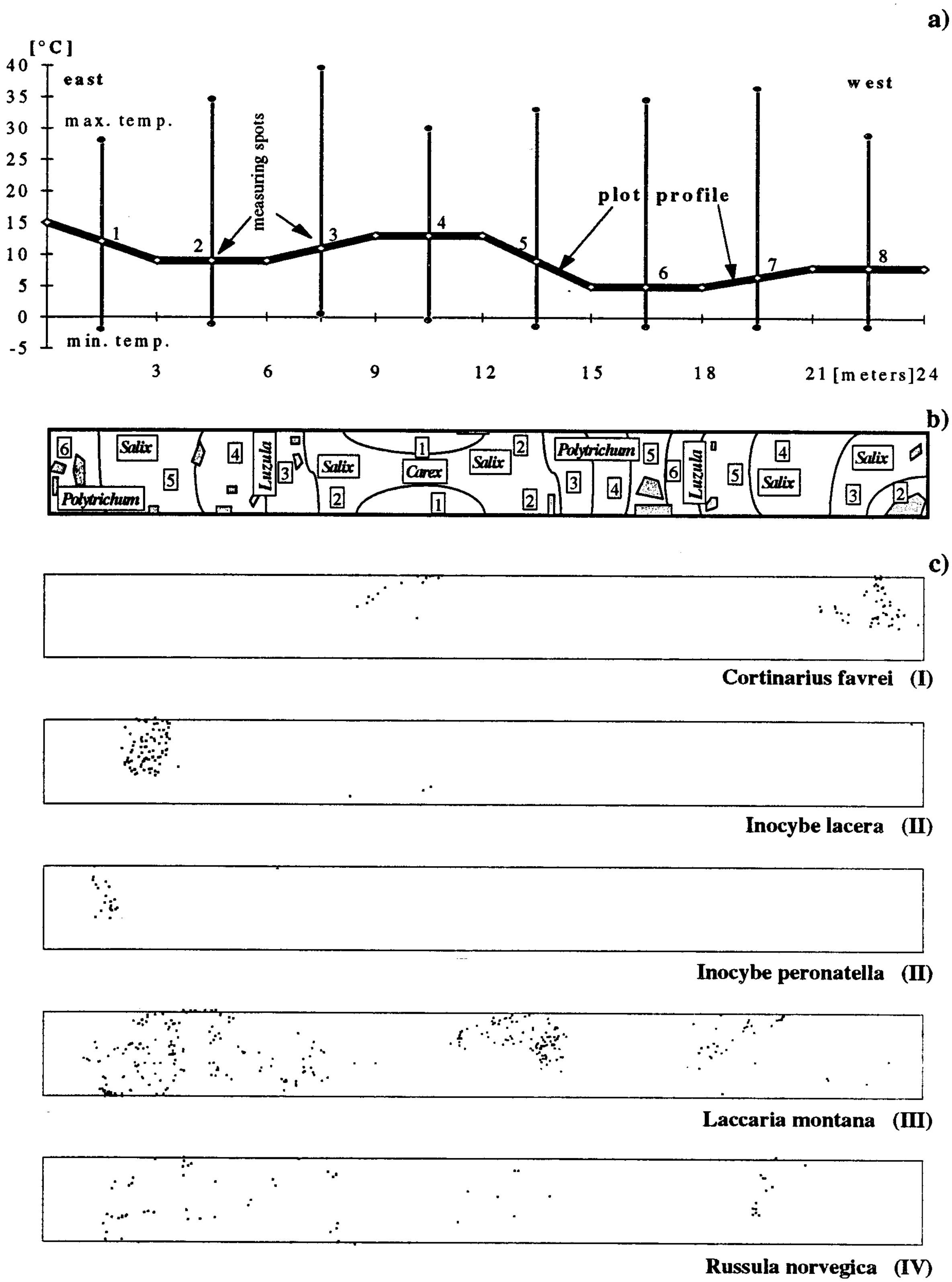


**Figure 4:** Plot 11: **a)** Extreme temperatures [°C] at eight (1-8) spots during 28 hours on a radiation day (20./21. July 1990); **b)** Isochiones (1 = early, 6 = late snow-free) from 1988 to 1990 and important plants with their dominating spots **c)** Mapping cards of ectomycorrhizal fungi (1988-89). **I, II** = at early, late snow-free spots; **III, IV** = early, late stage partners.

different situation in nutrients, less favourable climate conditions, and more competitive pressure of the plants, which started their development earlier. In the case of *Laccaria montana* which was registered nearly everywhere in association with *S. herbacea* it was observed that clustered occurrence of its carpophores were mostly restricted to border zones of the dwarf willow with mostly extreme climatic or edaphic conditions (snow cover, soil properties, max.-min.-temperatures). At places with well established patches of *S. herbacea* there was a significantly lower productivity of this macromycete. Similar observations were made for *Hebeloma* spp. and *Inocybe* spp. Conversely, *Cortinarius* spp., especially *C. favrei*, and *Russula* spp. showed the opposite behaviour (Fig. 4). These observations confirm their status as early- (**III**) and late-stage (**IV**) ectomycorrhizal partners, respectively (Ford *et al.* 1980).

## DISCUSSION

In recent years different strategies for alpine restoration were tested and described (CHAMBERS *et al.* 1984, 1988; GRABHERR *et al.* 1988; URBANSKA 1986, 1988, 1990). Concomittant numerous investigations were carried out checking the aptitude for high altitude revegetation of many plant species (CHAMBERS *et al.* 1987; FLÜELER 1992; SCHÜTZ 1990). However, in this connection, only little is known so far about the fitness of ectomycorrhizal host plants and their fungal partners naturally established throughout the alpine zones.
In the present study it was attempted to lay foundations for alpine restoration with such plant-fungus-systems (PFS). Of the 42 macromycetes suspected to form ectomycorrhiza with *Salix herbacea* only a few are predicted as potential and powerful partners for alpine restoration in combination with the dwarf willow. The main criteria the selection is based on are the ability to get auxenic cultures, to form ectomycorrhiza under non-natural conditions, a wide distribution throughout the alpine zone and taxonomically more or less well defined species. Following this propositions the following PFS are proposed as potential for restoration in the alpine zone where siliceous parent material is dominant:
***S. herbacea****-Cortinarius favrei, -Entoloma alpicola, -Hebeloma marginatulum, -H. repandum, -Hymenogaster saliciphilus, -Inocybe lacera, -Laccaria montana* and *-Russula norvegica*. In nature, these PFS cover a wide range of the possible ecological spectre of *S. herbacea*. Regarding alpine restoration, different fungal partners do different jobs at different places. To state only a few examples: *Entoloma alpicola* as the one partner in areas with shorter snow cover is substituted by *Inocybe lacera* and / or *Hymenogaster saliciphilus* at spots with longest snow cover. *Hebeloma* spp. and *Laccaria montana* seem to be most competitive in open and poor vegetation, whereas *Cortinarius favrei* and *Russula norvegica* prefer rather closed vegetation with a higher plant diversity (GRAF unpubl.).
Efforts should be undertaken to test this PFS thoroughly by replanting them in their natural, alpine habitat. Combined with careful soil and vegetation analysis of the slopes and their boarder zones, it should be possible to find the appropriate PFS, for each place to be treated. In the Swiss Alps the potential and powerful host plants on silicaceous rock material are *Salix herbacea, S. retusa, S. reticulata,* and on calcareous rock material *Dryas octopetala.*
Further inquiries should be undertaken in producing cultures of the proposed ectomycorrhizal macromycetes and in investigations of their specific responses to different environmental parameters, viz. nutrients, pH, soil moisture and snow cover. In this connection care

should also be taken in the composition of the soil fauna and their influence in nutrient cycling. NASCHBERGER & KÖCK (1983) and FLORINETH (1984) demonstrated, that well dosed applications of organic fertilizer at restoration sites increase the biomass of the plants and stimulate the propagation of the soil inhabiting microorganisms (INSAM & HASELWANDTER 1985; LUFTENEGGER *et al.* 1986). Such efforts may be secondary or even superfluous with a better understanding of the soil microflora and the appropriate consideration and application of a selection of such a fauna, concomitant with the planting of the suitable set of ectomycorrhizal and non-ectomycorrhizal phanerogames.

To sum up it seems obvious that still essential research and extensive work has to be done. Nevertheless, with a little enthusiasm and idealism (Fig. 5) and of course the appropriate financial support these investigations would certainly lead to successful contribution regarding recovery of nature.


**Figure 5:** New perspectives in alpine restoration ?! Reproduced with kind permisson of V. Morgen 19.2.1994.

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**POSTER SESSION ABSTRACT**

# APPLICATION OF MUNICIPAL BIOSOLIDS TO THE RECLAMATION OF SEMI-ARID MINED LANDS

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The Environmental Protection Agency published the final rules for the disposal of municipal sewage sludge on February 19, 1993 in the Federal Register, 40 CFR Parts 257, 403, and 503. These regulations were promulgated under authority of Sections 405 (d) and (e) of the Clean Water Act, as amended. One section of the regulations permits the application of sewage sludge to land for a beneficial use (as biosolids), i.e., for land reclamation.

In the past, research into the use of biosolids as a soil amendment has been conducted in humid climates with very little research performed in the semi-arid climate that is typical of the state of Utah. Thus, the purpose of this project is study the impact of biosolid application to mined land locations in Utah, therefore accounting for the climatic conditions of the Great Basin region. Specifically, this project will determine the success of vegetative growth after the application of biosolids, principally to the relatively flat slopes of the Kennecott Utah Copper tailings impoundment and a range of slopes at Barneys Canyon Mine. This proposal will utilize anaerobically digested (Class B) sewage sludge, from the Central Valley Water Reclamation Facility in Salt Lake County, as a soil amendment to enhance revegetation. The effects and progress of the biosolid applications will be evaluated using a linear, interactive experimental design. This research project is a cooperative effort between the University of Utah, Golder Associates, Inc., Kennecott Utah Copper, and Barneys Canyon Mine.

Products of the research project will provide a final technical/R&D report, as well as specifications for large scale reclamation including: biosolids application rates; fertilization, if required; recommended seed mixtures; erosion protection measures; and monitoring and maintenance requirements.

## Preliminary Revegetation Results for Leviathan Mine, Alpine County, California

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Leviathan Mine is a former open-pit sulfur mine, about 500 acres in size, located at about 7,000 feet elevation on the eastern slope of the Sierra Nevada Mountains in Alpine County, about 30 miles south of Lake Tahoe, California. Average annual rainfall is about 20 inches. Generation of sulfuric acid from oxidation of elemental sulfur and pyrite in exposed mine spoils has resulted in typical pHs of 3-4 for soils and pHs of 2-3 for subsurface drainage waters.

The California State Water Resources Control Board has spent over six million dollars to remediate the pollution by relocating and regrading one million yards of tailings, constructing 11.4 acres of evaporation ponds, channelizing streams to prevent contact with mine tailings constructing 17,000 feet of drainage ditches to prevent stormwater infiltration and revegetating the site.

Only moderate improvements to water quality, however, have been attained, primarily because initial attempts at site revegetation were not successful. Acid mine drainage (AMD) seeps, pond overflows, and erosion of bare soils continue to impair water quality. Establishment of adequate vegetation would minimize pollution of local waterways by: (i) minimizing soil erosion via physical soil stabilization, and (ii) reducing seepage of AMD and pond overflows by increasing evapotranspirational losses of soil water.

Butterfield and Tueller (1980) suggested on the basis of initial field and greenhouse revegetation/soil fertility/liming studies that the major limiting factors in stand establishment at Leviathan Mine are, in approximate order of importance:

(1) Acidity of mine spoils with associated metal (i.e. Al) toxicity.

(2) Low soil fertility (i.e. N, P, K, Ca, Mg) on leached acid spoils.

(3) Selection and establishment of acid-tolerant, high-altitude plants.

A study by Brown and Caldwell (1983), however, suggested that neither acidity nor soil fertility were major limiting factors, and selection of properly adapted acid-tolerant plant species was the most important factor.

Trees from field plot studies using indigenous acid-tolerant pine species planted as early as 1977, however, typically show stunting and yellowing. Also, Early attempts at grass establishment with moderate liming have failed. This suggests that soil acidity and fertility are the limiting factors in stand establishment.

Availability of soil moisture should not limit growth on the predominantly silty-clayey soils (about 30-40% water holding capacity). However, plants may not be able to utilize the moisture because of poor root growth induced by metal (Al) toxicity.

Proposed workplan for future remedial actions include the following:

Phase I—Site soil characterization

- Lime requirement (short- and long-term for immediate acidity and residual acidity from S oxidation, respectively).
- Soil nutrient status—NH4-N; NO3-N; Available P (Olsen's P, acetic acid extractable, Mehlich extractable, as appropriate); Exchangeable Ca, Mg, K
- Toxic elements—Al, Mn, Cu, etc.; DTPA-extractable soil metals; Volunteer (presumable metal tolerant plants) may be sampled and analyzed for metals as indicators of other potentially toxic metals)

Phase II—Pilot-scale field trials

- using appropriate rates of soil amendments, and the most promising plant species, determine feasibility/optimize strategy for site remediation

Phase III—Site Revegetation

- Based on results of Phase II, addition of appropriate amounts of soil amendments—lime, nutrients, etc. using appropriate plant species in correct density matched to site location.

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# *EX-SITU* CONSERVATION OF PLANT GENETIC RESOURCES

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L. E. Towill, and P. C. Stanwood[1]

## ABSTRACT

Local landraces and weedy relatives of crops that have evolved by human and natural selection over the millennia have been rich sources of resistance to new pathogens, insect pests, and other stresses as well as for traits to improve food and fiber quality, animal feed, and industrial products.

Because very few crops grown in the U.S. are native, plant introductions have been vital to our agriculture. The National Plant Germplasm System (NPGS) was established to acquire, preserve, and distribute plant genetic resources from centers of diversity around the world so that scientists have immediate access to these source materials.

*Ex-situ* collections of germplasm are being stored by NPGS as 1) living and growing organisms and 2) living but quiescent organisms. Most accessions in the quiescent state are currently orthodox seeds, but research at the National Seed Storage Laboratory focuses on the development of new and improved technologies for the long-term preservation of all forms of plant germplasm as living but quiescent organisms.

The NPGS is denoting a smaller core subset of each major crop which includes most of the genetic diversity of that crop species and its relatives to be used for initial screenings.

## INTRODUCTION

Thousands of plant and animal species have evolved; however, only a few of these have been domesticated to provide food, fiber, animal feed, medicinal, and industrial products for humankind. These crops have been improved and differentiated to an even greater extent by continuing human selection for thousands of years.

Only a few domesticated crops are native to the USA: sunflower, pecan, strawberry, blueberry, cranberry, certain grasses, and a few others. Our exceptionally productive farming system was founded on genetic resources from other countries. Native North Americans had introduced maize, beans, squash, and other crops from Central and South America. Early immigrants from Europe and Asia brought seed of many crops with them. In 1819, American consuls overseas were asked to collect seeds of useful plants. The U.S. Patent Commissioner administered the

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introduction of plants from 1836 to 1862. The continuing need to acquire and introduce germplasm into the U.S. was one of the reasons for establishing the U.S. Department of Agriculture (USDA). The Organic Act of 1862, establishing the Department of Agriculture, directed the first Commissioner of Agriculture, Isaac Newton, "to collect, as he may be able, new and valuable seeds and plants; to test, by cultivation the value of such of them as may require such tests; to propagate such as may be worthy of propagation; and to distribute them among agriculturists." In 1898, the Seed and Plant Introduction Section, which later became the Plant Introduction Office, was established to manage plant explorations and introductions.

Before the late 1940's, introductions were sent directly to interested scientists without any requirement that they be maintained. Adequate preservation methodologies and facilities were not available then, and many accessions were lost.

The local landraces and wild relatives of crops that have evolved through human and natural selection over the millennia have provided rich sources of genetic diversity to meet plant breeders' needs of sources of genetic resistance to new pathogens, insect pests, soil related stresses, and food quality. But, as farmers in centers of diversity switch to new stress tolerant, higher yielding cultivars, these rich sources of useful genes will be lost forever unless they have been collected and preserved *ex situ* in gene banks.

The sheer number of organisms and the genetic diversity within species makes conservation of our genetic resources a vast task requiring many approaches. The strategies of preserving these valuable resources in *ex situ* collections are briefly summarized.

## *EX SITU* CONSERVATION STRATEGIES

*Ex situ* collections of germplasm can be stored as 1) living and growing organisms and 2) living but quiescent organisms. Examples of the living and growing collections include field, orchard, and screen house collections; botanical gardens; plantations; and cell and tissue cultures. In the living but quiescent collections, organisms are stored in a state of "suspended animation." Examples of this type are seeds and cryopreserved tissues and cultures in gene banks. The National Plant Germplasm System (NPGS) uses both strategies. Only orthodox seeds (those which are tolerant to desiccation, i.e. most crop species) and dormant vegetative buds from apple are currently stored in quiescent collections, but the technology is developing rapidly that will enable us to store most forms of germplasm.

Technological demands are minimal in living and growing collections. However, these collections are expensive in terms of labor and space. Because of this, only a few individuals or specimens of a given species can be maintained. Hence, this strategy is not efficient for conserving the genetic diversity within a species. Most importantly, living and growing collections are susceptible to disasters such as fires, tornados, insects, diseases such as the fire blight epidemic, which threatens the apple collection in Geneva, New York, and hurricanes such as Andrew, which threatened the mango and avocado collection in Miami, Florida in August, 1992.

Collections of living but quiescent organisms and tissues provide a low risk backup to the living and growing collections. Once in storage, preserved organisms require minimal space and labor, and this allows us to maintain many collections. Given the restrictions of acquiring and documenting materials, this conservation strategy is the most efficient at preserving the genetic diversity within a species. However, preserving propagules in living but quiescent collections requires technological inputs. The National Seed Storage Laboratory (NSSL) preserves a large base collection of orthodox seeds. It serves as the prototype for other seed banks, including private institutions in the U.S. and national germplasm collections in other countries.

**Technologies for Maintaining *Ex Situ* Collections in a Living But Quiescent State**

The basic principle of preserving quiescent biological tissues is to limit chemical changes that are caused by either metabolism or the stochastic processes of aging. For many biological materials, the procedures used to limit chemical reactions (dehydrating and/or freezing) are lethal. Thus, these preservation procedures cannot be used in certain quiescent *ex situ* collections since the objective is to maintain living material so that it can be retrieved and grown when necessary. Because the ultimate goal is to regain an actively growing organism capable of reproducing, the tissues that are preserved must be propagules of the organisms they come from.

There are many different types of tissues than can be used as propagules. Propagules from plants that are sexually derived (seeds and pollen) can be used to preserve various combinations of genes. Propagules that are asexually derived (vegetative buds, shoot tips, somatic embryos, cell suspensions, and root tissues) can be used to preserve specific genetic combinations. Plants produced from asexually-derived propagules are clones of the parent plant. For purposes of conserving genetic diversity, the choice of propagule depends on the ease to which it can be preserved and whether a particular genetic combination is desired. A goal of NSSL is to cryopreserve vegetative propagules of clonal crops including apple, potato, garlic, grape, pear, pineapple, and sweet potato.

For seeds, we distinguish between 'orthodox' and 'recalcitrant' types. Orthodox seeds are easily stored, while recalcitrant seeds are more difficult. Fortunately, many of the crops important to U.S. agriculture form orthodox seeds. However, a number of crop species (e.g., wild rice, citrus, avocado, mango, cacao, coffee) and several tree species (e.g., oak, maple, buckeye) produce recalcitrant seed. The basic distinction between orthodox and recalcitrant seeds lies in their relative ability to survive desiccation. The extreme desiccation tolerance of orthodox seeds provides an excellent research opportunity to understand mechanisms by which tissues can survive without water. Eventually this capability may be incorporated into recalcitrant seeds and other desiccation sensitive propagules so that they may be more amenable to storage.

**Preservation of Othodox Seeds**

The technology for preserving orthodox seeds is well understood for the most part. A basic rule of thumb given by J. Harrington in 1960 (Justice and Bass, 1978) suggests an exponential relationship among seed longevity, temperature, and moisture content of storage such that a seed's life is doubled for every 5°C reduction in temperature and for every 1% reduction in moisture content. According to this longevity model, seeds that are dried to the lowest possible level and stored at the lowest possible temperature should remain viable for millennia. Current research at the NSSL (Vertucci and Roos, 1990, 1993) does not support this supposition at low temperatures and low seed moistures.

Research by Justice and Bass (1978), Bass (1980), and Bass and Stanwood (1978) showed that reducing the storage temperature from 5°C to sub-zero temperatures increased seed longevity from less than 10 years for some species to at least several decades for most species. For this reason, the protocols for seed storage at the NSSL were changed in 1979; seed vaults were remodeled, and temperatures were lowered from 5°C to -18°C. More than 258,000 accessions are stored in the vaults at the NSSL. The new facility, occupied since May 1992, has the capacity to store about 1 million samples. With the availability of this new storage space, we expect to receive backup samples from the remaining non-duplicated accessions in the active collections in the near future.

The use of cryogenics for orthodox seed storage was initiated at the NSSL in 1978. The ultra-low temperature of liquid nitrogen should extend seed longevity to several centuries. A test of this hypothesis is ongoing. After 10 years of storage, no major differences in viability were observed between onion seeds stored at -18°C and liquid nitrogen temperatures (Stanwood and Sowa, 1994). However, major differences were observed between the sub-zero temperatures and 5°C. The protocols for cryogenic storage of orthodox seeds were established by Stanwood and Bass (1981); these protocols provide the basis for cryogenic storage of seeds in germplasm banks around the world. Seeds are stored in the vapor phase above liquid nitrogen (approximately -160°C). This procedure minimizes risks to laboratory personnel who retrieve samples from cryovats (samples stored directly in liquid nitrogen may explode upon warming due to pressure build-up of the expanding liquid phase). Presently, the NSSL has 10 cryovats devoted to routine storage, each accommodating about 2500 seed samples. There is a capacity for at least 200 cryovats at the NSSL.

For routine storage the choice between using conventional storage at -18°C or storage at liquid nitrogen temperatures depends on whether 1) the accession shows damage during initial exposure to liquid nitrogen, 2) the species produces large seeds (higher cost per sample in liquid nitrogen), and 3) the longevity characteristics of the species. At this time of limited resources, we have decided to store seeds with relatively high longevities under conventional conditions since the operating costs of partially full and totally full freezer rooms are similar and the predicted impact of storage at -18°C and -160°C will probably not be realized for many decades.

In addition to studying the effect of temperature on seed longevity, research at the NSSL (Vertucci and Roos, 1990, 1993; Vertucci et al., 1994a) and in the UK (Ellis et al., 1989, 1990) investigates the effect of water content on the storage life of seeds. Both groups have demonstrated that there are limits to the beneficial effects of seed drying on longevity and that the moisture content limit varies with the chemical composition of the seed. Furthermore, work at the NSSL has shown that drying seeds beyond a critical moisture content can result in accelerated deterioration at above zero temperatures. Using basic thermodynamic principles, scientists at the NSSL have established that, contrary to the 'Thumb Rules' and viability equations, the effects of storage temperature and water content are not independent. Consequently, the optimum water content for seed storage varies both with the seed species and with the temperature of storage. Clearly, there are insufficient resources to determine the specific optimum moisture content for each of the 8,000 species represented in the NPGS collection. However, the thermodynamic principles used by Vertucci and Roos (1990, 1993) and Vertucci et al. (1994a) have enabled us to predict optimum moisture levels for all orthodox seeds at all storage temperatures based on a single water activity at 25°C (25% relative humidity). This procedure has eliminated the requirement of determining moisture contents for each accession and saves approximately two hours of processing time for each seed sample.

Research of the Plant Germplasm Preservation Research Unit at the NSSL is also addressing questions on the nature of seed aging under dry conditions and low temperatures, how the rate of deterioration can be predicted and efficiently monitored, and how the effects of aging can be reversed. With this information, we believe that the seeds in the cold-vaults at the NSSL will be a safely preserved legacy for our great-great grandchildren.

**Preservation of Orthodox Pollen**

Pollen from many plant species can be preserved using the same principles that are used for orthodox seeds (Connor and Towill, 1993). Preservation of pollen produced from long-lived perennial plants is especially useful for the plant breeder. Pollen storage requires little space and labor. Like orthodox seeds, preservation of pollen in living but quiescent collections can serve as a backup for living and growing *ex situ* collections (Towill, 1985; Connor and Towill, 1993).

**Preservation of Desiccation-Sensitive Propagules**

Unlike most biological tissues, orthodox embryos and pollen tolerate severe dehydration; this ability makes them amenable to storage in quiescent collections. Desiccation sensitive tissues cannot be stored at sub-freezing temperatures without major manipulations because the water that is necessary for their survival freezes with lethal consequences. At the NSSL we have developed a number of methods by which tissues can be exposed to sub-freezing temperatures without lethal ice formation. These methods involved optimizing the water content and then cooling tissues to the appropriate temperature at an appropriate rate. Two methods of handling recalcitrant seed have given results varying from excellent (>80%) (Vertucci et al., 1991; Wesley-Smith et al., 1992; Vertucci et al., 1993) to mediocre (30-50%) (Wesley-Smith et al., 1993). Survival rates depend largely on the seed species and its developmental status. Results using other propagules are also variable. Survival rates of 0 to 80% after exposure to liquid nitrogen can be obtained for vegetative buds of apple (Towill, 1990; Forsline et al., 1993) and apical shoot tips (Towill and Jarrett, 1992), survival being largely dependent on genetically-programmed developmental status, genetic constitution, and developmental stage.

The first method is applicable to those tissues that can survive water contents as low as 0.3 g $H_2O$/g dw (30% seed moisture) or water potentials as low as -15 MPa. Survival rates of embryos treated in this way range from 80 to 100% of control levels. In this method, the moisture content and temperature are optimized so that both desiccation and freezing damages are avoided (Vertucci, 1989; Vertucci et al., 1991, 1994b). We and others have shown that the critical moisture content for desiccation damage increases as temperature is reduced (Ellis et al., 1991; Vertucci et al., 1994b). Thus, the window of survivable moisture levels narrows as the storage temperature declines (Vertucci et al., 1991, 1993, 1994b). This method of storage is easy to implement and is not labor-intensive. We are now adapting this procedure to handle recalcitrant seeds of various crops (coffee, wild rice, citrus relatives) and seeds from some endangered species indigenous to the Continental U.S. (*Zizania texana, Howellia aquatilis).*

The second method for preserving recalcitrant seeds is for those which are extremely sensitive to dehydration and cannot survive water contents lower than about 0.6 g $H_2O$/g dw (60% seed moisture). Examples of species we have worked with include *Camellia sinensis, Podocarpus henkii, Artocarpus heterohyllus, Castanospermum australe, Araucaria angustifolia,* and several citrus related genera (Pammenter et al., 1991; Wesley-Smith et al., 1992; unpublished data). These materials must be preserved in the "vitrified" state. We have obtained LN-survival rates ranging from 30 to 90% of control, depending on the species and developmental status. Some of the larger embryos remain problematic.

In vitrified samples with high moisture contents, lethal ice crystals do not form even though samples are stored at sub-freezing temperatures (Fahy et al., 1984). Ice is prevented because the sample was treated with cryoprotectants and then was cooled at such a fast rate that ice crystals did not have time to form. The solution in these samples becomes a glass.

There are several steps required for successful cryopreservation through vitrification (Towill, 1990). First, a stable glass must be created. This is usually accomplished by loading cells with protectants, and then adjusting the water content of cells to optimal levels which limit desiccation damage but encourage glass formation. The sample must then be cooled appropriately, and this usually means at extremely fast rates.

The protectants that are used in cryopreservation have two purposes: 1) to prevent cell constituents from denaturation during the desiccation phase and 2) to stabilize the glass. Research shows that many plant systems naturally accumulate these protectants during particular developmental stages. For example, during fall, winter-hardy woody tissues acclimate and become more tolerant to sub-freezing temperatures. Also, during maturation, orthodox seeds accumulate massive quantities of sugars and proteins believed to be protectants against various stresses. Scientists at the NSSL and elsewhere are studying the mechanisms of protection with the objective of incorporating these chemicals into tissues that do not accumulate them naturally. Non-natural protectants such as dimethyl-sulfoxide (DMSO) and ethylene glycol are also commonly used.

There are several ways in which tissues can be dried to moisture levels optimal for vitrification. For example, shoot tips can be soaked in strong osmotica, which mainly serves to remove water. This method has been used at NSSL during vitrification procedures of shoot tips. Tissues can also be dried via the "two-step" cooling process (Sakai and Sugawara, 1978). First, tissues are slowly cooled to about -30°C. This allows intracellular water to migrate to extracellular spaces where it freezes. In this way, the intracellular solution is concentrated to an optimum level. This procedure has been adopted to preserve vegetative apple buds (Towill, 1990). The optimum level and the rate of water migration are a function of the species, tissue type, and level of acclimation to low temperatures.

Another method of drying that is used for embryonic axes excised from recalcitrant seeds is called "flash" drying (Berjak et al., 1989). This procedure, developed at NSSL in collaboration with scientists from South Africa, requires that small pieces of tissues be dried under a rapid flow of dry gas (Pammenter et al., 1991). Tissues are dried so rapidly that there is insufficient time for desiccation damage to develop.

Once the water content in tissues has been optimized, the tissues are rapidly cooled in liquid nitrogen. Cooling rates of up to 2000°C/sec are required to prevent lethal freezing. To achieve these rapid cooling rates, scientists at the NSSL are plunging capillaries holding minute tissues into liquid nitrogen or propelling samples into sub-cooled nitrogen slush using a spring loaded gun (Wesley-Smith et al., 1992).

Vitrified samples must be stored at temperatures where the glass cannot "melt." This necessitates storage at very low temperatures, either directly in liquid nitrogen (-196°C) or just above liquid nitrogen (about -160°C)(Fahy et al., 1984). Thawing cryopreserved samples is also critical and is usually done rapidly to avoid formation of ice. When samples are retrieved from storage, they are grown in culture and then transplanted or grafted on to existing stocks. The success of a certain cryopreservation treatment is evaluated by the proportion of propagules that develop into growing plants.

**Examples of Successful Cryopreservation**

Successful cryopreservation has been achieved in a number of different types of organisms. It has been known for about a century that orthodox seeds could tolerate exposure to liquid nitrogen temperatures without any loss of viability. The first case of routine storage of seeds in liquid nitrogen was initiated 16 years ago at the NSSL (Stanwood and Bass, 1981). As mentioned previously, the desiccation tolerance of seeds makes them extremely amenable to cryopreservation.

Preservation of spermatozoa from mammals has been routine for several decades, with survival rates ranging from 50 to 90% depending on species. Some species (e.g. porcine) continue to be problematic. The early success of these cryopreservation efforts can be attributed to the size of the propagule (less than 8 cells) and the degree of differentiation. The more recent challenge has been to preserve propagules with thousands of cells and much larger degrees of differentiation of the tissues. Successful cryopreservation has been reported for even larger tissues of plants: shoot tips by Towill and Jarrett (1992) and embryonic axes of recalcitrant seeds by Wesley-Smith et al. (1992).

The recent advances in cryopreserving propagules with several thousand cells have enabled us to adopt this technology for long-term preservation of many forms of germplasm. For example, NSSL initiated a program five years ago to cryopreserve dormant vegetative buds of apple, and in 1993 this was adopted as a routine preservation procedure. Our collection now contains over 160 accessions, many of which are sensitive to fire-blight. Eventually all of the 2,500 apple accessions in the Geneva orchards will be backed up in the base collection at the NSSL.

## THE NATIONAL PLANT GERMPLASM SYSTEM

The Research and Marketing Act of 1946 (Public Law 733) authorized the creation of four Regional Plant Introduction Stations (Ames, Iowa; Geneva, New York; Griffin, Georgia; Pullman, Washington) with the mission to acquire, maintain, evaluate, and distribute germplasm to scientists to be used for crop improvement. The National Small Grains Collection, now in Aberdeen, Idaho, began in 1894 as a breeder's collection in Beltsville, Maryland. The Inter-Regional Potato Introduction Station, Sturgeon Bay, Wisconsin, was established in 1947. National Clonal Germplasm Repositories were established in the mid-1980s to provide more systematic maintenance of vegetatively propagated germplasm. These repositories grow and maintain the active collection and distribute samples to scientists worldwide.

The National Seed Storage Laboratory (NSSL), Fort Collins, Colorado was established in 1958. The principal mission of NSSL is to preserve the base collection of the NPGS and to conduct research to develop new and improved technologies for the preservation of seed and other plant propagules. The goal of NSSL is long-term preservation of backup samples of all accessions maintained in active collections at national plant germplasm repositories.

These units have been integrated into a National Plant Germplasm System (NPGS) (ARS Information Service, 1990; Shands et al., 1989). The NPGS is a network of cooperating institutions, agencies, and research units in the Federal, State, and private sectors. The mission of the NPGS is: "To effectively collect, document, preserve, evaluate, enhance, and distribute plant genetic resources for continued improvement in the quality and production of economic crops important to the U.S. and world agriculture. This is achieved through a coordinated effort by the U.S. Department of Agriculture in cooperation with other public and private U.S. and international organizations. Plant genetic resources in the NPGS are made freely available to all *bona fide* users for the benefit of humankind."

In addition to the active and base collections in NPGS, plant breeders maintain working collections of plant materials used in their programs. As cultivars, parental lines, and elite germplasm are developed, released, and registered, these are entered in the NPGS active and base collections.

The activities of the NPGS help to provide high-yielding cultivars to farmers, improve the quality of agricultural and horticultural products, minimize production costs, reduce dependence on pesticides (thus enhancing the quality of the environment), and minimize the vulnerability of agriculturally important germplasm to pests and environmental stresses.

The Germplasm Resource Information Network (GRIN) is the official database of the NPGS and is currently maintained on a computer in the National Agricultural Library at Beltsville, Maryland. Data in GRIN are available to any plant scientist or researcher worldwide, either through a telephone connection to the database or through contact with the curator for the active collection of the crop.

Plant germplasm collections include older and current crop cultivars, elite breeding lines, landraces of crops that have emerged over millennia of selection by farmers, wild or weedy plants related to cultivated crops, and genetic stocks maintained for research.

As accessions propagated by seeds are regenerated or increased at the repositories, seed samples are divided with part staying in the local active collection and the other part deposited in the NSSL base collection. Seed samples received at NSSL are dried, counted, tested for viability and placed in moisture-resistant containers in sub-zero cold vaults (-18°C) or stored above liquid nitrogen (-160°C) in cryotanks. Samples are monitored periodically for viability, and sub-standard samples are regenerated by the appropriate repository.

Plant germplasm preservation research at NSSL focuses on the development of new and improved technologies for the long-term preservation of all forms of plant germplasm. This research is expected to increase: 1) the number of species that can be stored at NSSL, 2) the longevity of the various accessions, and 3) the efficiency of viability testing of accessions. Longer storage periods and reduced number of field and/or greenhouse regeneration cycles will result in lower costs and greater genetic integrity of the germplasm. In addition, basic research will add to our understanding of cryobiology and seed/cell aging through greater insights into the basic biological/biochemical processes in cells and their response to desiccation and low temperature stresses. Research scientists at NSSL work closely with all components of NPGS.

Minimizing genetic change during *ex situ* preservation is paramount to retain as much genetic variation as possible for future use. A key first step for seed is to preserve the initial regenerated sample in the base collection. This regeneration should be done with an appropriate number of plants under optimum growing conditions to produce high quality seed. Careful processing and drying are required to maintain high viability. Storage of dry, high quality seed at sub-zero temperatures can extend viability for many years before a second regeneration of the base collection is necessary. When continuing demand on the active collection occurs, seed from the base collection should be used for every second or third regeneration.

The National Plant Germplasm System is the largest *ex situ* collection of plant genetic resources in the world. A detailed report of the NPGS history, policies, and architecture is given in *Plant Breeding Reviews* (ed. by J. Janick, 1989). Since 1898, about 575,000 accessions with real or potential economic importance to U.S. agriculture have been acquired through the Plant Introduction Office. Many of these are among the more than 415,000 accessions, representing over 8,000 plant species, that are now preserved in the NPGS (Table 1).

The NPGS has been described as a "user-driven system." Between 1986 and 1992, the NPGS distributed an average of 175,400 samples each year to U.S. public scientists (67%), U.S. private industry scientists (12%), foreign public scientists (9%), foreign private industry scientists (10%), and international centers and USAID (2%).

## INTERNATIONAL COOPERATION AND COORDINATION

The need to preserve, exchange, and utilize plant genetic resources is now recognized worldwide. Even countries with great genetic diversity in certain crops are heavily dependent on many crops introduced from other areas. Because the U.S. has had to import nearly all of its crop germplasm, the NPGS maintains a very comprehensive germplasm collection from around the world. The NPGS has been able to assist several countries recover germplasm of their key crops which had been lost for various reasons.

Many countries now have genetic resource preservation programs with an associated gene bank. The NPGS maintains a close working relation with many of these programs and freely exchanges germplasm.

Table 1. National Plant Germplasm System Genetic Resources.

| Species | Crop | Number of Accessions |
|---|---|---|
| *Arachis hypogaea* | PEANUT | 7,943 |
| *Avena sativa* | OAT | 6,580 |
| *Avena sterilis, etc.* | OAT RELATIVES | 13,419 |
| *Cajanus cajan* | PIGEON-PEA | 4,156 |
| *Capsicum annuum* | PEPPER | 2,313 |
| *Carthamus tinctorius* | SAFFLOWER | 2,218 |
| *Cicer arietinum* | CHICKPEA | 3,962 |
| *Cucumis melo* | MELON | 3,374 |
| *Glycine max* | SOYBEAN | 14,316 |
| *Gossypium hirsutum* | COTTON | 4,746 |
| *Helianthus annuus* | SUNFLOWER | 2,607 |
| *Hordeum vulgare* | BARLEY | 28,612 |
| *Lens culinaris* | LENTIL | 2,618 |
| *Linum usitatissimum* | FLAX | 2,722 |
| *Lycopersicon esculentum* | TOMATO | 8,601 |
| *Medicago sativa* | ALFALFA | 3,454 |
| *Oryza sativa* | RICE | 18,213 |
| *Phaseolus vulgaris* | BEAN | 10,448 |
| *Pisum sativum* | PEAS | 3,590 |
| *Secale cereale* | RYE | 2,618 |
| *Solanum tuberosum* | POTATO | 5,486 |
| *Sorghum bicolor* | SORGHUM | 34,480 |
| *Triticum aestivum* | WHEAT | 34,391 |
| *Triticum durum* | DURUM WHEAT | 6,831 |
| *Vigna unguiculata* | COWPEA | 3,958 |
| *Zea mays* | CORN | 28,376 |
| Others | | 155,710 |

## CORE SUBSETS

When a breeder determines that there is inadequate genetic variation in available germplasm, new accessions are needed that will provide the highest probability of identifying useful source materials with minimum screening. Sometimes this can be achieved by obtaining accessions from an area where the problem has been endemic for many years; e.g., low soil pH, high altitude with low night temperatures, etc. A list of candidate accessions can often be generated from GRIN when appropriate information is in the passport or evaluation database.

In other cases, especially for new pathogen strains or insect biotypes, searching on database information is of little value. When the breeder must search within the crop collection for the desired trait, an initial screening of a smaller, diverse subset may reduce costs. The idea of developing such a subset was proposed by Frankel (1984) and further developed by Brown (1989a,b). A core collection (subset) should contain, with a minimum of genetic repetitiveness, the diversity of a crop species and its relatives. Brown (1989b) recommended stratified sampling methods whereby germplasm accessions are selected from groups based on geographical origin and genetic characteristics. The remaining accessions in the crop collection are called the reserve subset. In the event the desired trait is not found by screening the core subset, the reserve subset will be readily available for additional screenings. The core subset is suggested to be about 10% of the entire collection, but may be proportionally larger for small crop collections. In the process of developing the core subset, it may be noticed that important geographic areas were not represented in the collection. This will stimulate additional collection to include those areas. The core subset concept has gained wide acceptance and core subsets are being developed in many countries (Erskine and Muehlbauer, 1991; Hodgkin et al., in press). Crossa et al. (in press) discuss some practical problems of forming a core subset in maize and present an example.

The core subset will be used for more extensive characterization and evaluation. These data will be used to establish measures of genetic distance between accessions (Smith and Smith, 1992; Beer et al., 1993). The development of core subsets will be a dynamic process whereby similar accessions will be replaced by those with greater genetic diversity as pertinent information becomes available.

NPGS is developing a core subset for each of the major crop collections [e.g., peanut (Holbrook et al., 1993) and annual *Medicago* (Diwan et al., 1994)]. Once this is implemented, NPGS will have reduced costs associated with maintaining the reserve subset, and breeders will be able to screen for new sources of needed genetic traits more efficiently.

## SUMMARY

Because very few crops grown in the U.S. are native, plant introductions have been vital to our agriculture. The development of a comprehensive NPGS for *ex situ* preservation of plant genetic resources obtained from centers of diversity around the world has been necessary to provide scientists with source materials for their programs.

The more than 415,000 accessions maintained by the NPGS include local landrace collections, improved cultivars, wild crop relatives, and genetic stocks. The active collection is maintained and distributed by nineteen national plant germplasm repositories. The base collections for seed crops are preserved at sub-zero temperatures at the National Seed Storage Laboratory, Fort Collins, Colorado. Plant genetic resources of the NPGS are made freely available to all *bona fide* users for the benefit of humankind. Between 1986 and 1992, an average of 175,400 samples per year were distributed worldwide by NPGS.

It is important that genetic changes during *ex situ* preservation are minimized. The procedures now used by the NPGS for orthodox seeds include regenerating a high quality initial sample for the base collection, carefully drying and storing this base collection sample at sub-zero temperatures, and using seed from the base collection sample for regenerating every second or third generation for the active collection. Improved technologies and new facilities help insure that these valuable resources will be available in future years with minimum genetic shifts.

The technologies required to preserve genetic resource propagules in *ex situ* collections in a living but quiescent form is rapidly developing. In the past decade, there have been major technological advances which allow us to store living organisms in "suspended animation." This technology will enable us to store our valuable genetic resources safely and efficiently.

A core subset consisting of about 10% of each crop collection can be developed which would still represent most of the genetic diversity of that crop species and its relatives. The NPGS is identifying and characterizing a core subset of each major crop to be used for initial screenings to improve efficiencies of breeders and active collection curators.

Not only have public and private plant breeders used introduced germplasm from the NPGS and other sources effectively to produce stress tolerant and high yielding varieties and hybrids, but also farmers have used these improved products to increase yields and lower costs so that the average U.S. family now spends less than 12% of its income for food.

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*High Altitude Revegetation Committee*

*Compiled by*

*David L. Buckner, Patrick H. Murphy, and H. Ward Marotti*

** Part 1 - Subject Index and Part 2 - Author Index were made available to 1994 Workshop Registrants as part of registration materials.*

# PART 3
# SPECIES INDEX

**(Each item is ended with author in parentheses followed by year and page numbers; nomenclature follows the published articles and, thus, is of mixed origins.)**

## PARTICIPANT LIST

We were pleased to have a total of 210 participants at the Eleventh High Altitude Revegetation Conference. Representatives from three foreign countries, as well as from 16 states attended the conference (Table 1). As you can see from the data in Table 1, most of the participants came from Colorado, however, people from both coasts and from as far away as from Alaska were present.

For all of you that came, thank you for your participation in the conference. Make plans for attending in 1996. The High Altitude Revegetation conference will be held on February 21-22, 1996, at Fort Collins, Colorado. Pass the word to your colleagues, so that the 1996 conference will be a great success

Editors

Table 1. Geographical distribution of participants at the Eleventh High Altitude Revegetation Conference.

| Geographic Entity | Number of Participants | Percent of Total Participants |
|---|---|---|
| | | |
| **CANADA** | | |
| Alberta | 2 | 0.95 |
| | | |
| **SWITZERLAND** | 1 | 0.48 |
| | | |
| **UNITED STATES** | | |
| Alaska | 1 | 0.48 |
| Arizona | 4 | 1.90 |
| California | 8 | 6.67 |
| Colorado | 150 | 71.43 |
| Idaho | 1 | 0.48 |
| Illinois | 2 | 0.95 |
| Indiana | 1 | 0.48 |
| Montana | 6 | 2.86 |
| Nevada | 1 | 0.48 |
| New Mexico | 3 | 2.50 |
| North Carolina | 2 | 0.95 |
| South Dakota | 7 | 3.33 |
| Tennessee | 1 | 0.48 |
| Utah | 7 | 3.33 |
| Washington | 3 | 2.50 |
| Wyoming | 10 | 4.76 |
| | | |
| Total | 210 | 100.00 |

ELEVENTH HIGH ALTITUDE REVEGETATION WORKSHOP

MARCH 16-18, 1994

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