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Reestablishing Natural Succession on Acidic Mine Spoils at High Elevation: Long-Term Ecological Restoration

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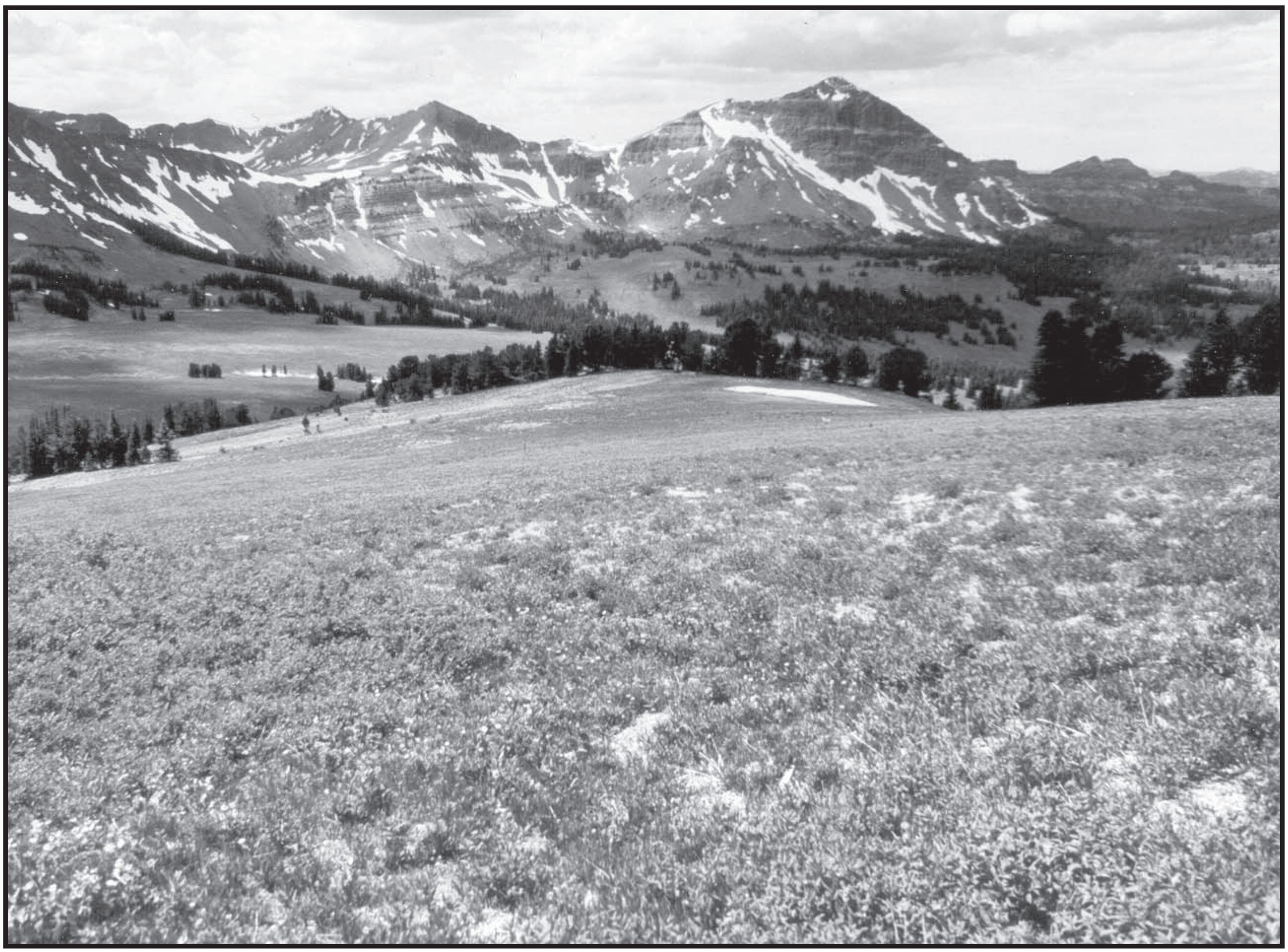

Abstract

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Methods for restoring native plant communities on acidic mine spoils at high elevations were evaluated in a "demonstration area" in the New World Mining District of southern Montana. Research plots installed in 1976 were assessed for 22 years and compared with adjacent native reference plant communities. A 1.5-acre (0.61-ha) area of mine spoils was shaped and treated with hydrated lime, organic matter, and fertilizer. The area was then seeded heavily with five native grasses collected from adjacent native plant communities. Natural seed rain, transplanting, refertilization, and use of introduced species were also studied.

During periods of fertilization, biomass and cover were twofold greater than in adjacent native reference communities in some years, but then rapidly declined to levels observed in native reference communities. Natural succession was accelerating within the demonstration area toward formation of a native community with characteristics similar to adjacent reference areas. Soil genesis was progressing and a soil "A" horizon was developing. Use of native seral species appears necessary for long-term formation of a self-sustaining natural community. Both transplanting and natural seed rain on treated spoils resulted in significantly lower biomass and cover levels than on the seeded area.

Our data demonstrate that acidic mine spoils, such as in the New World area, can be treated successfully in-place with lime, organic matter, and fertilizer, and then seeded with a mixture of native seral grasses, followed by surface mulching with erosion blanket. Capping with native soils is unnecessary. Reclamation principles and procedures are summarized.

Keywords: reclamation, restoration, acid mine spoils, alpine, native species

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Contents

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Introduction

A growing demand for natural resources throughout the Western United States is placing pressure on public land managers to implement effective ecological restoration of severely disturbed sites. Population centers and rural developments are rapidly expanding, and the natural resources needed to support them are being sought in increasingly more distant and remote areas. As a result water, minerals, fossil fuels, timber, grazing lands, recreational lands, wildlife habitat, and aesthetic attributes are in greater demand than ever before. However, disturbances to the land often alter the integrity of natural resources resulting in either their complete loss or a degraded condition that affects their availability and quality. Hence, public land managers are faced with the problem of treating both historic and current land disturbances in order to restore the integrity of impacted areas.

Both natural phenomena and human activities can result in severe disturbances of wild lands. For example, natural disturbances such as seismic events or volcanism, severe climatic events such as droughts and catastrophic storms, fires, and some biological cycles of insect and disease activity can disrupt the stabilizing influence of native vegetation and expose soils and parent materials to erosion, mass wasting, and landslides. However, natural disturbances are not necessarily destructive to ecosystem form and function. Natural ecosystems evolved under the influence of various types of disturbance, and some disturbances (such as periodic fire, insect and disease cycles, cycles of natural drought, and other climatic adjustments) are essential to continued ecosystem health (Bartos and Campbell 1998; Rapport and Whitford 1999).

The relatively recent advent of large-scale, high-intensity, and high-frequency disturbances created by human activity falls outside of the evolutionary capability of ecosystems to recover. Such human-caused disturbances as road and highway construction, mining and some forms of mineral exploration, pipeline and power line construction, developments of recreational facilities, various recreational activities, town site development and expansion, and other activities often result in severe disturbances to the land. These, together with the impact of human interference in natural disturbance cycles such as fire frequency, have been responsible in recent decades for widespread alterations in ecosystem form and function.

Disturbances are referred to as "severe" if they result in the complete loss of native soil and vegetation, and if they disrupt or destroy natural surface and subsurface hydrological pathways. When wild land areas become severely disturbed, especially by human activities, various natural ecosystem processes are often destroyed or greatly altered, thus leading to a degradation in natural resource quality and quantity. Mounting evidence shows that many severe human-caused disturbances lead to major alterations in ecosystems by greatly simplifying their structure and function (Rapport and Whitford 1999). Disturbed areas when left alone to recover naturally often degrade further because natural recovery processes cannot resume.

At least three consequences exist to not directly implementing restoration following human disturbances, according to Rapport and Whitford (1999): (1) disturbed systems become vulnerable to invasive, often exotic, and highly competitive organisms with alternative adaptations that block or hinder the reestablishment of native organisms; (2) disturbances of natural soils and the loss of their complex structural and chemical properties limit the ability of the system to support native organisms, thus leading to greater instability; and (3) a disruption of nutrient cycling changes the character of the system and disperses the nutrient base capable of supporting native organisms. Often the net effect of continued degradation is a loss of productivity, diminished biodiversity, and loss of resilience in the system to recover (Brown and Amacher 1999; Rapport and Whitford 1999).

Severe human-caused disturbances are normally most significant on the local or watershed scale, but may have far greater impacts on water quality and quantity, wildlife habitat, and other attributes than some much larger scale disturbances. Locally severe disturbances are increasing on public lands throughout the West as population and associated development expands. If left untreated, they often result in accelerated rates of erosion by both water and wind, sediment transport, and the contamination of natural streams, rivers, and riparian ecosystems. The environments most susceptible to damage from such disturbances include headwater areas of critical watersheds at high elevations in mountainous terrain, riparian areas, and arid and semiarid regions throughout the Western United States.

Some disturbances are so severe that natural recovery processes have become deflected, suspended, or terminated altogether. Under these conditions, natural recovery is extremely slow or does not occur at all. Areas often left to recover by natural processes include abandoned mines on public lands, which are particularly common in mountainous regions as well as in arid areas throughout the West. In many cases, waste rock and debris containing toxic chemicals have been exposed to surficial weathering, resulting in residual material bearing little resemblance to natural soil. Mining and mineral processing often concentrates such materials in the form of spoils and tailings. Erosion from these disturbances, especially where pyritic materials and other chemicals are exposed, results in sediment transport leading to acid, metal, or other chemical contamination of adjacent downslope plant communities, waters, and riparian and aquatic ecosystems (Amacher and others 1993; Johnston and others 1975). The chemical and physical properties of such toxic spoil material frequently exceed the physiological tolerance of virtually all vascular plants, and thus inhibit or completely retard the establishment of plant seedlings and other processes of natural succession. Consequently, erosion and other degradation forces continue, sometimes for decades, further degrading water quality and other resources. In addition, surface and subsurface hydrology of such areas has been totally redefined, often to the detriment of ecosystem balance and recovery. Although total precipitation tends to be low in many Western ecosystems, episodic high-intensity storms often have dramatic effects on landscapes, stream and river channel morphology, and riparian habitats.

Restoring native wild land communities that have been severely disturbed is a critical challenge for land managers (Brown and Chambers 1990) who must reinitiate natural succession and other recovery processes to reverse effects of severe disturbances and to repair natural resource integrity. Through restoration, the self-sustaining ecological processes responsible for ecosystem stability, diversity, productivity, and resilience that were disrupted or destroyed are reestablished (for example, Cairns 1995; Jackson and others 1995; MacMahon and Jordan 1994). To accomplish this on wild land areas, natural succession is reinitiated on the disturbance to serve as the primary "driver" for developing and reestablishing natural processes, which include both the abiotic and biotic components, required to sustain the system consistent with current climatic and other environmental conditions. For purposes here, succession is defined in the broadest sense and is intentionally not restricted to just the sequential development of vegetation or plant communities. Succession can be considered the natural universal process of ecosystem genesis and development responsible for the evolution, formation, and development of ecosystem components such as flora, fauna, microorganisms, soils, nutrient cycling, hydrological properties, as well as other constituents, and their interactions.

Land management practices such as revegetation and reclamation can be used as tools to reinitiate and accelerate succession, to enhance other natural recovery processes, and to inaugurate restoration. This approach is viewed as "active" restoration, the process of intentional intervention where restoration is operatively undertaken to reverse the effects of disturbance. The converse, or "passive" restoration, is viewed as the implementation of latent management policies designed to protect impacted sites from further abuse, and may involve site protection or withdrawal from use until mitigation occurs by natural succession processes. Unfortunately, such an approach is often adopted for economic reasons rather than ecological ones, and as noted by numerous workers (Brown 1995; Lesica and DeLuca 1996; Mills and others 1994; Rapport and Whitford 1999), the approach provides no guarantees that nature can assume a natural course following severe disturbance and treatment by inappropriate methods.

We present evidence in this paper that the practices of revegetation and reclamation can be utilized to initiate succession, and we present data and experiences gathered from a mine site at high elevations in the New World Mining District of southern Montana as examples of this approach. Although the research summarized here relates to a specific location, we suggest that the principles discussed here are equally applicable to a broad range of sites and conditions throughout the West where severe disturbances have suspended or arrested succession. This research is the result of a long-term study extending from 1976 through 1998 conducted in a set of demonstration area plots on the McLaren Mine in the New World Mining District.

Research Location and Characteristics

The New World Mining District is in southern Montana near the northeastern corner of Yellowstone National Park, about 5 miles north of Cooke City, Park County, Montana (fig. 1). The geology and history of mining in the district have been documented in numerous publications (for example, Crown Butte Mines, Inc., 1990; Elliott 1980; Elliott and others 1992; Furniss 1996; Kirk and Johnson 1993; Lovering 1929; Perry 1962; Williams 1980). A complex geological history defines the region and includes periods of folding, faulting, metamorphism, and igneous intrusions during Precambrian times followed by depositions of limestone sedimentary rocks in the Paleozoic and Mesozoic eras. During the late Cretaceous and early Tertiary periods many igneous intrusions occurred, resulting in the formation of highly mineralized zones near the surface, many of which can be observed in modern times. Periods of glaciation followed during Quaternary times to form the major features of the present-day topography (Kirk and Johnson 1993).

When the glaciers retreated from the Fisher and Henderson Mountain complex some 8,000 to 10,000 years ago, there likely was no developed soil or vegetation in place as presently observed. Probably a spectrum of geologic materials, with widely ranging chemical and physical properties, became exposed at varying rates as the glaciers melted. It is reasonable to suspect that exposed slopes in highly mineralized locations may have appeared much like the raw mine spoil observed on abandoned mine sites in modern times. No doubt the exposed mineralized material containing high concentrations of metal sulfides reacted with oxygen and water to form sulfuric acid (Hawley 1972; Thomas and Hargrove 1984); the large quantities of water that flowed from the complex must have created major erosion and sediment transport pathways both at and below the surface. There is strong scientific evidence (Furniss 1996) suggesting that the sulfide-bearing rocks in the area contributed significant amounts of iron oxide as a cementing agent to form layered aprons of sediments (for example, "ferricrete") during the last 8,600 years. These data also support the probability that huge quantities of acidic water formed the primary drainage channels that are observed in the area today, and that the water in these streams normally carried high concentrations of metals and other toxic chemicals.

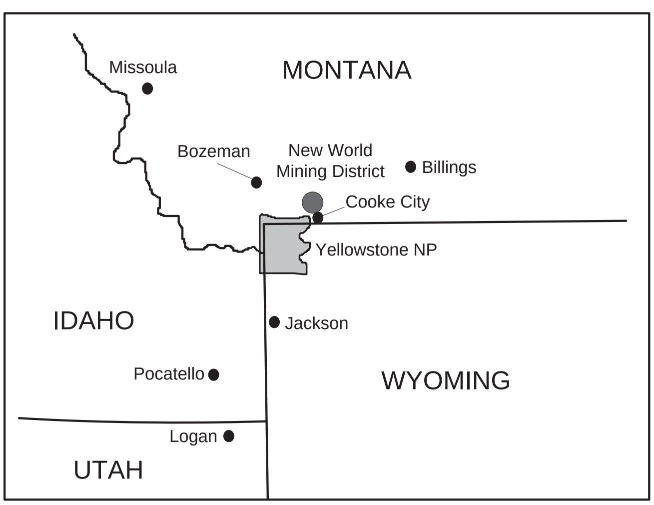

Figure 1—Location of the New World Mining District in Montana, near Yellowstone National Park.

It is believed that vascular plant seeds were transported into the area from surrounding locations by wind, animals, or other vectors, but that most were unable to become established because of physical and chemical limitations to germination and growth caused by the geologic materials exposed at the surface. It is likely, however, that some species were physiologically adapted, and that a few of these became established to form isolated pockets of vegetation in favorable locations. Today, "island" formations of Payson sedge (*Carex paysonis*) are observed on mine spoil as products of successional development, some of which support moderately complex communities of various graminoids and forbs (Haggas and others 1987; Howard 1978). Slowly, over time, we believe these islands of vegetation must have promoted soil genesis, perhaps leading to enhanced habitat diversity and species and life form richness. This would have resulted eventually in the coalescence of the small isolated vegetation patches to form varying degrees of solid stands intermixed with open nonvegetated areas. At some point the vegetation on Fisher and Henderson Mountains acquired the familiar physiognomy visible in the area today. It is likely that pyrite oxidation and sediment movement from the slopes gradually declined as the vegetation stabilized the surface and slowly minimized exposed geologic materials. It is equally likely that with continued development of plant communities, erosion and sediment transport from the more toxic materials also declined, and that some dynamic state of equilibrium was eventually achieved wherein water quality in the various streams assumed a chemical state sufficient to support some biological activity. Although it is questionable that the waters in Daisy and Fisher Creeks, the primary drainage of this mine complex, were ever truly pure or uncontaminated (Furniss 1996), it is likely that their water quality fluctuated as variable climatic events stressed the stability of the slopes above. Scattered isolated outcrops of limestone also probably mediated water chemistry in localized areas (Simonin 1988). The dynamic state of equilibrium between the stabilizing effects of vegetation and the weathering and chemical reactions that form acidity that affect water quality shifted dramatically when mineral exploration activities began in the late 1860s.

The zones of mineralization are composed of relatively high concentrations of largely unweathered acid-forming pyritic and metal sulfide minerals, which form sulfuric acid when combined with oxygen and water (Hawley 1972). These materials were observed either directly at the surface or in the form of ground water seeps by prospectors and early miners in the late 1860s in the region and were exploited to locate deposits of gold, silver, and copper. Numerous small adits and open pit mines were operated in the New World District between 1869 and the mid-1960s; the largest of these included the McLaren Mine, which operated from about 1938 to 1952, and the Como Pit and Glengarry Adit operations, which closed in the mid-1960s (Kirk and Johnson 1993). There were no formal legal requirements for reclamation of hard-rock mining operations in the 1960s, hence the abandoned mines in the New World District had not been reclaimed or treated to mediate acidic or other limiting soil conditions when mining was discontinued.

When these mines were abandoned, they were left much as they had existed while mining was active, and they are characterized by abrupt irregularly shaped spoil piles strewn across an area composed of materials of varying chemical and physical properties, often with deep rills caused by active erosion. Some abandoned mine sites supported ponds of acidic waters containing concentrated solutions of metals and other toxic chemicals that, during overflow, distributed high-volume pulses of the acid solution into the drainage. Snowmelt during the spring and frequent high intensity summer storms resulted in accelerated rates of surface erosion, surface rills, occasional mass-wasting, and transport of acid-bearing metal-loaded sediments to adjacent plant communities and into streams and other waters (Amacher and others 1993). The acidity of these mine spoils ranges between about 1.5 to 2.5 pH in the more extreme areas up to about 4.5 to 5.5 pH in mildly acidic areas.

The New World District is in the southern portion of the Beartooth Mountain Range and varies in elevation from about 8,500 to 10,500 ft (2,591 to 3,200 m). The major vegetation comprising the lower elevation zones of the area is montane, consisting largely of conifer stands of lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), and Engelmann spruce (*Picea engelmannii*), with some scattered stands of aspen (*Populus tremuloides*). At mid and higher elevations, stands of whitebark pine (*Pinus albicaulis*) mixed with subalpine fir (*Abies lasiocarpa*) are dominant, becoming scattered with open finger-shaped patterns grading to krummholz forests approaching the upper limits of tree line at about 9,800 ft (2,987 m). Near-classical krummholz trees are typical along ridges, in passes where wind is "tunneled" and concentrated, and on upper slopes near tree line. Avalanche chutes dominate the vegetation physiognomy on many steep upper slopes where coniferous forests are sharply stratified in vertical and nearly linear bands separated by unforested herbaceous communities. On gentle slopes between 9,000 to 9,800 ft (2,743 to 2,987 m) elevation subalpine communities consist of wet meadows and mesic herbaceous vegetation dominated by forbs, sedges, and grasses interspersed with islands and irregular linear stands of whitebark pine and subalpine fir. At above 10,000 ft (3,048 m), vegetation is often typical alpine consisting of low-growing forbs, sedges, and grasses. Most of the major mining operations in the New World District occurred at or near tree line within the subalpine and alpine zones.

The climate of the New World District can be characterized as a heat-limited environment in which short, cool growing seasons (45 to 60 days in length) predominate. Growing season air temperatures are often cool to cold, ranging from below freezing in the early mornings to rarely higher than 75 °F (24 °C) at mid-day, but most typically closer to 55 to 60 °F (13 to 16 °C). Although most annual precipitation occurs as snow during the winter, when more than 15 ft (5 m) may accumulate, growing season precipitation can be highly variable with rain or snow showers common during the afternoon. During the growing season, late daytime showers are often followed by cloudless nights and plummeting temperatures. Needle-ice is a frequent phenomenon throughout the growing season. Severe vertical frost thrusting at the soil surface results in significant displacement of surface soil particles and plant seedling uplifting (sometimes including roots) on disturbed barren or sparsely vegetated areas. Windspeeds and durations are highly variable but are most extreme on ridges and on the crests of sharp topographic features (such as the raw spoil piles), often displacing soil fines, organic debris, and strongly influencing the distribution of both precipitation and natural seed rain. Solar radiation flux densities are at the extreme high end of the scale for terrestrial environments, with high photon densities in the ultra violet bands.

Objectives

The principle objective of the McLaren Mine demonstration study was to determine the effectiveness of spoil treatments (liming, organic matter, fertilizer, and mulching) and planting techniques (seeding versus transplanting versus natural "seed rain") on long-term plant community development over a relatively large and variably diverse area. An additional objective was to determine the relative effects of refertilization on plant community development and soil formation. The specific questions addressed included:

1. Are results found on small research plots for establishing vegetation on acidic mine spoils equally effective on larger more variable sites?
2. Can a protective vegetation cover be established on acidic mine spoils at high elevations?
3. Does the establishment of a protective vegetation cover comprising native species lead to natural succession and the formation of natural communities?
4. Is plant establishment and community development significantly affected by planting technique?
5. Can soil cultural treatments modify limiting spoil conditions in both the short and long term to support native and introduced species?
6. Are native species required to reinitiate natural succession?
7. Does refertilization over several years enhance successional development?

Methods and Procedures

A relatively large-scale research site was installed in 1976 on the McLaren Mine (fig. 2), the largest of several abandoned mine sites in the New World Mining District, to test various hypotheses regarding the restoration of high elevation native communities disturbed by mining. The McLaren Mine, covering a surface area of approximately 35 acres (approximately 15 ha), was actively operated primarily to obtain copper, gold, and silver. The mine is on the west slope of Fisher Mountain, within a geologic intrusion that contains deposits of highly mineralized metal sulfides that, when oxidized in the presence of water, produce highly acidic byproducts (Hawley 1972). No surface reclamation or other treatments had been applied to the spoil materials on this mine following abandonment in 1952. By 1972, visible sites of active natural succession were confined to small, isolated, and scattered niches where acidity and metal concentrations did not exceed the physiological tolerances of the seral plant species in the area. Erosion and sediment movement downslope from the mine had caused substantial mortality of plant communities and

Figure 2—The McLaren Mine looking northward toward Fisher Mountain (10,300-ft elevation).

contamination of the headwaters of Daisy Creek, a major tributary of the upper Stillwater River.

The study site is along the north edge of the mine adjacent to a relatively undisturbed native plant community on a southwest-facing slope (fig. 3). The site is approximately at coordinates N45° 3.58' x W109° 57.31' at an elevation of 9,875 ft (3010 m), upslope from "Hot Hill" and the "Y" in the Park County road to Lulu Pass and Lake Abundance. This study site is routinely referred to here as the "demonstration area" (Brown and Johnston 1980a; Brown and others 1996a,b) because it was intended to demonstrate techniques and methods learned from smaller research plots in various other locations, and to illustrate the long-term effects these methods have on vegetation and soil development on larger more heterogeneous disturbed sites.

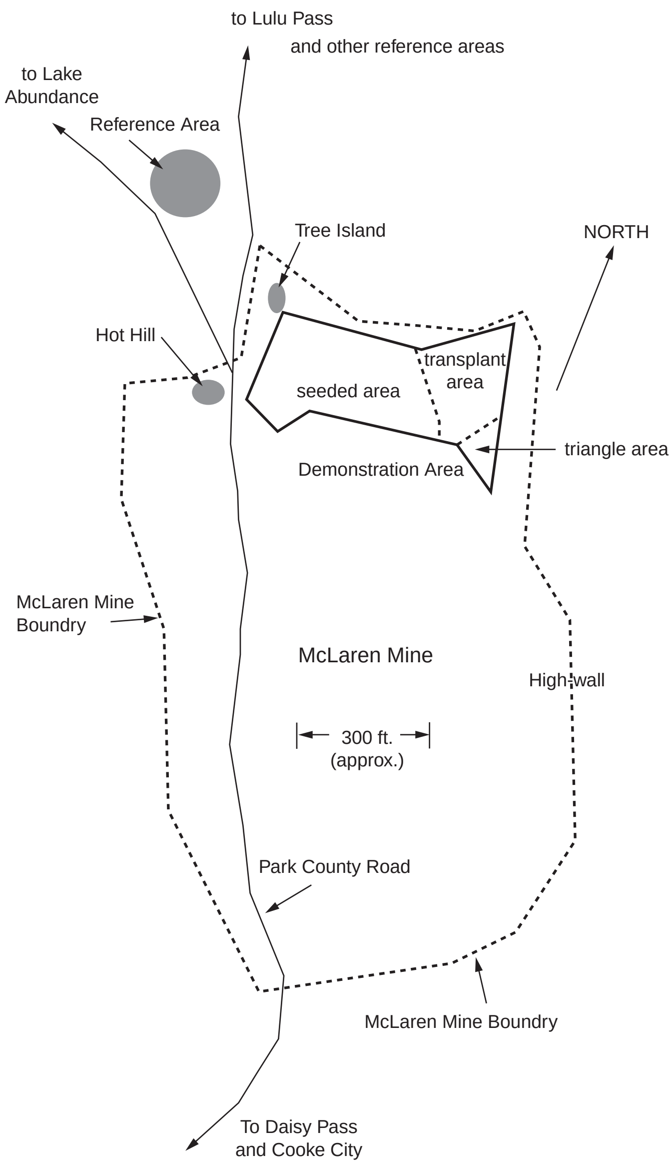

Figure 3—McLaren Mine as it existed in 1976 showing the location of the demonstration area, reference areas, and key surface features.

Specifically, the demonstration area was installed in response to several issues emerging in 1976: (1) to extend and apply the results of earlier revegetation research on the McLaren Mine and similar locations in the area (Brown and Johnston 1978a,b, 1979, 1980a,b; Brown and others 1978a,b, 1984); (2) to test new knowledge about acidic mine spoil reclamation arrived at by other workers at other locations; (3) the SEAM Program (USDA Forest Service national program, which provided funding for early research) encouraged the installation of "demonstration areas" as a means of demonstrating current techniques and illustrating current states of knowledge; and (4) at the time most experience and knowledge about revegetation and surface reclamation of high-elevation mines was based on small-scale research plot studies. Concerns regarding plant responses to treatments applied on highly heterogeneous mine spoil materials had not been addressed on large and highly variable areas. Therefore, a relatively large demonstration area that represented a broader range of surface spoil and microclimatic conditions than the usual research plot encompassed was installed to respond to these needs.

Shaping and Contouring

The site selected for the demonstration area consisted of mine spoil overburden adjacent to the north edge of the McLaren Mine. This site was between relatively undisturbed native meadow vegetation to the north and remnant mine spoil piles dissected by drainage channels and trenches to the south. In 1976 the surface was highly variable topographically: composed of numerous irregular mine spoil piles of varying sizes, shapes, and chemical compositions on a southwest-facing slope of about 15 to 20 percent steepness. In early August 1976, a D-7 bulldozer was used to contour and shape an area of approximately 1.25 acres (0.51 ha) to approximate the original surface contour based on observations of the immediately adjacent undisturbed slope. The intent was to blend the different spoil materials and to integrate the shape and slope of the entire area with the adjacent native plant communities upslope of the site.

Mine Spoil Amendments

After the shaping and contouring, spoil samples from the upper 6 inches (15 cm) depth were collected from 18 locations on a grid pattern across the demonstration area and were analyzed for pH, general nutrients, and other chemical composition (table 1). Based

Table 1—Mine spoil properties measured in the demonstration area following shaping and contouring, but before being treated with amendments, August 1976.

Sample no.	Depth	pH	ECe mmhos/	Coarse fragments	NH4OAc extraction K	Ca	Mg	P	DTPA extract Cu	Fe	Mn	Zn
			cm	*% by wt*	*- - - mg/kg - - -*							
1	0–15	3.5	0.2	42	11	94	28	9	8.6	175	2.0	2.2
2	0–15	4.8	.4	56	51	125	36	12	16.0	26	5.0	4.7
3	0–15	2.3	1.2	58	42	192	21	5	8.9	196	3.0	1.4
4	0–15	3.1	.3	44	28	216	25	8	37.0	127	1.8	17.3
5	0–15	3.4	.3	48	22	489	36	19	6.9	210	5.9	16.5
6	0–15	3.2	.4	56	36	79	68	11	3.8	69	11.3	8.0
7	0–15	4.1	.2	62	38	233	42	4	57.0	243	2.3	2.8
8	0–15	3.6	.4	49	41	382	52	7	77.0	108	12.9	1.0
9	0–15	3.8	.3	52	30	588	34	16	32.0	86	8.0	8.9
10	0–15	3.3	.4	55	55	109	62	14	4.9	217	11.0	5.6
11	0–15	3.7	.3	53	52	944	41	10	2.4	263	18.0	2.8
12	0–15	4.1	.7	41	19	631	48	7	1.8	146	2.8	.9
13	0–15	3.5	.2	48	31	211	52	5	2.9	202	4.9	1.8
14	0–15	3.6	.6	58	26	197	39	4	5.6	149	5.1	2.7
15	0–15	4.1	4.8	56	12	288	41	3	7.2	169	19.0	3.6
16	0–15	3.5	.5	47	18	309	20	9	1.8	249	.2	.4
17	0–15	3.3	.1	45	28	366	96	16	28.0	181	1.5	2
18	0–15	4.1	.4	61	36	99	47	10	3.1	218	1.9	3.8
Mean		3.61	0.65	51.72	32.00	308.44	43.78	9.39	16.94	168.56	6.48	4.80
Standard error		0.13	0.25	1.52	3.09	54.04	4.34	1.09	5.05	15.43	1.35	1.17

on these analyses, requirements for lime, organic matter, and fertilizer amendments were determined. Decisions about application rates and other amendment concerns were guided by using information largely developed for agricultural applications and by comparing the spoil material soil properties with those on adjacent undisturbed reference sites as well as on several prominent active successional mine spoil communities. Lime requirements to partially neutralize spoil pH (Barber 1984; Sorensen and others 1980) were determined by incubating a series of samples containing a known mass of 2 mm sieved spoil, each sample mixed with a different mass of hydrated lime in saturated solution, followed by monitoring pH over time until stability was achieved (the pH of our samples stabilized within 30 days). Fertilizer and organic matter (steer manure) rates were determined by bioassay comparisons of plant growth and development of tufted hairgrass (*Deschampsia caespitosa*, a native species) and Garrison meadow foxtail (*Alopecurus pratensis*, a commercially purchased introduced species) in greenhouse trials (Brown and Johnston 1980b).

In late August 1976, hydrated lime ($Ca(OH)_2$) was applied over the entire surface at the rate of 1.44 tons per acre (3,227 kg per ha) using a manure spreader pulled by a small bulldozer. Organic matter in the form of sterilized steer manure was similarly applied to the entire area at the rate of 4.24 tons per acre (9,500 kg per ha). Both amendments were incorporated simultaneously into the upper 6 inches (15 cm) of mine spoil over the 1.25-acre (0.51-ha) site, smoothed, shaped, and contoured using a spring-toothed harrow pulled by a small bulldozer. This was completed a full month before seeding and planting to minimize any potential adverse chemical reactions between the hydrated lime and seeds or live plant tissues. The rate of lime application raised the pH of the upper 6 inches (15 cm) of spoil from about 3.5 to about 5.5 to 6.0 over the entire treated area within about 30 days.

In September 1976, a granular form of 18-40-5 (18 percent nitrogen, 40 percent phosphorus, and 5 percent potassium, by weight) + 5 percent Zn fertilizer was uniformly distributed over the entire 1.25-acre (0.51-ha) area at the rate of 100 lb N per acre (111 kg N per ha), and then incorporated to an approximate depth of 6 inches (15 cm) using the same equipment described above. This resulted in a bulk application rate of about 555 lb per acre (623 kg per ha) fertilizer.

Seeding

Following the incorporation of the fertilizer and other amendments, an approximately 0.75-acre (0.30-ha) area on the lower slope of the site was selected to be seeded with a mixture of locally collected native grasses and sedges (designated the “seeded area”). A smaller

0.5-acre (0.2-ha) site up the slope was selected for transplanting native species (designated the "transplant area"). A small triangular shaped area (designated the "triangle area") at the southeast corner of the site was used to observe the effects of natural seed rain (fig. 4).

The 33,600-ft^2 (3139-m^2) seeded area was seeded with a mixture of seven native species (table 2) collected from native plant communities in the immediate vicinity of the McLaren Mine. Species selection was based on observations of natural succession on surrounding disturbances in the area. Only the major graminoid species were targeted for collection because forbs produce small quantities of seeds in highly scattered stands, hence sufficient seeds of forbs could not be collected by hand in the time available. The graminoid seeds were collected by individual species throughout the summer (principally August and early September 1976) by hand stripping. The bulk seeds were maintained separately by species during air drying, then were weighed mixed together. The ratio of seed weights by species displayed in table 2 reflect seed availability

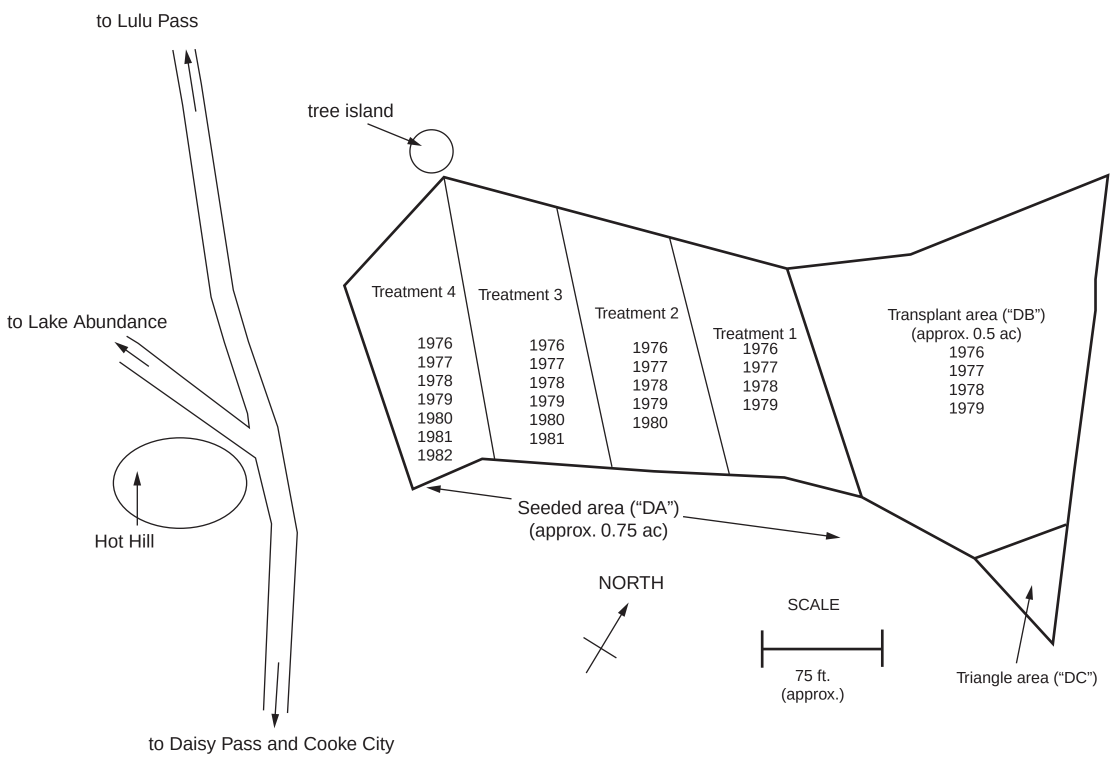

Figure 4—The demonstration area showing individual plot areas, including the seeded area, transplant area, and natural seed-rain ("triangle") areas. The four refertilization treatments (showing the years of fertilizer reapplication) are all located within the seeded area.

Table 2—Native plant seed mixture, quantity, and germinative ability used in the seeded demonstration area, September 1976.

Scientific name	Common name	Pounds per acre	Kilograms per ha	Percent germination
Agropyron scribneri	Spreading wheatgrass	1.4	1.6	36
Agropyron trachycaulum	Slender wheatgrass	7.7	8.6	58
Carex paysonis	Payson's sedge	6.9	7.7	6
Deschampsia caespitosa	Tufted hairgrass	40.2	45.1	72
Phleum alpinum	Alpine timothy	4.6	5.2	78
Poa alpina	Alpine bluegrass	11.3	12.7	84
Trisetum spicatum	Spiked trisetum	1.7	1.9	49
Total		73.8	82.7	

at the time and was not a predetermined quantity or objective. Seeding rates were not adjusted by seed germinative ability, although germinative ability was determined. The mixed seeds were distributed over the seeded area at the equivalent bulk rate of 73.8 lb per acre (83 kg per ha) using a Brillion seeder-packer with a top-mounted "hopper" pulled by a small bulldozer. The mixed seeds fell from the hopper along the leading edge of a gang of cast iron wheels that pressed the seed into the freshly turned, treated spoil to a depth ranging between 0 and approximately 0.5 inch (0 to 1.3 cm) following incorporation of the fertilizer. The last gang of wheels on the seeder-packer rolled over the surface roughly smoothing it and leaving shallow linear grooves in the soil surface. Large rocks and stones on the spoil surface prevented the seeder-packer from creating a perfectly uniform grooved surface. At the time we felt that this was an ideal means for placing the seed because it provided protection against predation, wind redistribution, and dehydration. However, the variable size, density, and shape of the seeds of the different species often resulted in stratification of species within the hopper, requiring frequent hand mixing to maintain a semblance of uniformity in distribution of the seeds. We no longer recommend this procedure, but rather suggest broadcasting of seed mixtures followed by raking to lightly cover them with soil.

Surface Mulching

Following seeding, the entire area was surface mulched with straw at the rate of 5,080 lb per acre (5692 kg per ha) using a straw blower pulled by the small bulldozer. The straw blower mixed a water-based asphalt emulsion agent with the straw fibers as they were blown out over the area. This asphalt emulsion material provided a sticking agent to the individual straw fibers to minimize their redistribution by wind. Following mulching, the surface of the spoil material was still partially visible when observed vertically through the individual straw fibers, but not when viewed from an oblique angle across the entire area.

Transplanting

The transplant area was installed following the application of straw mulch. A total of 5,363 grass "plugs" (whole grass plants grown in 1 x 6 inch [2.5 x 15 cm] greenhouse polyvinyl chloride tubes) were planted in this area. Of these, 3,929 (73 percent) were native species and 1,434 (27 percent) were introduced species (Brown and Johnston 1978b) (table 3). The native species were grown from seeds of the same grasses used in the seeded area. Plants of the introduced species were grown from seed purchased from commercial sources. All plants were grown at the Coeur d'Alene Nursery in northern Idaho by the USDA Forest Service and then transported in the tubes to the research site for a 20-day "hardening-off" period under local conditions. The root system of each plant plug was planted in approximately 6 to 8 inches (15 to 20 cm) deep holes dug into the amended spoil material. Holes were on 2-ft (60-cm) centers in straight rows across and perpendicular to the slope, and each row was

Table 3—Number of native and introduced plant species transplanted in the demonstration area, September 1976.

Scientific name	Common name	Number planted
Native species		
Agropyron scribneri	Spreading wheatgrass	8
Agropyron trachycaulum	Slender wheatgrass	124
Deschampsia caespitosa	Tufted hairgrass	993
Phleum alpinum	Alpine timothy	1,016
Poa alpina	Aopine bluegrass	1,682
Trisetum spicatum	Spiked trisetum	86
Total native species		3,909
Introduced species		
Alopecurus pratensis	Meadow foxtail	349
Bromus inermis	Smooth brome	272
Dactylis glomerata	Orchardgrass	270
Festuca arundinacea	Alta fescue	245
Phleum pratense	Timothy	248
Poa compressa	Canada bluegrass	70
Total introduced species		1,454
Total all plants		5,363

spaced also at 2-ft (60-cm) intervals. Each row consisted of between about 50 to 86 plants; each row contained either all native or all introduced species. Usually two consecutive rows of native species were followed by one row of introduced species.

Care was taken to minimize variables of technique and procedures that could influence plant survival. For example, we sorted out and discarded all underdeveloped or unhealthy appearing plants; we also were careful to spread the root systems of each plant in the access hole and cover and firmly pack the root system with fine-grain spoil material to minimize exposure to drying air. The distribution of native and introduced species was alternated over the area to minimize possible effects of slope position and heterogeneity in the spoil material. Because the weather during planting was warm and dry, following the planting of each row each plant was provided with about half of a quart (0.5 l) of water collected from an adjacent meadow.

Natural Seed Rain

A small triangular portion of the southeast corner of the demonstration area (fig. 4) is referred to as the natural seed-rain area (or "triangle area"). This 2,500-ft^2 (232-m^2) area was treated with hydrated lime, organic matter, fertilizer, and straw surface mulch, but was not planted either with seed or transplants. All plant establishment and growth in this area resulted from natural invasion and colonization resulting from normal seed rain.

Treatments and Refertilization

The entire demonstration area was fertilized with 18-40-5 granular fertilizer at 100 lb N per acre (111 kg N per ha) in 1976, 1977, 1978, and again in 1979, resulting in 4 consecutive years of fertilization. Beginning in 1980, the 0.75-acre (0.30-ha) seeded area was divided into four separate, approximately equal-sized blocks across the slope (treatments 1, 2, 3, and 4 in fig. 4). Each of these blocks, or plots, was subsequently treated differently (Brown and others 1984). Treatment 1 was fertilized for 4 consecutive years (1976 to 1979), treatment 2 for 5 consecutive years (1976 to 1980), treatment 3 for 6 consecutive years (1976 to 1981), and treatment 4 for 7 consecutive years (1976 to 1982). The transplant plot and the natural seed-rain area were fertilized only during the same 4 years as treatment 1.

Reference Area Comparisons

Native reference areas, representing a range of relative levels of successional development in the area, were selected to compare the vegetation characteristics, soil properties, and other attributes of the demonstration area with those of natural communities. These relatively undisturbed areas were intended to serve as optimal natural reference points or "targets" toward which natural succession will guide the developing revegetated communities. Although ecologically simplistic, the basic concept is considered to be valid within certain limitations. For example, we recognize that the demonstration area probably will not achieve identical features of vegetation, soil development, or other characteristics observed in adjacent reference areas for many decades, if ever. However, the characteristics within the reference areas still provide a general measure of conditions toward which potential successional development will lead, and eventually provide a quantitative destination for the developing communities.

The reference areas are considered relatively "undisturbed" because they were never mined or impacted directly by road or other construction. However, uncertainty exists about the history of these communities during the period of active mining in the area; likely some areas were disturbed to some degree as a result of human activity, especially by grazing horses or mules. Some areas remain lightly grazed by domestic horses used by hunters and recreationists as they pass through the area.

The performance of the vegetation within the demonstration area was compared and contrasted with that of native vegetation in these nearby reference areas in most years from 1978 through 1998 (table 4). These comparisons provide a relative measure of the rate of successional development within the demonstration area.

Restoration Retreatments (1993)

In 1993, a portion of the seeded area was retreated to determine the effects of followup treatments in long-term surface restoration. Figure 5 shows the location of the 12 retreated plots involving four treatments:

1. Control (no treatment)
2. Limestone (crushed fine grain agricultural-grade limestone) at the rate of 4,000 lb per acre (4,400 kg per ha)
3. Fertilizer 16-16-16 (N-P-K) at 100 lb N per acre (111 kg N per ha)
4. Fertilizer + lime, at the same rates as above A complete randomized-block design with three blocks each consisting of four plots was used. Each plot was 10 ft (3 m) wide by approximately 120 ft (36 m) long. The limestone and fertilizer were applied as a top dressing in each plot and were not incorporated into the developing soil.

Table 4—Years in which cover and biomass data were collected (marked by “X”) in the demonstration area and reference areas.

Season no.	Year	Demonstration area Live cover %	Demonstration area Total biomass	Reference areas Live cover %	Reference areas Total biomass
1	1977		X		
2	1978	X	X	X	X
3	1979	X	X	X	X
4	1980	X	X	X	X
5	1981	X	X	X	X
6	1982	X	X		X
7	1983	X	X	X	X
8	1984	X	X		X
9	1985				
10	1986	X	X	X	X
11	1987				
12	1988	X	X		X
13	1989	X	X	X	
14	1990				
15	1991	X		X	
16	1992	X	X	X	X
17	1993				
18	1994		X		X
19	1995	X	X	X	X
20	1996	X	X	X	X
21	1997	X	X	X	X
22	1998	X	X	X	X

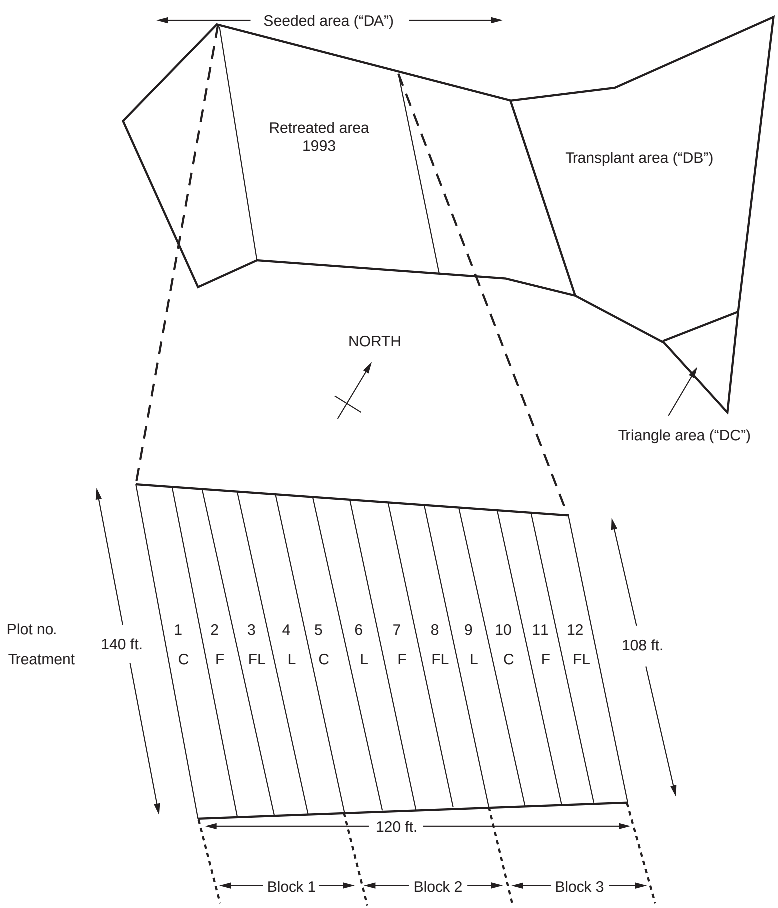

Figure 5—The demonstration area in 1993 showing the “retreated” restoration plots within the seeded area: C = control; F = retreated with fertilizer; FL = with fertilizer + limestone; L = with only limestone.

Assessment of Vegetation

Disturbance from mineral exploration and drilling in 1988 and 1989 reduced the original size of the demonstration area to about 1.1 acres (0.45 ha) through reconstruction of the road along the south and east sides of the site. In addition, substantial damage within the seeded and transplant areas was created by exploration drilling. These latter disturbances were not retreated and allowed to recover by natural colonization. Some of the differences in vegetation characteristics between the demonstration area and the native reference areas are at least partially due to these disturbances.

The vegetation in the demonstration area and adjacent native reference communities were assessed for cover and plant biomass within quadrat frames distributed across each area. Each quadrat frame defined a small sample of the vegetation, litter, rocks and stones, bare ground, and cryptogam components that made up the surface of the area. A statistically adequate description of these attributes for each community requires that a number of quadrat frames be sampled within each community to account for the spatial variability that naturally occurs. We used a large number of small 0.1-m^2 quadrats, 7.87 by 19.69 inches (20 by 50 cm), in the earlier years of our research, but later used a fewer number of larger 0.25 m^2-quadrats, 13.8 by 28.1 inches (35 by 71.44 cm). These larger quadrats appeared to account for the natural variability and distribution of native plants in New World communities with at least equal reproducibility, efficiency, and dependability as the smaller frames. The number of frames sampled in each community varied, depending upon the number of workers and time available to collect data.

The term "cover" used here is the percent of the total ground surface covered either at the surface or as vertically projected vegetation canopy within a quadrat frame. We interpret cover as a multilayered quantity consisting of live plants including cryptogams (mosses, lichens, liverworts), litter, and rocks or stones larger than 2 mm diameter. The sum cover of all these components, plus any bare ground, is never greater than 100 percent. This quantity describes the likelihood of a vertically falling raindrop, hailstone, or snowflake being intercepted by a component of cover that will dissipate its energy before impacting bare soil or the spoil surface. This cover measure provides a quantitative description of potential surface protection conditions that permits statistical comparability between sites.

Prior to 1981 we estimated cover visually in each quadrat frame by estimating the proportion of total cover contributed by each component. However, the variability among crew members was so great that we abandoned this estimation method and adopted a photographic procedure. Vertical photographs (slides) were taken over each labeled quadrat frame; these were later projected onto a 100-point grid from which the number of "hits" was recorded at each intersection point on the grid for each of the cover component. These photographs provided a permanent record of surface conditions of each site that could be revisited if questions arose regarding the validity of data. In addition, they provided a means of quantifying the data and of removing personal bias and estimation errors.

Biomass is a measure of the current year's net growth of vegetation, and includes all plant parts such as leaves, stems, flowers, seeds, and other tissues. Tissue that developed in the current growing season and then died is also included. Litter, the dead tissue standing or laying on the surface developed in previous growing seasons, was not included in biomass estimates. Biomass was collected by clipping the vegetation at ground level with scissors, placing it in labeled paper bags, and oven dried in the laboratory at 80 °C until a constant weight was achieved. We express biomass in units of ovendried grams per square meter. Our sampling protocol required that only vegetation within a vertical projection of the quadrat frame be clipped and included in the sample; aerial portions of plants rooted within the frame but extending outside of the sample projected area were excluded. Similarly, portions of plants rooted outside of the frame but that extended into the sample projected area were included. The end product is an estimate of the total biomass productivity of the site for three-dimensional volumes per unit area of surface. We clipped the vegetation within the quadrat frames by individual life form class (grasses, forbs, sedges/rushes, shrubs, and trees). In this manner, biomass could be expressed as both a total mass per unit area for all species and by life form.

It is not uncommon to observe as many as 20 to 30 individual species per 2.69 ft^2 (0.25 m^2) in many native communities in the New World. In 1995 we installed monitoring plots designed specifically to show changes over time in the distribution and abundance of individual plant species on the demonstration area, and to permit a comparison of species diversity with nearby sites that retain native soil development and that have not been altered appreciably by human-caused disturbance. The method selected, nested frequency, is similar to that used by National Forest Service Regions 1 and 4 for monitoring species changes on grassland areas. It is designed to provide quantitatively valid data with minimum effort. Frequency, although a "relative" and not an "absolute" value such as weight or density (number of individuals), is closely related to plant density when determined with appropriately sized plots. A linear relationship exists between frequency and density up to about 15 percent frequency; density diverges from frequency at higher frequency levels in a logarithmic way (Brown 1954). Density and frequency measures tend more readily to reflect long-term species trends than weight because they are not affected nearly as much by yearly variations in weather.

Our frequency sampling system consisted of establishing a permanent 65.6- by 65.6-ft (20- by 20-m) macroplot on the demonstration area and on each of three nearby undisturbed sites that reflected different levels of productivity (high, medium, and low) as judged from soil profiles and native vegetation. Five randomly selected and permanently marked transects were established across each macroplot. Ten nested frequency plots were carefully placed at 2 m intervals along each transect, for a total of 50 permanent frequency plots per site. Each nested frequency plot consisted of a 2.69-ft^2 (0.25-m^2) plot frame subdivided into a 1.35-ft^2 (0.125-m^2) and a 0.68-ft^2 (0.063-m^2) plot. These three sizes of plots appeared suitable for frequency determination of between 30 and 70 percent for the major species on the sites. In addition, the plot frame contained six points at which ground cover class was recorded, resulting in 300 ground cover points for each macroplot.

Species frequency and ground cover on the demonstration area were measured in 1995, 1997, and 1998. The high and medium production reference areas were measured in 1995 and 1997, while the low production reference area was measured only in 1995.

Characterization of Soil/Spoil Properties

Soil properties have been systematically studied at New World by Forest Service research scientists since 1973. Most of the studies of soil/spoil properties were conducted on or near the McLaren Mine on mine spoils, associated successional areas, and in adjacent native reference communities. The primary objectives in studying soil characteristics for reclamation and restoration purposes were to understand the nature of the mine spoil properties compared with natural soil, and to identify limiting conditions to plant physiological tolerances that require remediation. Numerous soil and spoil samples, ranging in depth from 0 to approximately 6 inches (0 to 15 cm), were collected primarily to characterize soil/spoil conditions in the rooting zone of vascular plants; much deeper samples were collected and analyzed at various times from numerous other locations throughout the New World area. In most cases samples were extracted using a shovel, trowel, or coring tool to specific depths. The extracted samples were stored in labeled plastic-lined paper sample bags to minimize contamination during storage and transportation. Prior to 1990 the samples were analyzed by either the Soil, Plant, and Water Analysis Laboratory, Utah State University, Logan, UT, or by A&L Laboratories, Omaha, NE. Since 1990 soil samples were analyzed jointly by Forest Service scientists in the soil laboratory at the Forestry Sciences Laboratory in Logan and by scientists in the Soil, Plant, and Water Analysis Laboratory at Utah State University.

Prior to 1989 there was a tendency to collect erratic numbers of samples from different sites, sometimes at irregular depths necessitated by a high rock content in the mine spoil, and often the properties analyzed were inconsistent. Despite this, however, a substantial body of rigorous comparable data were collected that characterize the soil/spoil properties of numerous sites at New World over time.

The most consistent and numerous samples were collected on the demonstration area and adjacent native reference communities in 1976, 1978, 1983, 1988, and 1995. The soil/spoil properties most consistently analyzed during these years include: pH, plant nutrients (including Kjeldahl nitrogen in percent, and extractable phosphorus and potassium in mg per kg), and metals using DTPA extraction (including copper, iron, manganese, and zinc in mg per kg). In 1995 we collected extensive data on rooting depths and acidity by horizon in the developing soils within the demonstration area and compared with that on the well-developed soils in adjacent native communities.

Soil/Spoil Erosion

One of the principal concerns about mine areas such as New World is the threat of erosion and movement of sediments containing toxic and other limiting chemicals to waters and offsite areas. The establishment of self-sustaining vegetation cover has been found to be the most effective and efficient means of stabilizing spoil materials and minimizing erosion and sediment transport in the long term. Methods of measuring the effectiveness of revegetation and restoration treatments, however, rarely include direct measurements of how effective these treatments are for actually minimizing and reducing erosion. We therefore attempted to directly measure with a rillmeter changes over time of various spoil and soil surface characteristics related to erosion and potential sediment movement.

The rillmeter is an instrument that measures surface roughness with a series of vertical metal pins mounted 0.10 ft (3.04 cm) apart along a straight line such that when the pins are lowered to the surface they define the surface topography. The pins are all the same length; hence the tops of the pins, when viewed against a solid background, illustrate the surface roughness of the spoil or soil. The rillmeter is mounted on a fixed and permanent set of steel stakes driven far enough into the soil to prevent frost or other forces from changing their vertical disposition. These stakes provide permanent reference points upon which the rillmeter is reset each time measurements are collected. The first set of measurements form a baseline against which all future measurements are compared.

Our instrument was 60 inches (152.4 cm) in length and contained 50 vertical stainless steel pins. If the surface defined by the pins is also 60 inches, then the surface roughness is zero. However, rill erosion or deposition creates changes in the length of the line defined by the pins. In addition, a change in the overall elevation of the line created by the top end of the pins reflects the amount of soil/spoil loss or deposition, assuming the reference stakes had not changed elevation.

We established a series of these rillmeter plots in both the demonstration area and in adjacent native reference communities that were monitored annually between 1994 and 1998.

Results and Discussion

Because most of the data were collected on the seeded area, its results are treated separately. The transplant and natural seed-rain areas are discussed together because of apparent strong interactions between the two areas, and the data from both were collected and analyzed less frequently than that in the seeded area.

Seeded Area

Biomass and Live Cover—Total vascular plant biomass and percent live cover were the most sensitive and descriptive data collected in the seeded area. The seeded area and adjacent reference areas were assessed for these attributes during or immediately following the period of peak growth and production (usually mid to late August) in most years (fig. 6). These data show that both the biomass and live cover of the demonstration area were generally significantly higher during the period of active refertilization (1977 to1982) than after refertilization was terminated. Biomass and live cover within the demonstration area declined and more closely resemble the biomass and cover data collected in the reference areas after refertilization was discontinued (1983 to1998).

The history of the seeded portion of the demonstration area was complicated by various substudies, including the four refertilization treatments studied between 1977 and 1982, and by the 12 retreatment plots installed in 1993. To understand the implications of these various studies on the overall development of vegetation within the seeded area and how

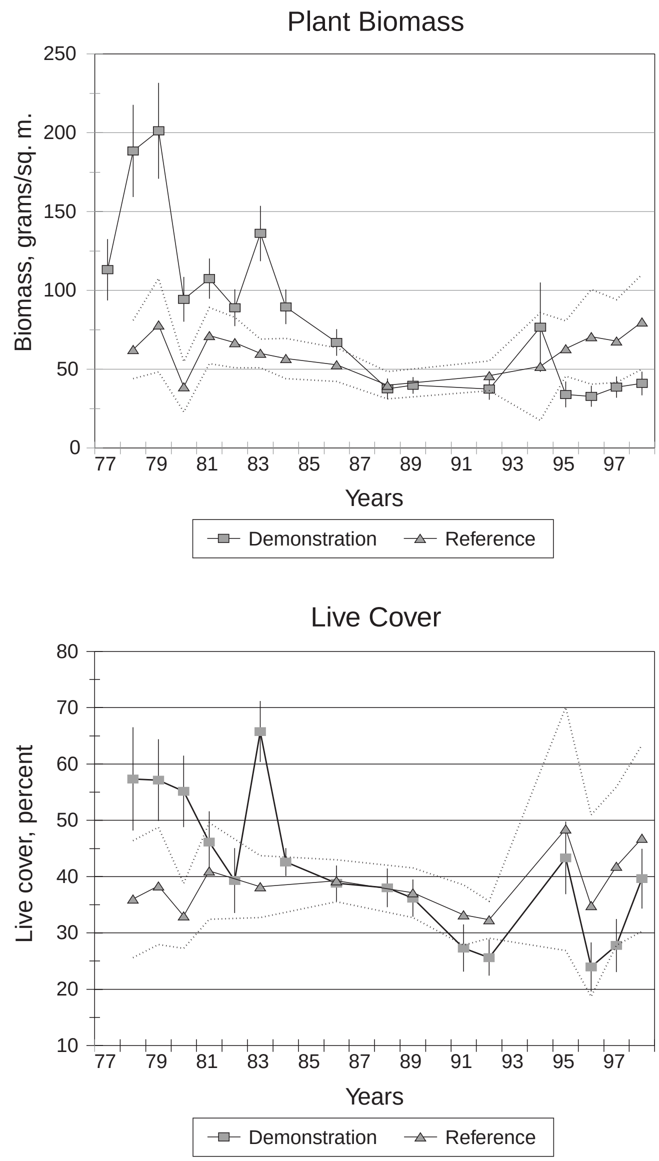

Figure 6—Mean biomass and percent live cover (with 95-percent confidence intervals) of vegetation within the demonstration area contrasted with native reference areas, 1977 to 1998.

these different studies may have affected comparisons with reference areas, the biomass and live cover data were partitioned into "periods" of various duration that reflect the research history of the site. The data illustrated in figure 7 display mean annual total biomass and live cover for each of three periods: (1) the period of active refertilization 1977 to1982; (2) the post refertilization period 1983 to 1992; and (3) the late post refertilization period between 1993 to1998.

The average annual biomass for the reference areas was 542 lb per acre (60.8 g per m^2) between 1977 to1998, whereas for the demonstration area the mean

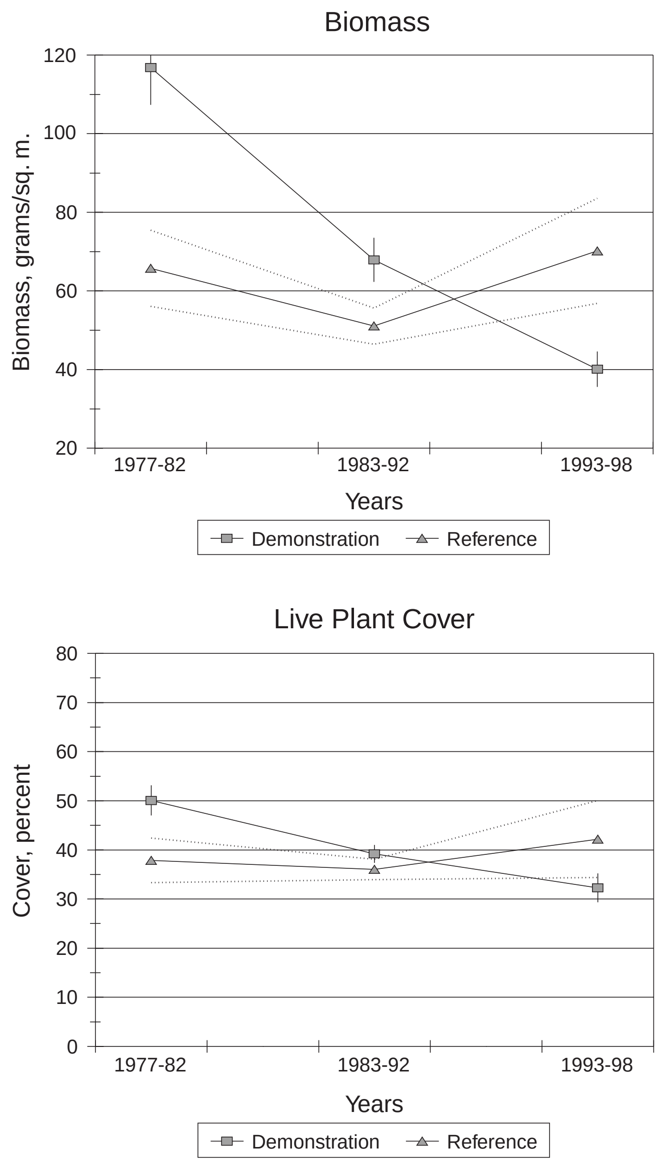

Figure 7—Mean biomass and percent live cover (with 95-percent confidence intervals) for the demonstration area and reference areas averaged for specific time periods: 1977 to 1982, (active refertilization; 1983 to 1992), early, postrefertilization; and 1993 to 1998, late, postrefertilization.

was 706 lb per acre (79.14 g per m^2). Mean annual percent live cover in the reference areas was 39 percent during this same period and averaged 42 percent for the demonstration area. Thus, the demonstration area averaged somewhat higher biomass and live cover than the reference area over the entire period of the study. Biomass and live cover can vary considerably between years, but the greatest variability occurred within the demonstration area. Data differences can be attributed to at least two variables: annual and cyclic variations in climatic conditions, which can be substantial, and variations in sampling rigor. In some years only a few quadrat frames were measured for biomass and live plant cover in both areas while in others, especially during the last 5 years of the study, large samples were collected in more rigorous standardized formats.

Analysis of variance (ANOVA) was used to determine if differences in the data between the demonstration area and the reference areas are statistically significant ($p \leq 0.05$); a summary of the results from these tests for years when compatible data were available is shown in table 5. Differences in total biomass for the entire period 1978 to1998 were highly significant ($p \leq 0.01$), but differences were not significant ($p \geq 0.05$) for percent live cover. Also, differences between the two areas in each individual year were highly variable, reflecting the variability in sampling rigor between years. Only the raw data from each site in each year were used for all ANOVA calculations.

Differences between the demonstration area and reference areas were highly significant for both total biomass and live cover during the 1978 to1982 period of active refertilization (fig. 7). During this period mean annual biomass was 1,042 lb per acre (116.8 g per m^2) for the demonstration area while only 586 lb per acre (65.7 g per m^2) for the reference areas; mean cover was 50 percent for the demonstration area and only 38 percent for the reference areas. During this period of 4 to 7 consecutive years in which abundant nutrients were reapplied annually to the demonstration area, the grasses flourished and assumed a growth form much larger than individuals of the same species in natural adjacent communities not fertilized. We suspect that during this period the grasses within the demonstration area were consuming near optimum quantities of relatively abundant nutrients, and their large size and aggressive competitiveness were instrumental in suppressing the successful invasion of native sedges, rushes, and forbs from undisturbed areas.

However, during the immediate post refertilization years of 1983 to1992, both plant biomass and cover within the demonstration area declined (fig. 7). This was presumably a result of the withdrawal of abundant nutrients. After 1993 through 1998 the mean biomass in the demonstration area was significantly less than that in the reference areas, but difference in live cover was not. The vegetation within the demonstration area may be less responsive to normal cyclic climatic variations than the reference areas, perhaps due in part to its more poorly developed soils.

To better understand the relative performance over time of the vegetation in the demonstration area relative to that in native reference areas, the algebraic differences in biomass and live cover between the two

Table 5—Summary of analysis of variance (ANOVA) of total biomass and live cover data in the seeded demonstration area and adjacent reference area comparisons, 1977 to 1998 (ns = not significant at $p > 0.05$; * = significant at $p \leq 0.05$; ** = highly significant at $p \leq 0.01$). Blank spaces indicate years when no data were collected.

Variable	Biomass	Live cover	Interact. Yr x trmt (biomass)	Interact. Yr x trmt (live cover)
Demonstration area versus reference areas:				
All years, 1978–1998	**	ns	**	**
1977–1982 (years of active refertilization)	**	**	**	*
1983–1992 (years post-refertilization)	ns	**	**	ns
1992–1998 (years following retreatment)	**	ns	*	ns
By individual year:				
1978	**	ns		
1979	*	ns		
1980	ns	ns		
1981	ns	ns		
1982	ns			
1983	**	**		
1984	**			
1985				
1986	ns	ns		
1987				
1988	ns			
1989		ns		
1990				
1991		ns		
1992	ns	*		
1993				
1994	ns			
1995	**	ns		
1996	**	ns		
1997	*	*		
1998	**	ns		
Treatment effects within demonstration area:				
Biomass and live cover (Refertilization treatments 1, 2, 3, 4) 1979–1992				
1 Differences among all treatments, 1979–1992	ns	**	**	**
2 Differences among years for each treatment:				
Treatment 1 by year: 1979–1992	**	**		
Treatment 2 by year: 1979–1992	**	**		
Treatment 3 by year: 1979–1992	**	**		
Treatment 4 by year: 1979–1992	**	**		
3 Differences among treatments (1, 2, 3, 4) for each year				
1979	ns	ns		
1980	**	ns		
1981	**	*		
1982	**	**		
1983	**	**		
1984	ns	**		
1986	**	ns		
1988	*	ns		
1989	ns	*		
1991		**		
1992	ns	**		

areas were plotted by years along with the 95-percent confidence interval depicting the expected range of the differences between means (fig. 8). In this analysis, the 95-percent confidence interval defines where the mean of the real differences between the two areas will fall within the defined interval range. These data clearly show that during the period of active refertilization, the demonstration area maintained significantly more biomass and cover than the reference areas; this is consistent with the results in table 5. Following the discontinuation of refertilization, however, the differences between the two areas in biomass and cover approached zero. As early as 1986 the differences between the two areas in both biomass and live cover were no longer significant. After 1994, however, demonstration area biomass and live cover continued to decline each year and became less than that of the reference areas. These data reflect the calculations of significance in table 5 and again suggest that refertilization temporarily boosts both biomass and cover to artificially high levels by the unnatural abundance of nutrients. When artificially abundant levels of nutrients are no longer available for such luxury consumption (especially prevalent in grasses), biomass and cover decline to levels sustainable by the soils developing within the demonstration area. It appears that these levels of biomass productivity and live cover are approaching that displayed by the native communities in the immediate area. For the demonstration area to permanently sustain these same levels of productivity and cover requires that nutrient cycling and soil development be sufficiently advanced to provide the basic levels of energy needed. The data in figure 8 also suggest that nutrient cycling and soil genesis on such spoils may not be developed sufficiently even after 20 years to support the same levels of vegetative productivity that are being maintained in adjacent reference areas.

These results of the analyses of vegetation development within the demonstration area are encouraging. However, long-term nutrient cycling and soil formation studies will be required to determine the levels of energy needed within the demonstration area to perpetually sustain the biomass productivity and live cover observed in adjacent reference areas. Soil formation occurs slowly in severely disturbed high-elevation environments such as those of the New World District. The 22 years of data covered in this study may be brief relative to that actually required for the formation of a sustainable and resilient ecosystem on the demonstration area, and minuscule to that where soil formation has not been accelerated by treatment. Figure 9 illustrates the development of vegetation on the demonstration area.

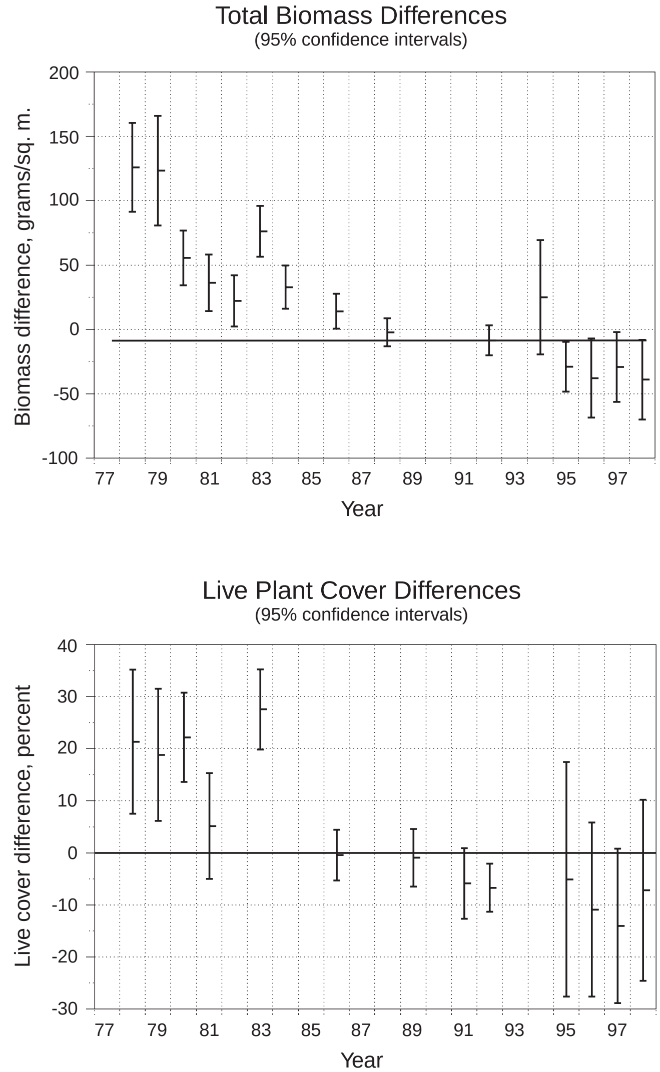

Figure 8—Differences between the demonstration area and reference areas biomass and percent live cover (with 95-percent confidence intervals), relative to the total difference between areas, 1977 to 1998.

Number of Plant Species—The number of vascular native plant species occurring within an area is an indication of its ecological diversity and may suggest the degree of relative successional development attained. The total number of native vascular plant species observed in the New World Mining District between 1974 and 1998 is about 118 species (appendix A). Of these, grasses comprise 16 taxa, sedges and rushes nine taxa, forbs 80 taxa, woody shrubs nine taxa, and trees four taxa. Obviously, not all of these species are observed in any one location nor necessarily visible in any one growing season. It is unlikely that we noted every species actually present in the New World; new species were encountered nearly every year. Abundance of some species was highly variable over time, apparently being greatly influenced by annual climatic variables and perhaps other

Figure 9—The seeded area and portions of the transplant area of the demonstration area in 1979 during active refertilization (upper), and in 1997 long after active fertilization ceased (lower).

factors. In some years various species were not encountered, and yet in other years were noticeably abundant. Specimens of each species were usually collected, identified using reputable flora guides appropriate to the area (for example, Hitchcock and Cronquist 1973), and preserved in the herbarium of the Forestry Sciences Laboratory at Logan, UT.

The total number of species observed each year between 1977 and 1998 within the seeded demonstration area, in reference areas, and in some successional communities on mine spoils are shown in figure 10. These data tend to illustrate the degree of successional development within the demonstration area. The data were collected sporadically during the early years of research but routinely after we realized the significance of such information. The number of species found in the seeded portion of the demonstration area during the period of active refertilization (1977 to1982) remained between six and 14, primarily species that were seeded in the area. This corresponds to the period of maximum biomass and cover development. When refertilization was discontinued, however, the total number of species increased rapidly and appeared to reach a plateau of around 50 in the late 1990s.

The total number of species observed in adjacent reference areas is difficult to quantify because the boundaries and area of these sites were only generally defined. Because the number of species encountered increases as the area observed increases, our data are only indicative of the actual number of species representing each reference site studied. The number of plant species observed in the six major reference areas range from 25 to 73. Consistently more species were

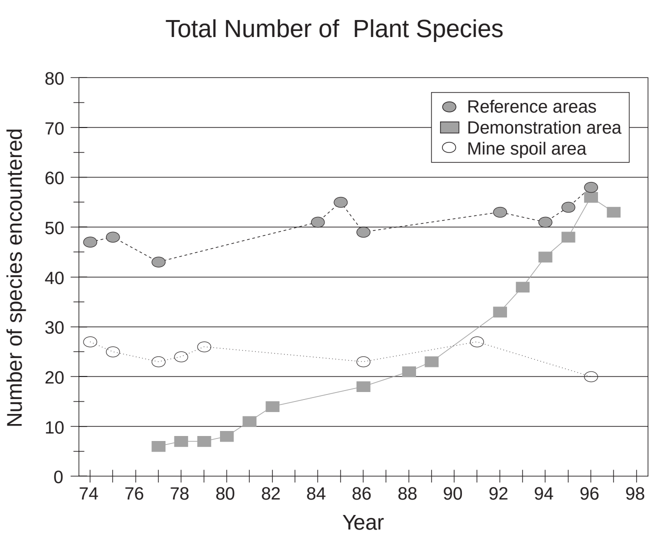

Figure 10—The number of vascular plant species observed in the seeded demonstration area, adjacent native reference communities, and in successional areas on mine spoil between 1974 and 1998.

observed in the highest successional communities, and the least in the lower successional communities (appendix A). Only the data from the three reference areas in the Daisy Creek (areas AA, AB, and AC) drainage were used in the statistical analyses of comparative data between the demonstration area and reference areas. These three reference areas occur on slopes and habitats near and similar to that of the demonstration area. Information provided here about the remaining three reference areas found in the Fisher Creek drainage (areas AD, AE, and AF) is provided only for background to provide a broader overlook of the diversity of the entire New World area.

Life-Form Comparisons—Comparisons of composition by life forms (number of species within grass, sedge, rush, forb, shrub, and tree classes) provide a basis for contrasting developmental stages of different communities and for indicating broad ecological similarity, even though the species themselves may differ considerably. Although many of the individual plant taxa occurring on the demonstration area differ from those found on the reference areas, the relative composition of life forms among all of these sites is surprisingly similar (table 6). Forbs compose by far the largest number of species in all of the New World areas. Generally grasses compose the next largest component, followed by sedges, rushes, shrubs, and trees. The grasses, sedges, and rushes, together with seral forbs, constitute the majority of species found in the demonstration area; the reference areas are similar but often contain more shrubs and trees. The sampling techniques we used on the reference and demonstration areas managed to encounter almost 50 percent of the total 118 plant species observed in the New World area (appendix A).

Table 6 includes a summary of species numbers by life form class for four representative McLaren Mine successional areas. These areas were raw untreated mine spoil comprising a variety of heterogeneous chemical and physical properties on which succession occurred naturally. Only slightly more than 20 vascular species were consistently observed as active colonizers on these areas between 1974 and 1992 (after which the various spoil piles were reshaped and amended with lime, fertilizer, and seeded by Crown Butte Mines, Inc.). Apparently about 20 percent of all species present in the New World District are active successional colonizers on mine spoil materials. Not only are the total numbers of species involved in active succession here much lower than those observed in other more advanced communities, but the proportion by life-form distribution differs as well. On untreated mine spoil, dominance in active succession appears to be uniformly shared among forbs and graminoids (grasses, sedges, and rushes). Generally our experience indicates that the earliest stages of succession

Table 6—Number of species by life-form classes on the demonstration area, in the six reference areas, and on natural succession on untreated mine spoil.

Life-form class	New World District	Demon-stration area	Reference areas: Daisy Creek AA	AB	AC	Reference areas: Fisher Creek AD	AE	AF	Successional areas on raw spoil: Strip	Hill	Hill	spoil
(*Relative successional development*) =			(*high*)	(*mid*)	(*low*)	(*high*)	(*mid*)	(*low*)				
Grasses	16	9	10	10	8	10	3	5	5	6	6	5
Sedges/rushes	9	5	7	5	1	5	5	5	4	6	0	4
Forbs	80	38	52	40	27	21	11	13	12	10	8	14
Shrubs	9	1	1	3	0	0	4	1	0	0	0	3
Trees	4	2	3	0	1	2	2	2	0	0	1	3
Total species	118	55	73	58	37	38	25	26	21	22	15	29

almost always begin with graminoid colonization, and that forb establishment tends to be later, although exceptions occur on nonacidic spoils. Howard (1978) and Haggas and others (1987) summarize observations regarding initiation of succession on acidic spoils in this area by the dominant sedge, Payson sedge (*Carex paysonis*).

Figure 11 illustrates the frequency of life forms observed (percent of quadrats sampled in which a given life form occurs) in the demonstration area between 1977 and 1998. Grasses maintained nearly constant 100 percent frequency between the years 1977 and 1998. No other life forms were observed until 1986 when forbs were encountered in about 22 percent of the quadrat frames. The forbs gradually increased to about 95 percent frequency by 1998. Sedges and rushes were first encountered in 1988 and then steadily increased until about 1994 before declining sharply in 1995 to 1997, but then increased to about 67 percent by 1998. We suspect the 1995 to 1997 decline may have resulted from misidentification between grasses and sedges by some members of the sampling crew. Woody plants were first encountered on the seeded portion of the demonstration area in 1998, occurring in only 2 percent of the quadrat frames. The fertilization indicated in 1993 (fig. 11) occurred only within the appropriate newly retreated plots established that year, and may have adversely influenced forb and sedge colonization in favor of grasses over a portion of the seeded study area. It seems reasonable, in view of "luxury

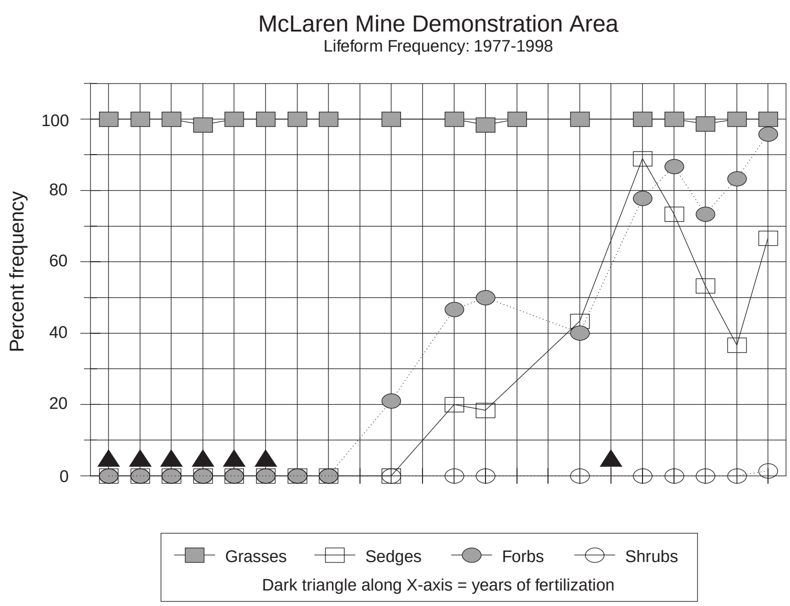

Figure 11—Frequency (percent of total quadrats sampled) of observed plant life forms within the seeded demonstration area between 1977 and 1998.

consumption" of abundant nutrients by grasses, that a decline in sedge and forbs species numbers might be expected following a new pulse of fertilizer.

Comparisons of the relative proportions of life form biomass in the demonstration area with that in reference areas are shown in figure 12. Inconsistent data collection in the early years of the study prevents these comparisons prior to 1994. Grasses contributed overwhelmingly to the biomass in the demonstration area with only minor amounts of forbs and sedges until about 1996. By 1998 grasses still composed over 70 percent of the total biomass within the demonstration area. In contrast, reference areas biomass consisted heavily of forbs, comprising between about 40 to over 65 percent of the total produced. Grasses only contribute between about 5 to 15 percent of the total reference areas biomass, and sedges between about 15 to over 25 percent. In some reference areas, shrubs and other woody plants contribute a significant proportion of the total biomass produced. A single shrub plant, grouse whortleberry (*Vaccinium scoparium*), was encountered for the first time on the demonstration area in 1998, but its relative contribution to the total biomass was minimal.

An additional revealing measure of life-form composition for comparing the demonstration area with reference sites is the frequency of occurrence of life forms in the quadrats sampled (fig. 13). The

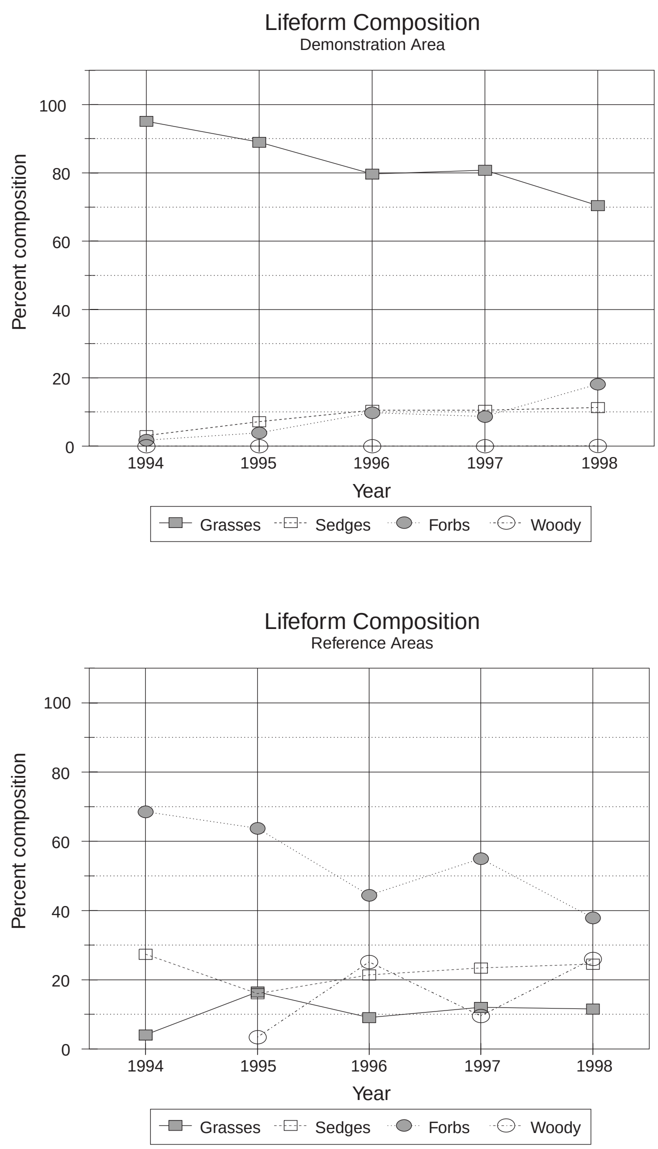

Figure 12—Percent composition of each life form observed in the demonstration area compared to native reference areas, 1994 to 1998.

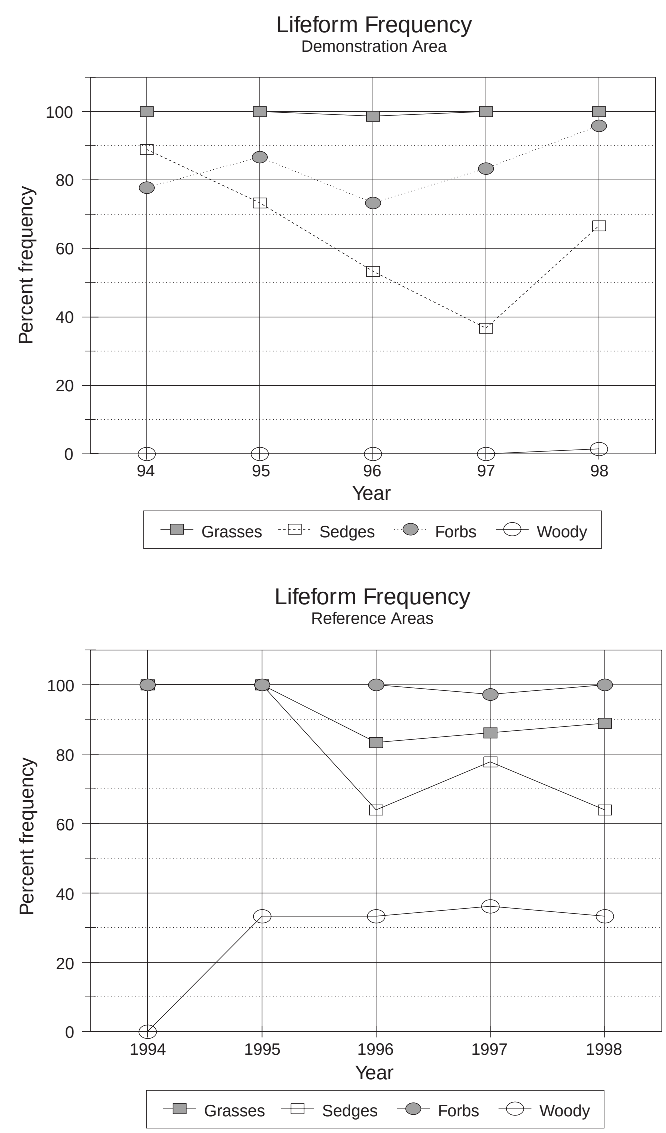

Figure 13—Percent frequency of each life form encountered in the demonstration area compared to native reference areas, 1994 to 1998.

demonstration area maintained virtually a constant 100 percent frequency of grasses between 1994 to 1998. Forbs, sedges, and rushes also composed a significant distribution throughout the demonstration area, but woody plants were only recorded in 1998. In the reference areas, grasses generally had a somewhat lower frequency than the demonstration area and generally shared a codominant position with the forbs. In addition, native reference areas maintained a significant proportion of woody plants, about 30 to 35 percent frequency, in most locations and years. These data substantiate expected trends in the development of vegetation diversity within the demonstration area and show a gradual increase in life-form diversity over time toward a more similar physiognomy with that of reference areas.

Species Frequency Comparisons—A comparison of the frequency of occurrence of vascular plant species on the demonstration area with those on selected nearby reference areas is shown in appendix B. The three reference areas used in this comparison were selected to span the range of productivity on undisturbed sites of similar elevation and exposure. Although the frequency plot size differs depending upon the abundance of the species, the size for a given species is consistent across all four sites to facilitate direct comparisons across sites. (Frequency comparisons of different species within a single site are valid only if the plots are of the same size.)

Species richness (diversity) on the demonstration area compared to that on the three McLaren reference areas is of special interest (fig. 14). These data differ from those in table 6 in that each site was sampled by the same total area, 50 permanent plots each 2.65 ft^2 (0.25 m^2) in size, whereas table 6 data represent an accumulation of careful reconnaissance observations over several years on entire areas of different sizes. Figure 14 data show that 20 years after installation the demonstration area contained half the number of species as the high production native reference area, three-fourths as many as the medium production reference area, and slightly more than the low production area. The high and medium production reference areas contained almost twice as many forbs species as the demonstration area. Only nine of the species on the frequency plots in all three of the reference areas were the same, which indicates the composition dissimilarities of the native undisturbed vegetation.

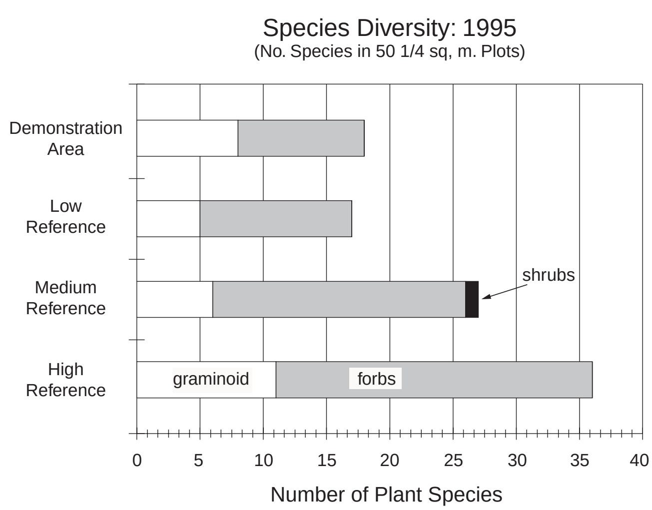

Figure 14—Number of vascular plant species by life-form classes encountered on 50 permanent one-fourth m^2 plots on the demonstration area compared to three nearby reference areas selected to represent different levels of productivity.

Although the diversity of species on the demonstration area was gradually approaching that of the more productive native reference areas, the frequency of species not deliberately planted was still different (appendix B). Only those grasses in the seed mixture that was planted on the demonstration area had high frequency levels comparable to or exceeding those on the reference areas. Forb frequencies were low on the demonstration area; the very presence of these forbs, however, indicates that the process of natural succession was accelerating.

Although species diversity after 20 years on the demonstration area remained well below that on the high production reference area, the amount of ground protected by vascular vegetation plus litter equaled that of the high production reference area (appendix B; fig. 15). This large amount of vascular plant cover reflects the abundance of tussock grasses, especially tufted hairgrass (*Deschampsia caespitosa*), which not only have relatively large bases but also produce considerable litter. The greatest difference in ground cover elements between the demonstration area and high production reference area was the amount of ground surface covered by cryptograms, primarily mosses and liverworts. Both the medium and low production reference areas had twice the amount of exposed bare ground plus rock than the demonstration area. Thus, the soil surface on the demonstration area appeared well armored against water and wind erosion.

Effects of Refertilization—The purpose of the refertilization treatments was to determine to what extent repeated applications of fertilizer result in enhanced site productivity and cover. The refertilization treatments were not replicated. We believed initially that up to four consecutive years of fertilization in a sterile medium, as with these mine spoils, would be necessary to load the spoil with residual nutrients in great enough quantities to support long-term nutrient cycling. Therefore we fertilized the entire demonstration area for 4 consecutive

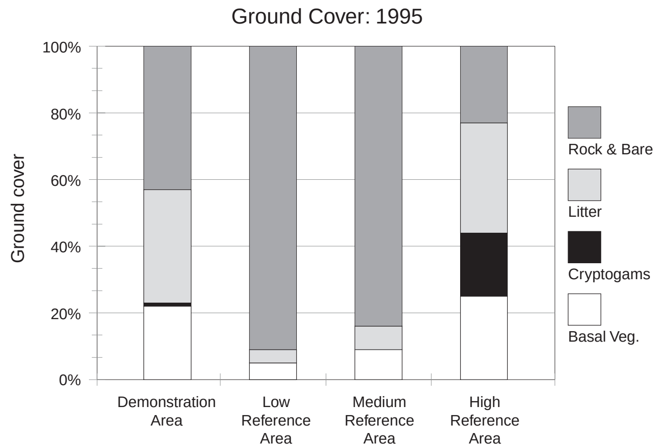

Figure 15—Ground cover on the demonstration area compared to three nearby reference areas selected to represent different levels of productivity; data are based on 300 points of basal intercept per area.

years as a minimum treatment. In effect, fertilization was viewed as a means of "pushing" the formation of nutrient loading and cycling, and of accelerating soil genesis and successional development. It became obvious by the time the first treatment was withdrawn from refertilization in 1979 that refertilization was favoring the growth and development of graminoids to the near exclusion of forbs and other life forms. Under refertilization, the grasses had developed into far more robust plants with levels of cover far greater than that observed in native adjacent reference communities.

A fairly consistent increase in biomass and live cover occurred with each additional year of fertilization. All fertilization was terminated after the 1982 growing season, but the carryover effect appeared to extend through at least 1992. Thus, 10 years after fertilization was discontinued, the differences in relative production and cover characterized by each treatment were still evident, although the total productivity and cover of all the treatment blocks declined.

Normal annual weather variability is great in the New World District. It is difficult to separate the effects of local weather and refertilization treatments. However, it appears that biomass and live cover enhancement due to readily available fertilizer begins to deteriorate within 2 to 3 years following the discontinuation of fertilization. Figure 16 illustrates this point for various repeat fertilization schedules ranging in length from 4 to 7 consecutive years. These data show that repeated annual applications of fertilizer resulted in progressively higher biomass productivity and live cover and that the effect persisted for at least 2 to 3 years beyond the termination of refertilization schedules. Figure 17 shows the overall decline in biomass and cover that followed the termination of fertilization compared with that of the native reference areas that were never fertilized.

Differences between refertilization treatments for all years 1979 to1992 were not significant for biomass but were highly significant for percent live cover (table 7). Differences among years for each treatment were highly significant for both biomass and cover, indicating strong year-to-year variability in both vegetation attributes. The data are more variable when analyzed for individual years. Carryover effects of refertilization appear evident, but the overall boost declines soon after nutrient enhancement is withdrawn. General observations reveal that spoil surface organic matter buildup and subsequent colonization by other plant species and life forms appear to be greatly enhanced by repeat fertilization.

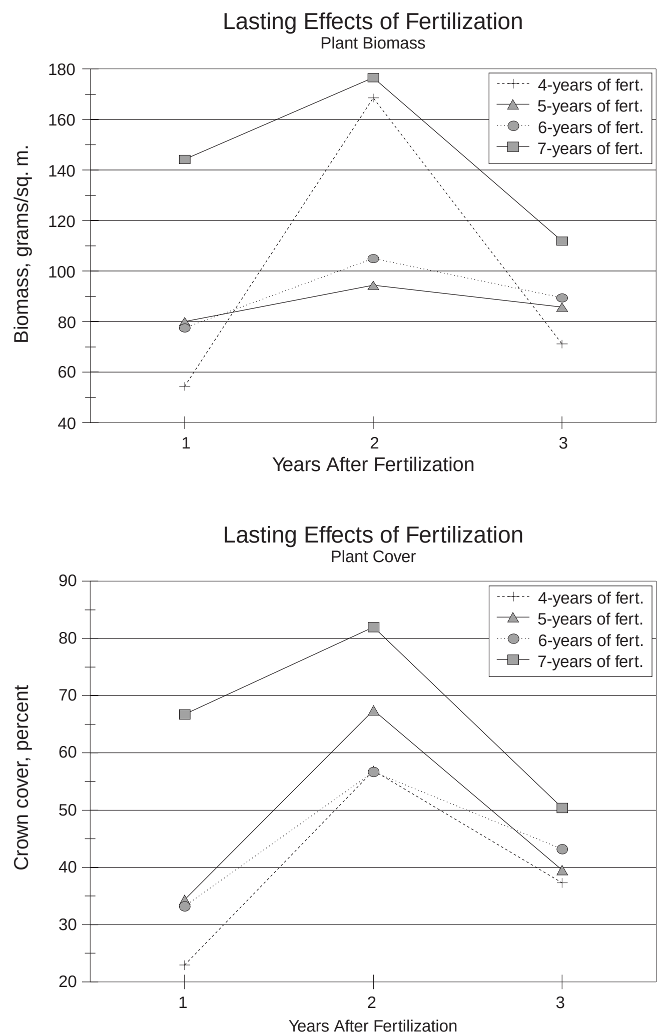

Figure 16—Consequences of 4 to 7 consecutive years of repeat fertilization on biomass and live cover during the first 3 years after this fertilization was discontinued.

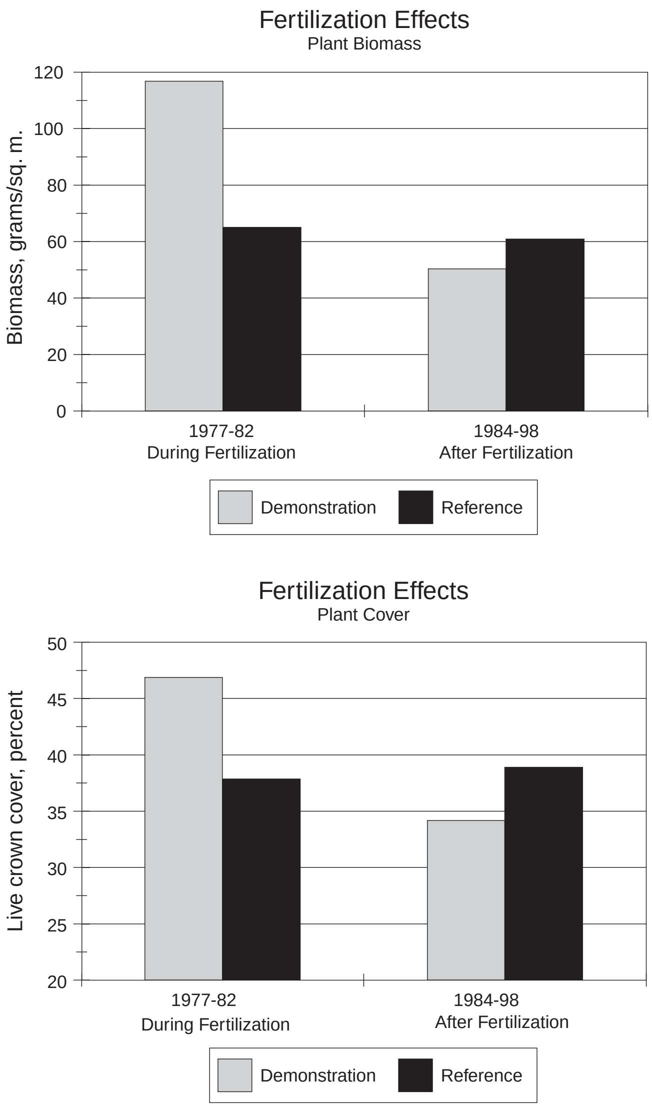

Figure 17—Cessation of prolonged fertilization during 1977 to 1982 resulted in a dramatic decline in both biomass and live cover in the demonstration area (1984 to 1998); there were no significant changes in the unfertilized reference areas during the same period.

Although grasses remained the dominant life form in the demonstration area after 22 years, forbs, sedges, and woody species were clearly increasing. This strongly suggests that succession within the demonstration area was actively progressing toward consistency with natural communities in the New World area in terms of biomass, cover, species number, and life-form composition. Convergence of these attributes began to become evident about 15 to 18 years following seeding and about 10 years following the discontinuation of active fertilization. These data strongly indicate that the methods we used hold promise for reestablishing natural ecosystem development and recovery on high-elevation acidic mine spoils.

Soil Properties—In 1976 the properties of the raw mine spoil material on the McLaren Mine were limiting the establishment and long-term survival of vascular plants in most areas, hence natural succession appeared inactive. Various amendments were incorporated to promote development of protective plant cover that would minimize erosion and the movement of sediment from the site. The long-term objective in applying these amendments was to permanently ameliorate the limiting conditions of the spoil material so that succession of the planted vegetation would ultimately return the site to a self-sustaining natural condition. Considerable uncertainty guided most decisions in 1976 regarding the application of spoil amendments, including kind of amendments, rates of application, frequency of application, and concerns about amendment degradation over time. These concerns were compounded by uncertainties regarding seeding and planting, species adaptability, and the compatibility of specific spoil amendments with the species selected for the seed mixture and transplant

Table 7—Summary of analysis of variance (ANOVA) of total biomass and live cover data in the seeded demonstration area refertilized treatment plot comparisons, 1979 to 1992 (ns = not significant at $p > 0.05$; * = significant at $p \leq 0.05$; ** = highly significant at $p \leq 0.01$). Blank spaces indicate years when no data were collected.

Variable	Biomass	Live cover
Among all treatments, 1979–1992	ns	**
Among years for each treatment:		
Treatment 1 by year: 1979–1992	**	**
Treatment 2 by year: 1979–1992	**	**
Treatment 3 by year: 1979–1992	**	**
Treatment 4 by year: 1979–1992	**	**
Among Treatments 1, 2, 3, and 4 for each year		
1979	ns	ns
1980	**	ns
1981	**	*
1982	**	**
1983	**	**
1984	ns	**
1986	**	ns
1988	*	ns
1989	ns	*
1991		**
1992	ns	**

list. Therefore, soil/spoil samples were collected in most years to assess the relative state of the spoil properties in the demonstration area compared with the natural soil in adjacent reference areas. Soils sampled during the 1976, 1978, 1983, 1988, and 1995 growing seasons were adequately replicated and analyzed to provide comparable and enlightening information about changing soil conditions over time on the demonstration area.

Acidity (pH) is probably the most meaningful and significant soil property in the New World District relative to plant growth because it integrates the effects of numerous other soil/spoil properties. Figure 18 illustrates soil/spoil pH levels collected within the root zone in five separate years from the demonstration area and adjacent native reference communities. The spoil pH in the demonstration area in 1976, before spoil amendments were incorporated, was only about 3.6, whereas in native communities, soil pH ranged between 4.5 and 5.0 at all locations and in all years (table 8). Following the 1976 incorporation of amendments into the demonstration area, spoil pH remained between about 5.25 and 5.97 with no apparent indication of decreasing or that the incorporated lime was being consumed by weathering sulfides. There was no evidence that the pH in the demonstration area was degrading. The levels of pH were maintained at a level more similar to that in native soils than that of untreated mine spoil for more than 20 years following the addition of lime.

Comparisons of concentrations of copper, iron, manganese, and zinc (using DTPA extractions), and of essential plant nutrients (Kjeldahl nitrogen, phosphorus, and potassium) between the demonstration area and native reference communities are also summarized in table 8 and illustrated in figure 19 for the metals and figure 20 for plant nutrients. Data for metals and nutrients were not collected in the native reference areas in 1976 but were collected in the other years. The samples were analyzed by two laboratories in different years, and we suspect that laboratory analysis techniques may have changed over the period these data were collected. One laboratory analyzed samples in 1976, 1978, and 1995, and another in 1983 and 1988. Although we have concerns about interpreting these data, the range of data provides some insight into how these attributes may vary over time. The data show that DTPA extractable copper, manganese, and zinc may have been increasing in the demonstration area since 1976. However, the high degree of variability of these data from the native reference areas (fig. 19) reinforces our uncertainty about the overall reliability of the metals data.

The data for the three plant nutrients, N, P, and K (fig. 20; table 8), appear more reliable than those for metals; they at least reflect plausible explanations. The levels of nutrients in the demonstration area before the spoils were amended in 1976 were low as expected, but following treatment maintained levels of availability similar to, or higher than, those observed in adjacent native reference communities. The long-term carryover effects of fertilization in the demonstration area likely explain in part these relatively high levels of available nutrients.

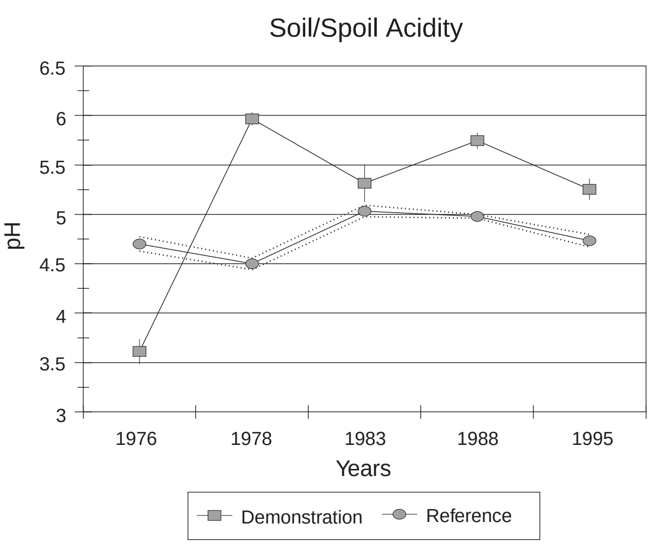

Figure 18—Mean soil-spoil pH (with 95-percent confidence intervals) in the demonstration area and reference areas over the study period.

Soil Genesis and Development of Horizons—Apparent development and formation of natural soil on the demonstration area were first detected visually in the mid to late 1980s as a darkening in color near the surface of the treated mine spoil in response to accumulating organic matter from the growing vegetation. By the early 1990s the darkening coloration of the surface layer was more pronounced. An intensive matched set of soil samples were collected in 1995 in both the demonstration area and reference areas and stratified by apparent horizon based on color differences (brown to dark brown "A" horizons, and light to dark orange "C" horizons). An additional matched set of spoil samples was also collected from adjacent untreated spoil outside the demonstration area in which no horizon formation was observed. Within the demonstration area, the "A" horizon in 1995 ranged in depth from 1.2 to 4 inches (3 to 10 cm), with a dark upper layer of organic matter under the crowns of the plants, gradually lightening in color with depth. The "C" horizon in the demonstration area often contained streaks of gray-colored materials. The "A" horizon in native reference areas was much more developed, ranging in depth from 7.9 to 26.7 inches (20 to 68 cm);

Table 8—Soil/spoil chemical properties of the demonstration area and adjacent reference areas for 1976, 1978, 1983, 1988, and 1995 (mean is the statistical mean of all data; se is ± 1 standard error; NA = no data collected).

Location	Year	Mean se	pH	Cu (DTPA metals)	Fe (DTPA metals)	Mn (DTPA metals)	Zn (DTPA metals)	N (Essential nutrients)	P (Essential nutrients)	K (Essential nutrients)
				mg/kg	*mg/kg*	*mg/kg*	*mg/kg*	*Percent*	*Mg/kg*	*Mg/kg*
Demonstration Area	1976	mean	3.61	16.9	168.6	6.5	4.8	0.0	9.4	32.0
		se	.13	5.0	15.4	1.3	1.2		1.1	3.1
	1978	mean	5.97	21.7	50.2	6.8	9.2	.1	50.0	167.3
		se	.07	1.9	6.6	1.4	1.5	.0	4.9	8.3
	1983	mean	5.31	22.5	55.3	8.5	10.9	.1	64.3	151.8
		se	.19	4.4	6.4	1.2	3.2	.0	16.0	17.8
	1988	mean	5.75	34.7	68.3	14.0	9.5	.1	51.4	127.9
		se	.08	4.1	3.5	.9	1.5	.0	4.2	4.9
	1995	mean	5.25	36.0	64.1	8.4	14.3	.3	56.9	165.0
		se	.11	7.6	7.5	1.0	3.3	.0	6.5	17.2
Native Reference	1976	mean	4.70	NA	NA	NA	NA	NA	NA	NA
		se	0.7							
	1978	mean	4.50	21.4	92.0	23.0	1.4	.3	20.7	132.7
		se	.06	6.2	10.8	2.3	.2	.0	5.4	11.3
	1983	mean	5.03	26.0	141.3	16.7	2.2	.3	8.3	132.7
		se	.06	8.2	32.1	6.2	.4	.0	1.5	5.8
	1988	mean	4.98	29.4	95.5	22.5	1.5	.3	26.3	142.5
		se	.02	7.4	3.6	1.4	.1	.0	1.7	5.3
	1995	mean	4.73	4.4	71.5	5.1	2.3	.3	7.7	94.1
		se	.06	.9	13.2	1.2	.9	.0	0.7	5.9

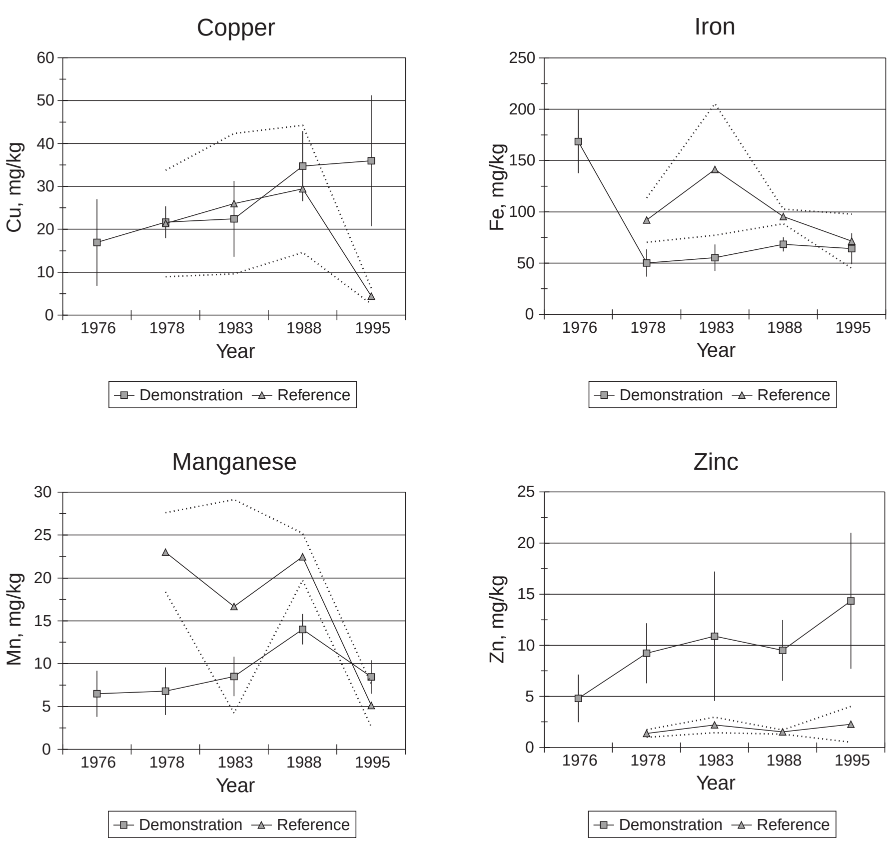

Figure 19—Mean concentrations of metals (with 95-percent confidence intervals) in the demonstration area compared with metals observed in native reference community over the study period.

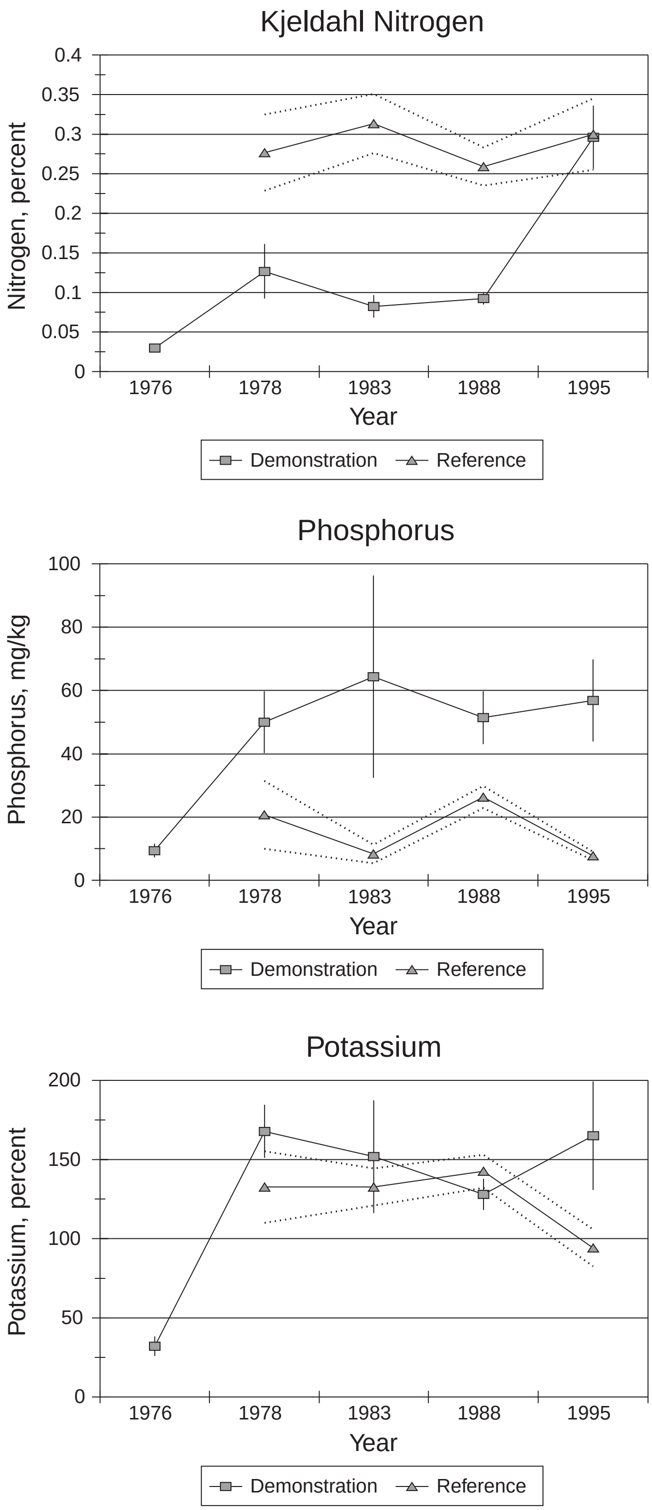

Figure 20—Mean concentrations of essential plant nutrients (with 95-percent confidence intervals) in the demonstration area and reference area soils over the study period.

the "C" horizon in native areas varied from light brown to light orange.

Apparent rooting depths (visible roots) of vascular plant species in both the demonstration area and reference areas in 1995 ranged from about 3.1 to 9.8 inches (8 to 25 cm) and 9.8 to 32 inches (25 to 82 cm), respectively. Interestingly, the rooting depths of many plants observed in the demonstration area exceeded the 6-inch (15-cm) depth to which amendments were applied in 1976. The mean rooting depth in the demonstration area in 1995 was 7.6 inches (19.3 cm), whereas in the reference areas mean rooting depth was considerably deeper at 19.7 inches (50.1 cm). In both locations the overwhelming root density was confined to the upper 4 inches (10 cm) of soil or treated spoil; no rooting depth was observed in untreated spoil.

Spoil pH in 1995 in untreated mine spoil averaged about 3.1 in 1995 but was highly variable across the spoil materials. Crown Butte Mines, Inc., reshaped most of the McLaren Mine in 1992 and treated most spoil areas with lime, seed, and fertilizer. The 1995 sampling of spoil material was confined to those areas left untreated, which may have been responsible for some of the large variations in the data. The data collected from the demonstration area and reference areas were much less variable, with pH means of 5.25 and 4.73, respectively. These data are consistent with pH data collected throughout the study and indicate that soil pH within the demonstration area was not declining with time.

The availability levels of essential plant nutrients (N, P, and K) generally remained higher in the demonstration area than that observed in adjacent reference areas (fig. 21), reflecting the years of heavy fertilization applied prior to 1983 and apparently sustained by nutrient cycling. The demonstration area samples obtained in 1995 were from portions of the seeded area that had not received any additional treatment after 1982.

The 1995 levels of DPTA extractable metals were generally much higher in the demonstration area, especially in the A-horizon, than in the raw spoil or the reference areas (fig. 22). The amendments applied to the demonstration area in 1976 may have influenced these levels of availability. Raising spoil pH from 3.5 to 5.5, as occurred in the demonstration area, certainly enhanced the of DTPA extractable metals. The C-horizon of the demonstration area probably was at least partially affected by the original amendments in 1976, but we are uncertain to what extent metal availability in 1995 would reflect those applications. Levels of DPTA extractable metals appear generally higher in the A-horizon of the demonstration area than in the C-horizon, but differences in Cu are not

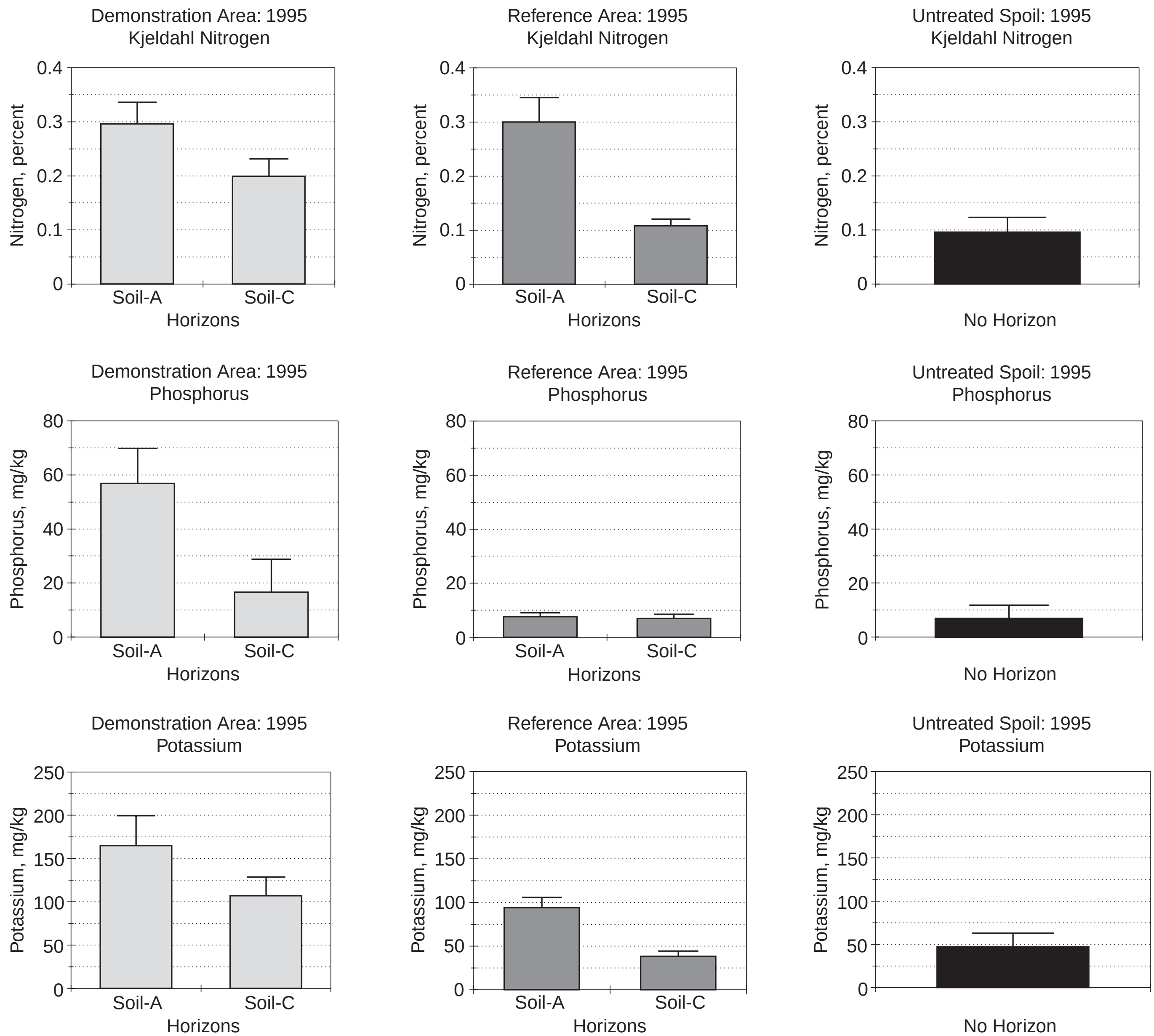

Figure 21—Essential plant nutrients (with 95-percent confidence bars) in the soil horizons of the demonstration area, reference areas, and untreated spoil in 1995.

significant. A similar condition prevailed in the reference area soils, although none differed significantly by horizon. Differences in DPTA extractable metals between A- and C-horizons and between treated demonstration area and raw spoils areas can best be explained by differences in soil pH. DTPA metal complexes are unstable at low pH levels (O'Connor 1988). Thus, higher levels of DTPA extractable metals were found in limed spoils than in untreated spoils. For this reason, the DTPA soil test remains a poor choice for comparing metal availability in soils of widely different pH levels (O'Connor 1988). We now recommend extraction with a neutral salt (for example, NH_4Cl) to compare metal availability in limed and nonlimed areas of soils and mine wastes of differing pH levels (Amacher and Brown1999). Despite these uncertainties, there did not appear to be any long-term limitations to the developing vegetation and community structure within the demonstration area.

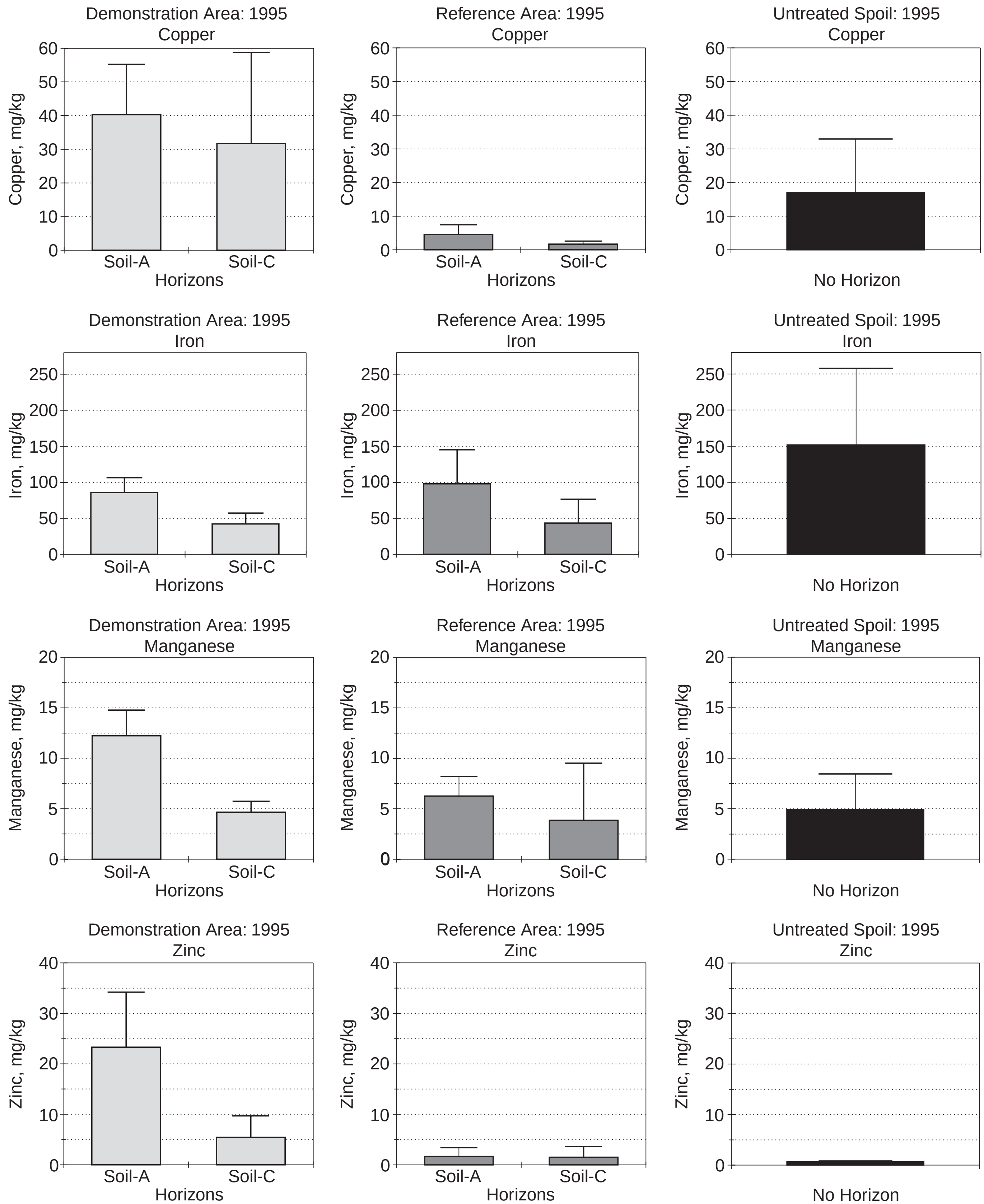

Figure 22—Concentrations of metals (with 95-percent confidence bars) in the soil horizons of the demonstration area, reference areas, and untreated mine spoil in 1995.

The strongest evidence supporting the hypothesis of active nutrient cycling in the demonstration area is the data for C, N, and C/N ratio status illustrated in figure 23. These data suggest that C, N, and the C/N ratio in the demonstration area are strikingly similar to that observed in the naturally developed soils of the reference areas, and by 1995 they no longer reflected properties similar to those in raw untreated mine spoil. Data for apparent rooting depth, soil-spoil pH, plant nutrients (fig. 21), metal (fig. 22), and carbon and nitrogen status (fig. 23) appear to confirm that soil genesis and nutrient cycling had become active processes within the developing soil of the demonstration area. Natural soil development appears to have been initiated and active nutrient cycling enhanced by active and rigorous applications of amendments to the New World mine spoils.

In addition, mycorrhizal activity was observed in the developing soil and roots of the demonstration area in 1983 and 1984 (Allen and others 1987). The demonstration area soil supported mycorrhizal infection rates in both the percentage of roots infected and

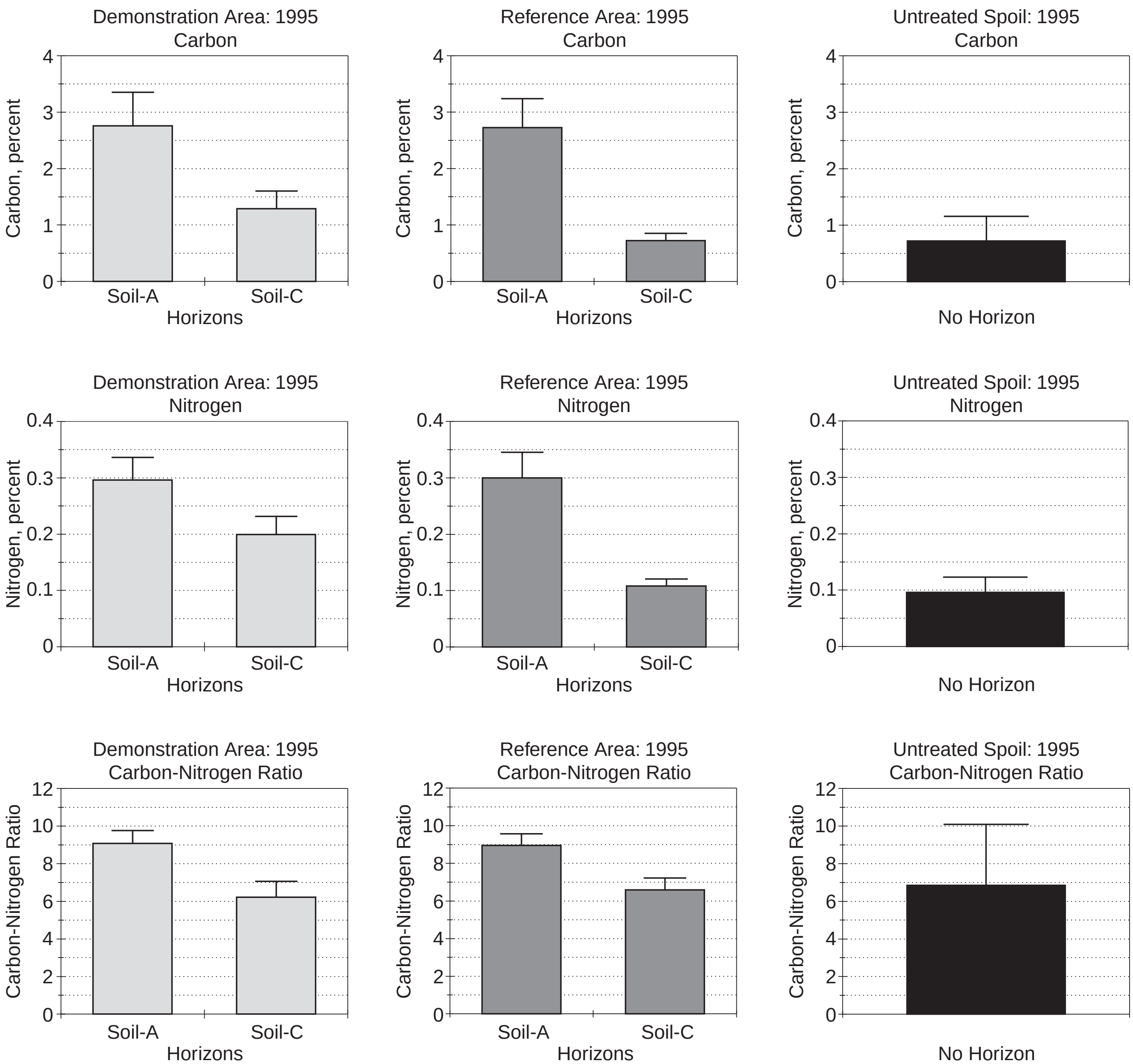

Figure 23—Carbon, nitrogen, and the C/N ratio (with 95-percent confidence bars) in the soil horizons of the demonstration area, reference areas, and in untreated mine spoil in 1995.

number of spores per gram of soil as high or higher than adjacent undisturbed reference area soils. A similar demonstration area established in 1980 on the Como Pit Mine supported mycorrhize infection rates equaling those observed in undisturbed soils after only 3 years. This suggests that mycorrhizal infection rates may occur quickly even in these harsh environments. Although succession is normally believed to be a slow arduous process, it may occur much more quickly than suspected when conditions are favorable.

Erosion and Surface Stability—Baseline rillmeter data collected to detect soil erosion and changes in surface roughness from 1995 through 1998 showed no significant differences in surface elevation between consecutive years in either the demonstration area or the reference areas. However, accumulated elevation differences from 1995 through 1998 were significant ($p \leq 0.05$) in both areas. The total elevation change within the demonstration area was 0.519 inch (1.32 cm) over the 3 years and 0.384 inch (0.97 cm) in the reference areas. No significant differences occurred in surface roughness in either the demonstration area or reference areas between years or in the accumulated roughness between 1995 to 1998. Because no visible evidence of surface rilling or particle deposition was apparent to indicate active erosion in either the demonstration area or reference areas, we suspect changes in surface elevation can be explained by frost heaving of the reference pins on which the rillmeter was mounted. These data support the hypothesis that erosion is not a major factor affecting the development of vegetation and soils within the demonstration area or reference sites.

Transplant and Natural Seed-Rain Areas

The transplant and natural seed-rain portions of the demonstration area were located immediately upslope and to the northwest of the seeded area (fig. 4). Both of these research areas were studied less intensely and less frequently than the seeded area, but the information gained from them adds significantly to the overall understanding of how natural succession can be used as a tool in the ecological restoration of native communities that have been severely disturbed.

Plant Survival—Following transplanting in 1976, survival of each plant was noted for 4 consecutive years (1977 to 1980). After the 1980 growing season the original transplants were no longer distinguishable from invading colonizing plants of the same species, hence survival counts were discontinued. We believe that a significant number of the colonizing grasses originated from seed produced by the native transplants. Not only was the majority of colonizing plants the same species as those transplanted, but high densities of these seedlings surrounded many of the original transplanted native plants. We never observed seedlings of any of the introduced species. At least some seed was contributed from adjacent native communities because other species—for example sedges, forbs, and some climax trees of whitebark pine (*Pinus albicaulis*) and Engelman spruce (*Picea engelmannii*)—common to these communities, but not planted intentionally, were observed within the transplant area. These observations lend credibility to the hypothesis that intensively treated "islands" can promote diversity and vegetation development in localized treated areas.

Survival of both native and introduced species rapidly declined in the years following transplanting (fig. 24). Mortality of introduced species was far more rapid than that of the native species within the first 4 years following planting. The introduced species selected for transplanting represent those frequently used by land managers for revegetation of disturbed areas on public lands. These species were clearly not well suited physiologically to this alpine environment. The native species chosen for transplanting represent the species most frequently observed as major components of active natural succession on disturbed areas throughout the New World District,

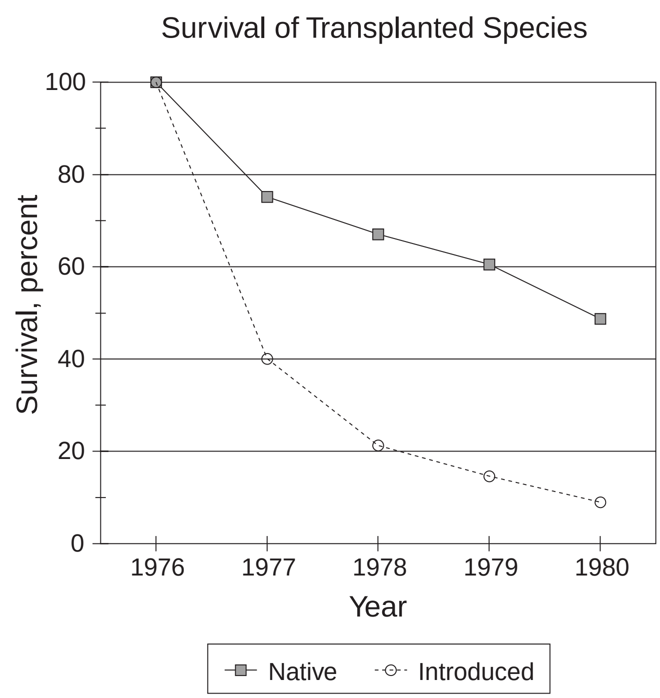

Figure 24—Survival of transplanted native and introduced species in the demonstration area, 1977 to 1980.

especially on acidic spoil materials. By the end of the 1980 growing season, fewer than 10 percent of all the introduced plants remained alive, whereas nearly 50 percent of all native plants were still viable. Assessments after 1980 showed that all introduced transplants had died except for a few lingering individuals of Canada bluegrass (*Poa compressa*).

Survival rates of the six individual native species 4 years after transplanting are as follows, in approximate percentages: alpine bluegrass (*Poa alpina*) 60 percent, alpine timothy (*Phleum alpinum*) 45, tufted hairgrass (*Deschampsia caespitosa*) 40, slender wheatgrass (*Agropyron trachycaulum*) 40, spike trisetum (*Trisetum spicatum*) 5, and Scribner wheatgrass (*Agropyron scribneri*) 0. Survival rates of the six introduced species 4 years after transplanting are, in approximate percentages: reed foxtail (*Alopecurus arundinacea*) 20, smooth brome (*Bromus inermis*) 15, Canada bluegrass (*Poa compressa*) 5, timothy (*Phleum pratense*) 2. Both orchardgrass (*Dactylis glomerata*) and reed foxtail (*Festuca arundinacea*) disappeared from the site by 1978. By the middle 1980s, only a few persistent plants of Canada bluegrass were observed; all other introduced species had disappeared, and the areas they formerly occupied in the amended spoil material of the transplant area were colonized by native species.

Biomass and Live Cover—Plant biomass and cover were studied in the transplant area beginning in 1981 and in the natural seed-rain area in 1988. Both areas were largely ignored for these attributes in earlier years because their vegetation development lagged far behind that of the seeded area. When it became obvious that individual transplants were no longer distinguishable, sampling procedures similar to those used in the seeded area were adopted to assess both of these areas.

Data on total plant biomass and percent live cover were collected on these areas between 1981 and 1998 (fig. 25). These data show that the transplant area had only half as much, or less, biomass and live cover as the seeded area and seed-rain plot by 1998. Biomass and live cover increased substantially over time in the natural seed-rain area and reached levels similar to those observed in the seeded area by the time observations ceased.

Statistical analyses (ANOVA) showed that both biomass and live cover differed significantly ($p \leq 0.01$) among the seeded area, transplant area, and natural seed-rain area. However, differences between the seeded and seed-rain areas were not significant for the period 1996 to 1998. These data indicate that amendments applied to mine spoil effectively ameliorated limiting conditions and allowed native colonizers to become established within about 15 years, if a natural seed source is nearby. Natural seed rain appears to be a much more aggressive process of succession in the New World area than we originally believed. The primary disadvantage of relying on seed rain, however, appears to be that a long period may be required before a diverse community is established. The use of seed rain as a seed source is compelling for restoration, particularly in high-elevation areas where seed of native species is in limited supply or high in cost. However, the use of seed rain as the sole source of native plant establishment is not recommended because the dynamics of seed production in adjacent communities, dispersal by wind and other vectors, and

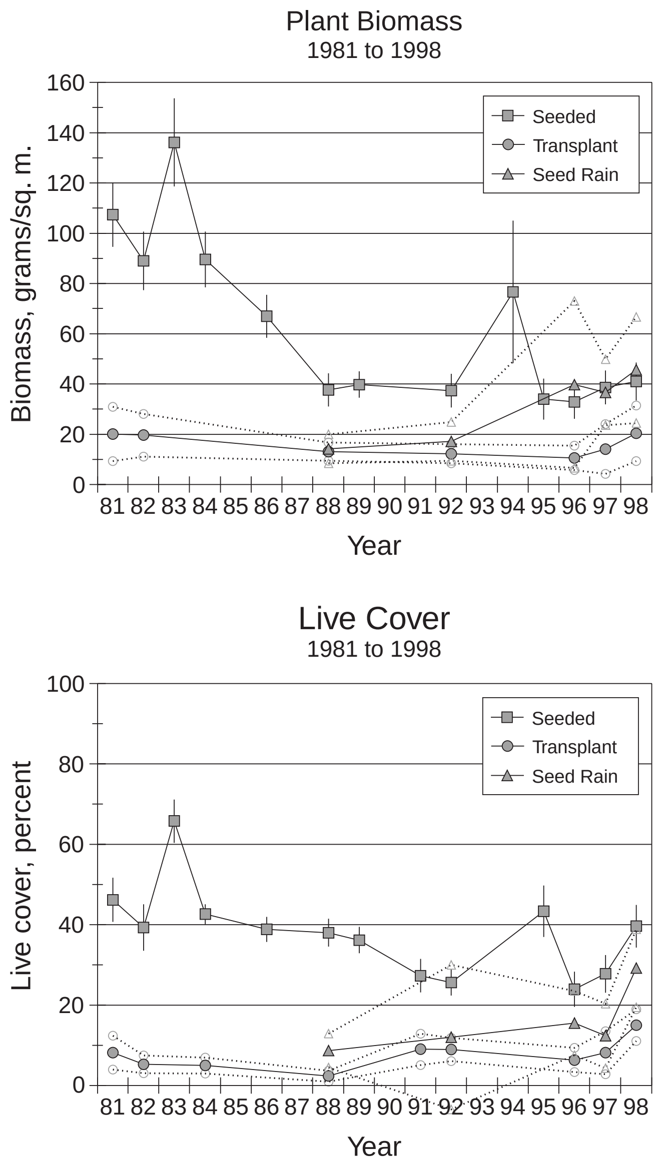

Figure 25—Plant biomass and live cover (with 95-percent confidence intervals) in the seeded, transplant, and natural seed-rain areas of the demonstration area, 1981 to1998.

colonization relative to slope position and other natural variables are highly complex and poorly understood. Also, these data show that it takes more time to achieve the same levels of development than in seeded areas. The actual time to achieve levels of biomass and cover similar to that in native communities may have been "artificially" accelerated in this study because of proximity to the nearby seeded plots in the demonstration area.

Transplanting may have value as a restoration tool but does not appear to promote community development nearly as completely nor as quickly as seeding or natural seed rain. Perhaps transplanting should be reserved for severe sites where seeding or seed rain is deemed ineffective, such as on steep, unstable slopes. Although the transplant area was treated and ameliorated with amendments at the same time and rates of application used on the seeded and seed-rain areas, rates of colonization and total species diversity lagged far behind that in other areas of the demonstration site. About 22 years after transplanting was completed, and 18 years after refertilization was discontinued, the total biomass productivity and live plant cover on the transplant area had not changed significantly. However, in the same period, and with the same levels of amendment application, the seeded and the natural seed-rain areas had about doubled the biomass and cover characteristics as the transplant area.

Restoration Retreatment Plots (1993)

The retreated plots were installed in 1993 within the seeded portion of the demonstration area to determine the effects of long-term, reapplication of fertilizer and limestone. The vegetation within the demonstration area had received no additional fertilizer applications since 1982 nor lime since installation in 1976. Concerns about the possible deterioration of pH and nutrients in the developing soil of the demonstration area before full, sustainable nutrient cycling occurred motivated installation of these retreated plots.

Total plant biomass data for each treatment (control, limestone, fertilizer, and fertilizer + limestone) are shown by year in figure 26. Biomass was highest the year following retreatment (1994) in all plots, including the unretreated control; it then declined substantially in 1995 and little thereafter. The biomass in the untreated control plots was similar to that observed in the rest of the untreated seeded demonstration area for this period. As expected, the fertilizer retreatment resulted in the highest amount of biomass produced in 1994, but the effect rapidly deteriorated. Only 1 year later the fertilizer treatment biomass declined to less than half and then leveled off with little further decline. By 1998 the biomass of the refertilized plot did not differ significantly ($p \geq 0.5$) from the biomass of the control. This suggests that the single pulse of nutrients applied in 1993 resulted in a short-lived burst of production that rapidly deteriorated to the "base" levels that had been reached and maintained throughout the seeded demonstration area. The limestone application appeared to have somewhat suppressed biomass productivity throughout the trial period, although the difference is not statistically significant ($p \geq 0.5$). In the fertilizer + limestone

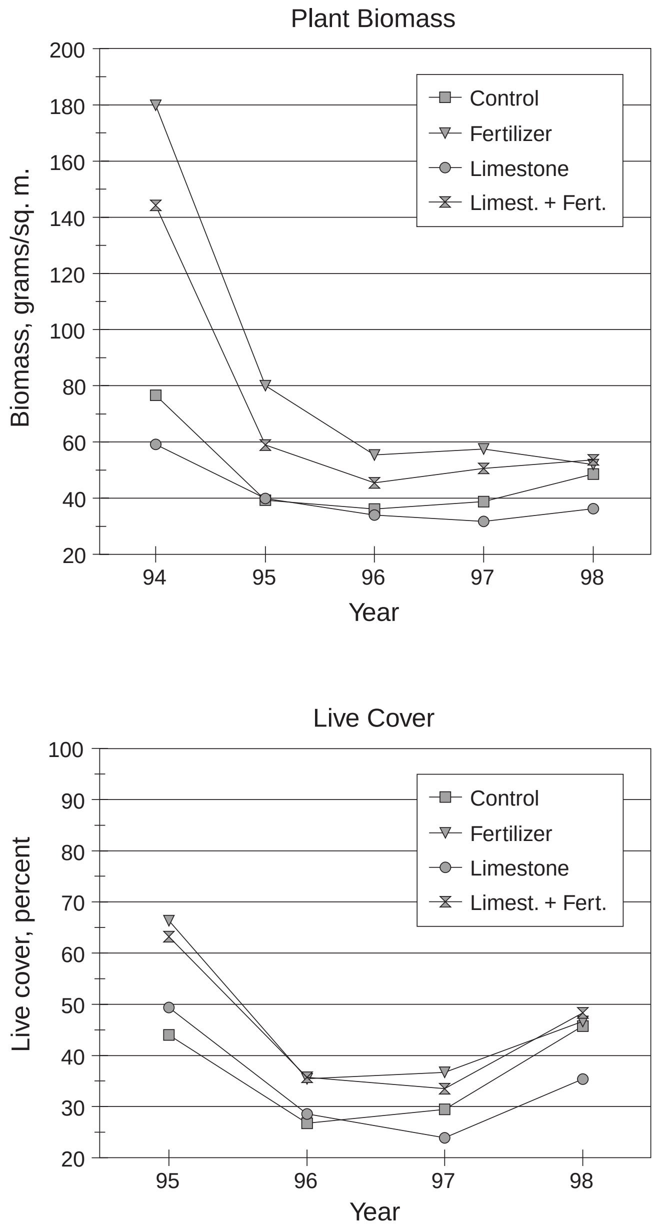

Figure 26—Plant biomass and live cover by treatment in the 1993 retreated plots of the demonstration area comparing the control plots, fertilizer plots, limestone plots, and the fertilizer + limestone plots for 5 years following retreatment.

treatment, biomass productivity was intermediate to that of the limestone and fertilizer treatments. In this case, however, biomass deterioration appeared to be more rapid, falling in 1995 to levels that did not differ significantly from the control or limestone treatment levels ($p \geq 0.5$).

Figure 26 also shows the effect of the 1993 retreatment on percent live canopy cover, but only for 1995 through 1998. Overexposed film prevented assessment of 1994 live cover. The same general trend was observed in all the treatments, resulting in a decline in live cover after 1995. The fertilizer plots had significantly greater live cover ($p \leq 0.5$) in 1995 than that observed in the control plots but then decrease in subsequent years to approximately that in the control. Similarly, live cover in the other retreatments was greatest in 1995 but then decreased to "normal" levels. In all treatments, including the control, live cover increased significantly ($p \leq 0.5$) in 1998 over that observed in 1996 and 1997, presumably attributed to more favorable weather.

These biomass and live canopy cover data serve as an important indicator of the ecological condition of the demonstration area and show that additional treatments with fertilizer and limestone appear to have only a short-term pulse effect with no apparent long-term benefit. This suggests that nutrient and acidity levels in the developing soils of the demonstration area are maintaining biomass, cover, and other attributes of the developing community at near-optimum levels that can be sustained in this environment. Thus, there appear to be no obvious deficiencies or serious deterioration in site characteristics that require continued inputs of resources.

Conclusions and Recommendations

We have attempted by this demonstration study to show what land managers can do to "reset" the successional clock that was terminated, deflected, or suspended when highly mineralized alpine areas are disturbed by mining or other human influences. As a guide for making careful decisions about land reclamation and restoration, we discuss in detail the techniques and methods for ameliorating severe disturbances and the long-term consequences of using them. The following methods, procedures, and results of reclamation research are believed to have broad applicability to a wide range of disturbances throughout the West, and they are designed to address the surface reclamation of most disturbances and types of conditions encountered. Over the past 25 years our research at New World has focused primarily on the remediation of surface disturbances and on the amelioration of conditions limiting plant establishment by revegetation and natural succession. During the past 10 to 15 years we expanded our research from just revegetation to a broader focus that included studies on characterizing soil/spoil properties and their interaction with biotic components of the ecosystem, water quality, and chemistry in New World watersheds, physiological tolerances and characteristics of native successional plant species, and soil erosion.

Our primary focus here is on the techniques and results of restoration research on surface disturbances covered by the demonstration area, and how these approaches can be used to enhance succession and the reestablishment of native communities on severe disturbances. This is consistent with the premise that a primary objective is restoring natural conditions to severely disturbed lands to return them to a self-sustaining, diverse, and resilient state. We view ecological restoration as the process of *reestablishing* succession and other natural ecosystem-forming processes on severely disturbed lands. We are confident that techniques can be implemented that not only "trigger" or reinitiate succession, but that also hasten its rate of development and guide its trajectory to ensure consistence with the overall forces of the prevailing ecosystem. Further, we believe sustainability can be achieved in this process by including the initiation of soil genesis, nutrient cycling, and other abiotic as well as biotic forces leading to the development of native communities on severely disturbed lands.

Our major research hypothesis states that *permanently successful reclamation of New World disturbances, including the improvement of water quality in impacted watersheds, can only be achieved through the restoration of natural ecosystem form and function*. Our research suggests that the ultimate solution to the problem of site degradation at New World, and elsewhere in the West, will not be achieved with structural or engineering manipulations of mine spoil, waterflow, or adit closures alone. Nor is revegetation alone sufficient. We conclude that returning the New World site to a natural self-sustaining, diverse, and resilient condition requires a long-term commitment to a restoration program involving physical, chemical, and biological intervention by managers that ameliorates limiting conditions and initiates plant establishment. This will entail a management policy that permits succession to follow a natural trajectory dictated by ecosystem forces. The material covered by this paper offers promising approaches toward this objective not only at New World but on similar sites throughout the West.

Site Preparation Methods

The first objective addressed by our research was to determine the effectiveness of amendments for reestablishing native communities on relatively large heterogeneous mine spoil areas containing toxic properties. The results of this study show that the amendments and methods used promote active natural succession while supporting an increasingly diverse self-sustaining community that protects the site from erosion and movement of sediment. The application of spoil amendments (lime, organic matter, fertilizer, surface mulches) had a significant and long-lasting impact on site conditions and obviously ameliorated otherwise limiting spoil conditions. Application of hydrated lime to achieve a pH level above approximately 5.5 appears to have been suitable for initiating vegetation establishment and long-term succession on the area.

A few small pockets of underdeveloped vegetation occurred in scattered locations across the demonstration area, some of which were created in the late 1980s by mineral exploration activities. Others apparently resulted from a few "hot-spots" (pH below 5.0) where reacidification by pyritic materials occurred. These spots may have been high concentrations of pyrites that were undertreated in 1976 with the hydrated lime applied at a rate calculated for "average" site conditions. Continued geologic weathering and exposure of metal sulfides are likely a natural process in such areas, and some subsequent reacidification of formerly limed areas should be expected. The hydrated lime applied to the area in 1976 likely has a finite life and may eventually become consumed as weathering of metal sulfides progresses. This process could have been minimized had we incorporated finely ground agricultural limestone into the spoil material along with the hydrated lime. The hydrated lime typically reacts immediately with exposed pyritic materials, whereas the limestone would react more slowly as new sulfides weather and become exposed. Despite this, the methods used in the demonstration area reinitiated natural succession rather early following treatment. And after more than 20 years there was no consistent evidence at most locations across the entire demonstration area that the spoil material within the active rooting zone of plants was reacidifying below the original goal of a pH about 5.5.

Our data indicate that initiation and progression of soil development has occurred on the amended mine spoil material. The interactions among the incorporated amendments, subsequent development of vegetation, and climatic variables appear to have triggered the successional processes responsible for this phenomenon. Development of soil horizons appears to have progressed much more rapidly than expected, particularly in this alpine environment. Our data suggest that a threshold in soil genesis was achieved in the late 1980s within the seeded portion of the demonstration area when plant invasion and increases in species and life-form diversity coincided with the appearance of a darkening soil A-horizon. Although this darkening in color was obvious to a considerable depth, it was still in an early stage of development because it was significantly shallower than that in native reference soils. Our observations that plants were rooting beyond the depths at which the spoils were amended in 1976 further support progression of soil development.

Although active succession progressed continuously within the demonstration area over the 22 years since the site was treated, the untreated spoil areas remained largely unchanged. This demonstrates that we can amend the raw spoil materials of the New World area so they become favorable "growing media" in which natural succession can occur and presumably be sustained. The real significance of this is that long-term restoration of natural conditions in the New World District can be obtained without the need for artificial "caps" or other materials that attempt to isolate the raw spoils from growing vegetation or natural waters. The toxic properties of the mine spoils in this area are treatable by standard procedures. Our data demonstrate that the approach we suggest not only makes the site able to support plant growth but also promotes and supports the intricate and complex dynamics of successional development. It should not be surprising that the treated mine spoil materials at New World support soil genesis and active succession because the treatments are the natural parent materials of the native soils in the area. Although our data are limited, it is likely that the chemical properties of surface and subsurface waters that subsequently move through the ameliorated spoil materials that support native vegetation will be significantly improved over that observed in raw spoils. Quantitative assessments of spoil movement show that erosion and sediment movement are minor problems on both the McLaren Mine and surrounding native communities. Apparently the spoil material on the McLaren Mine is not highly erosive several years following disturbance, although erosion may be more severe immediately after disturbance. If succession on the demonstration area is following a trajectory leading toward native community conditions, it is reasonable that the quality of water moving through the system will ultimately achieve similar properties. We therefore recommend that caps consisting of imported materials such as clays or soils of undetermined origin, or artificial materials intended to isolate or contain the spoil materials, be avoided.

We also recommend that capping spoil piles and other exposed disturbed materials in the New World District with native soil (top soiling or topsoil dressings) be avoided. Such practices create new disturbances that require yet additional reclamation and restoration efforts and significantly add to the overall financial expenses of cleaning up disturbed sites. Our study clearly demonstrates that these practices are unnecessary at New World and that the natural spoil material can be amended and utilized in place.

Plant Species Selection

The use of native species in the initiation of natural succession appears essential on harsh sites such as those of the New World District. Although our research did not attempt to determine the effects of varying compositions of native species on the initiation of succession, the use of *seral* native grass species appears highly effective. Our selection of the native species for this study was based solely on observations of natural succession in adjacent disturbances throughout the New World area (except for the selection of Scribner wheatgrass [*A. scribneri*], which was based on observations of succession in communities occurring on granitic soils in another portion of the Beartooth Mountains). Confidence in the ability of these species to reinitiate succession was gained through both our seeding and transplant experiments. In both instances, the seral grasses performed nearly identically in terms of relative performance and cover characteristics. Additional confidence was gained by observing that these same native seral grass species were natural colonizers in the seed-rain plots; these species became established naturally in treated spoil that had not been seeded or transplanted. Therefore, it is with considerable confidence that we recommend the use of the five primary seral grasses discussed above in all seeding and planting efforts within the New World District for revegetation, reclamation, and restoration of disturbances (see appendix C).

Use of introduced species did not appear to initiate natural succession. Our trials with the introduced species used in this study, although limited, indicate that this class of plants is unlikely to meet management objectives. The environment of the New World District is generally severe, hence only a narrowly limited pool of species appears adapted for long-term survival and consistent completion of their entire life cycle. Careful inventory of various disturbances (road cuts and fills, old spoil piles, drill pads, recreational disturbances, bulldozer cuts and tracks, erosion rill channels) in the New World area revealed that the key colonizer species almost uniformly consisted of the same five principal grasses, with some local variants and some forbs depending on specific environmental conditions. We never observed any introduced species voluntarily colonizing any of these disturbances, even though introduced species had been seeded along roads and other disturbances in the general area. This observation alone is overwhelming evidence that introduced species are not likely to contribute to restoration in the New World District. Obviously the environment in this area is so harsh and narrowly limiting that few vascular species are suited for long-term survival and consistent reproduction within it. We therefore recommend that only those native seral species observed in active local succession be utilized for reclamation and restoration purposes and that all unadapted exotic organisms be avoided.

The relative viability and vigor of each species is highly variable from year to year and seed-quality designation is rarely a guarantee of species performance. The native plant species we used in our research in the demonstration area were collected by hand from plants in various habitats of the surrounding area. Although many of these species are highly aggressive on disturbed sites, and are normally observed as early seral colonists on acid spoils, some of our seed collections had lower viability and germinative ability than others. Based on our data and experience, the single most aggressive and best suited plant for all-around revegetation and reclamation purposes on New World sites is tufted hairgrass (*D. caespitosa*; Brown and others 1988). However, alpine bluegrass (*P. alpina*) and alpine timothy (*P. alpinum*) always performed well and could be included as a significant portion of any seed mixture used. Somewhat more variable performance was observed in slender wheatgrass (*Elymus trachycaulus,* formerly *A. trachycaulum*) and spiked trisetum (*T. spicatum*), but only slightly so. These five grasses are abundant in the New World area and relatively accessible for seed collection.

A purely applied and nonquantitative ranking of overall adaptability, ease of collection, ease of seeding, and expectations for performance of these five grasses is listed below in descending order of desirability:

tufted hairgrass	*Deschampsia caespitosa*
alpine bluegrass	*Poa alpina*
alpine timothy	*Phleum alpinum*
slender wheatgrass	*Elymus trachycaulus* (formerly *Agropyron trachycaulum*)
spiked trisetum	*Trisetum spicatum*

Although the last species in the list is indicated as being less desirable for revegetation than the first, the overall difference in their relative adaptability and value as components of a revegetated community is not great. All of these species have many desirable characteristics and all can be successfully used. However, the most tolerant species of all New World vascular plants, based on apparent adaptability to acidic conditions alone, appears to be Payson sedge (*C. paysonis*). Unfortunately, this species is extremely difficult to reproduce from seed on disturbed sites but has high survival following transplanting. The least tolerant vascular species studied at New World are the various species of willow (*Salix* spp.) found in riparian areas.

Planting Techniques

Planting technique had a strong effect on species establishment and consequent cover and productivity characteristics of a site over the long term. Seeding in combination with amendment applications was conspicuously more effective for initiating natural succession, providing a protective cover, and for accelerating the development of natural soil and nutrient cycling than transplanting or depending on natural seed rain. The potential role that seeding rate may have on these attributes is uncertain. The seeding rate used on this demonstration area was high, 74 bulk lb per acre (83 kg per ha), relative to that used in other areas; the effectiveness of lower rates on ultimate cover and productivity remain unanswered. Our attempts to estimate the amount of seed distributed onto the McLaren Mine via natural seed rain from surrounding plant communities did not provide a consistent and quantitative estimate. However, estimates based on greenhouse seed germination studies of collected surface samples of mine spoil suggest that about 24.2 viable seeds per square ft (260 per m^2) were distributed on portions of the McLaren Mine in some years. We broadcast about 105 viable seeds per square ft (1,130 per m^2) on the seeded area in 1976, over four times this natural seed-rain rate. Undoubtedly rates of seed rain vary greatly with year and location, but seed rain provides tremendous seed input that potentially could play a significant role in the successional development of native communities if limiting spoil and other site conditions were ameliorated. Subsequent succession on the demonstration area suggests that native species can invade quickly in the open niches in these environments once factors limiting plant establishment are remedied.

Refertilization

One of our major concerns was the possible need for several years of repeated fertilization for the development of a plant community on these high-elevation mine spoils. Solid swards of grasses, to the near exclusion of all other life forms, are likely to develop during the period of active fertilization. Grasses are well known "luxury" consumers of abundant nutrients; as a result they are able to fully utilize available resources within the developing community. It is expected that species and life-form diversity will be artificially suppressed during the period of active fertilization and limited to a few of the most aggressive grasses and perhaps an occasional forb or shrub. However, during active fertilization the grasses are able to produce large quantities of organic matter on and in the spoil material as surface litter and subsurface root debris; this then becomes the organic base for initiating soil genesis and nutrient cycling.

When refertilization is discontinued, a decline in productivity is expected, and in some cases can be dramatic. In the demonstration area, various niches began to open over time as the productivity of the grasses declined. These open niches became available to invading species. We observed a significant increase in species and life-form diversity within a few years after the discontinuation of fertilization. This spurt in species diversity occurred concomitantly with an overall decline in site productivity, but without a significant change in protective surface cover. The cover component lost by the decrease in amount of grass canopy apparently was replaced by the increased litter produced during active fertilization and by the presence of other invading life forms. Heavy and frequent fertilization suppresses the invasion and establishment of species other than grasses, but the advantages of a rapid buildup of organic matter and nutrients in the soil appear to far outweigh any temporary losses in species diversity. Our data indicate that species and life-form diversity accelerate within a few years after terminating refertilization; organic matter and nutrient loading occur more slowly. The benefits of heavy refertilization in harsh environments appear to exceed the negative aspects of its cost and inconvenience because it promotes the rapid soil genesis and nutrient cycling required to "push" toward a sustainable ecosystem. Therefore, a 3- to 5-year program of heavy fertilization following the seeding and planting of disturbed sites at New World and other similar areas is likely to lead toward sustainable ecosystems.

There does not appear to be any clear association with mycorrhizal activity and number of years of repeat fertilization (Allen and others 1987). Mycorrhizal associations in the root systems of some species showed greater activities in the shortest refertilization treatments, whereas in others the reverse was observed. Mycorrhizal activities in the developing soils of the demonstration area suggest that intensive treatment with the amendments used here, together with the use of native species, may advance the establishment of mycorrhizal populations and activity more quickly than expected, and may advance overall successional development significantly.

Interpreting Research Data for Field Application

Restoration techniques applied in the demonstration area evolved from earlier studies on small plots (Brown and Johnston 1976). Such small research plots generally are established on relatively homogeneous spoil materials and cover much smaller ranges of environmental conditions than studies conducted on larger sites. Usually small research plots are designed to study specific objectives that would be difficult to address over larger areas. However, observations of the effectiveness of various treatments on vegetation development and productivity conducted on small research plots at New World were generally consistent with the results and trends observed on the demonstration area, with only minor variations due to spoil material heterogeneity. Some research questions simply cannot be addressed on large heterogeneous sites and require study by intensive designs on less variable small plots before applying the results to larger areas. The more applied and broader issues are preferably studied on large heterogeneous sites. We suggest that the land manager use prudence and judgment when applying the results of any research study to specific problems outside the scope of the reported research. In most instances, short-term results rarely reflect long-term ecological realities; caution should be used in extrapolating research results to reflect long-term goals.

Some resource management problems require, by their very nature, extended periods to arrive at demonstrably successful solutions. When little is known, a period of trial and error is frequently necessary to gain sufficient familiarity with the potential problem variables to arrive at possible solutions. Insights are gained by doing. And true success often cannot be determined for decades. Such has been the case here in our study of reestablishing natural succession on high elevation, acidic mine spoils. This study demonstrates the benefits of having the flexibility to engage in research on a given problem over an extended time.

Principles for Restoring Natural Communities

We include here 10 general principles of ecological restoration based primarily on our research at New World since 1972. We believe that these principles are equally applicable to similar disturbances throughout the West where managers desire to restore natural communities.

1. ***Save and redistribute natural soil*** **on disturbances, where possible, prior to revegetation and restoration.** Unfortunately, few if any older disturbances have native soil available for reapplication. However, at New World and similar sites where topsoil must be imported, we do not advocate the use of soil caps to cover spoil materials. Our data, combined with our experience, show that the raw mine spoils at New World can successfully be treated with readily available amendments at rates sufficient to ameliorate any conditions limiting establishment and growth of native seral plant species adapted to the area. Treated mine spoil at New World not only will support the development of vegetation, but will initiate soil genesis and nutrient cycling as well. Based on the available evidence, rooting depth will ultimately exceed the 6-inch (15-cm) depth of treatment, and rooting activity and organic matter turnover will increase in depth with time. Soil capping, applied even at the shallow depth of only 6 inches (15 cm), would require a significant disturbance of another area at great expense for hauling and redistributing the material. Importing soil material from outside sources should be avoided.
2. ***Shape and contour disturbed areas*** **to approximate the original slope and topographic conditions.** Concerns about drainage and ponding of accumulated water can be managed during this step. Attempts should be made to provide topographic diversity that mimics natural slope features of exposure and slope angle and that provide conditions for amendment application and seeding. Slightly roughened surface conditions also should be provided that optimize trapping of seed while minimizing the potential for wind scour.
3. ***Analyze the soil/spoil properties*** **of substrate materials near the surface.** In the New World District, the general properties of greatest concern include soil pH, availability of macronutrients such as N-P-K, and concentrations of toxic chemicals such as metals (especially Cu, Al, Fe, Mn, Zn). The weakest link in using such data appears to be in translating the quantitative limits of these soils into needed amendments to meet plant physiological tolerances. Consultation with Rocky Mountain Research Station scientists is recommended.
4. ***Apply soil amendments*** **specifically designed to ameliorate the limiting factors identified by the soil analyses.** These include:
    a. Apply lime to spoils with pH values lower than about 4.5 to 5.0; incorporate the lime into at least the upper 6 to 12 inches (15 to 30 cm) of spoil material, but 24 inches (60 cm) is better. Rates of lime application will vary with local site conditions, but generally our experiences suggest rates from 2 to 4 tons per acre (4.5 to 9 metric tons per ha) on the least acidic materials, ranging up to 10 or more tons per acre (22 metric tons per ha) on the most acidic areas.

b. Incorporate organic matter to the same depth as lime. Use sterilized manure, straw, peat, or other organic products to enhance nutrient retention and water-holding capabilities, to complex and immobilize free metals, to minimize compaction, and to improve aeration.

c. Apply and incorporate fertilizer to a depth of approximately 6 inches (15 cm) to increase the availability of the primary nutrients that may be limiting for plant growth. Commercial sources of fertilizer with N-P-K ratios such as 16-16-16, 21-8-8; 16-41-5, 31-4-4 appear useful for establishment of plants on these materials. Nitrogen appears to be the most limiting macronutrient, followed by phosphorus. We recommend application rates that provide 100 lb N per acre (112 k per ha) and 200 lb P per acre (242 k per ha) during the initial fertilization. Subsequent refertilization may be applied only as surface dressings in future years, with heavy applications of N, but less P and K may be needed. We suggest that refertilization treatments be done with 100 lb N per acre (112 k per ha) and lower amounts of P and K. We do not know if lower rates of refertilization with N will be satisfactory in the New World area.

5. ***Observe natural succession* on old disturbances in the area such as road cuts and fills, and old mine piles, and compare the abundance of different volunteer plant species to use as a guide to species selection.** The New World area is unusually rich in disturbances of various types and ages, hence it has a wide variety of successional communities that could serve as a guide for identifying native species adapted for use in reclamation of these acid spoils.

6. ***Select native plant species* based on the observations from old, natural succession areas.** Our research, and that by others, strongly supports our recommendation that introduced species should be avoided (Brown and Amacher 1999). To our knowledge, no scientific evidence exists to support the use at New World of either exotics or "naturalized" nonnatives from habitats outside of the southern Beartooth Mountains of Montana. All available data clearly show that seral grasses native to the area should be used. We strongly recommend avoidance of the temptation to substitute nonnative species for local natives in limited supply. We also recommend the early initiation of a program to collect supplies of seed of local native species for use in reclamation and restoration of the New World site. These seed collections should be cleaned and stored for future use, using appropriate techniques (Bermant and Spackeen 1997; Majerus 1999; Young and Young 1986).

The total natural vascular flora in the Fisher Mountain area, including Daisy, Fisher, and Miller Creeks of the New World District, probably number only slightly more than 100 plant species, including grasses, forbs, shrubs, and trees. About eight to 10 of these appear adapted to conditions on acid mine spoil materials and suitable for use in revegetation. These are:

Species	Common name	Life form
Agropyron trachycaulum	Slender wheatgrass	grass
Carex paysonis	Payson sedge	sedge
Deschampsia caespitosa	Tufted hairgrass	grass
Phleum aplinum	Alpine timothy	grass
Poa alpina	Alpine bluegrass	grass
Trisetum spicatum	Spike trisetum	grass
Agoseris glauca	Mountain agoseris	forb
Potentilla diversifolia	Varileaf potentilla	forb
Sibbaldia procumbens	Sibbaldia	forb

Payson sedge (*C. paysonis*) is best used as a transplant species because seed germination is extremely unreliable and difficult (Haggas and others 1987). Although there are several species of sedge (*Carex* spp.) in the area, including black alpine sedge (*C. nigricans*) and Dunhead sedge (*C. phaeocephala*), and all are particularly hardy plants, only Payson sedge (*C. paysonis*) appears to be especially well adapted to extreme acid conditions.

We hesitate suggesting inclusion of forbs, sedges, or other life forms in seed mixtures at New World because they tend to be expensive to collect or purchase, have poor viability, and all appear to eventually invade the revegetated communities. Our experience indicates that forbs and sedges are highly aggressive and mobile in the native communities of the area and rapidly invade and establish themselves following the termination of refertilization. Seed trapping and natural succession should occur rapidly within a few years after terminating fertilization. Invading forb species on the McLaren Mine demonstration area currently outnumber the grasses three to one (see appendix A). We therefore recommend that the expense of adding forbs and other life forms be avoided, and that site stabilization be accomplished with grasses.

Seeding rates should be based on the number of seeds desired per unit area (for example seeds per ft^2) rather than on pounds per acre. Every species has unique seed characteristics of mass and shape, hence total weights vary greatly from species to species. For instance, tufted hairgrass (*D. caespitosa*) commonly has about 1,750,000 seeds per pound, whereas slender wheatgrass (*A. trachycaulum*) may only have about 175,000 seeds per pound, a difference factor of 10 times. If both species were seeded at the same weight per unit area, tufted hairgrass would have a decided competitive advantage over slender wheatgrass because of the potential difference in number of plants produced per unit area.

We recommend that seeding rates be adjusted according to the individual seed characteristics of each species so that equal numbers of seed of each species are applied per unit area. A summary of suggested seed mixtures with equal seed numbers per species per unit area for use on acidic or slightly acidic New World disturbances is shown in appendix C. Following this approach will minimize any competitive advantage of one species over another. We generally recommend about 75 to 150 seeds per square ft (800 to 1600 per m^2) for each species.

Seed mortality is usually high. We have observed about 90 percent mortality in planted seeds during the first winter and growing season. Of those seeds that survive and germinate to become seedlings, mortality during the first growing season is also high, often ranging between 75 and 90 percent. Mortality rates decline as plants mature into adult growth forms; as maturity is approached mortality may drop below 50 percent and decreases appreciably thereafter. As a consequence, our recommended seed mixtures and planting rates in appendix C would be expected to produce about six mature seed-producing plants per square ft (65 per m^2) in two or three growing seasons following seeding.

7. ***Perform revegetation-restoration activities in the fall of the year.*** Autumn planting and seeding appears to be more successful than spring because:

   a. Fall coincides with the period when native plant species mature and disperse their seeds.
   b. Fall timing ensures that seed will be in place during the winter to coincide with potential dormancy requirements.
   c. Seeds will be in place during spring snowmelt when conditions are ideal for germination, seedling emergence, and seedling growth.
   d. Spring-time access at high elevations is uncertain during most years due to late snowmelt, muddy roads, and unfavorable saturated soil conditions.

8. ***Apply seed by broadcasting*** **rather than by drilling or other mechanical means.** Native seeds are highly variable in shape, size, mass, and surface characteristics, and are therefore not well suited to mechanical devises developed for more uniform agricultural crop plants. Native seeds tend to clog mechanical seeding devises, as well as become sorted in hoppers according to relative density producing irregular patterns in seed distribution on the ground.

Following seed application, the seed should be lightly raked to cover them with soil, and then the soil packed to firm the seed into the soil fines. This step is critical for some species because it ensures hydraulic conductivity between the seeds and fine soil particles, minimizes seed drying due to exposure at the surface, and it protects the seed from redistribution by wind, water, and predation. Some alpine species, especially sedges (*Carex* spp.) and rushes (*Juncus* spp.), require light for germination and should be applied on the surface in a separate operation following seeding of nonphotoblastic species.

Application of seed by hydromulching and hydroseeding techniques is not recommended in high-elevation environments. Hydroseeding often covers the seed with fibrous mulching materials, but the hydraulic conductivity between these materials and the soil can be lost during high winds, frost heaving, or severe drying conditions. The seeds may then become separated from the soil, and severe dehydration and subsequent mortality often results.

Mixtures of at least several different species are generally more successful than a single species alone. This practice will enhance species diversity, and will be more compatible with natural succession. Mixtures of species are also less susceptible to complete annihilation by such natural phenomena as disease, insect outbreaks, drought, frost, and other natural catastrophes.

9. ***Apply surface mulch*****, such as erosion blankets, following seeding and planting.** This material protects and stabilizes the surface, and promotes restoration because it:

   a. Minimizes surface rilling and erosion caused by rain drop impact and surface runoff.
   b. Reduces evaporation of surface soil water.
   c. Reduces wind erosion and redistribution of seed and soil fine particles.
   d. Reduces the incidences of frost and other temperature extremes at the surface.
   e. Increases trapping of snow and rainwater.
   f. Improves trapping of native seed.

Light to moderate application rates are better than heavier applications. The surface of the soil should be visible when viewed vertically through the fibers or other materials used. Erosion blanket materials provide about 2 to 3 tons per acre (4.5 to 6.7 metric tons per ha) equivalent rates of straw fiber, and appear to be near ideal for most revegetation-stabilization work. Stapling or otherwise securing the mulch to the surface is essential. We recommend stapling intervals about 30 percent shorter than that recommended by the manufacturer, especially on steep unstable slopes where water and wind movement can dislodge the blanket material. We have used blown straw secured in place with liquified tackifiers (as on the demonstration area described here), but this method is far more cumbersome than commercially available erosion blankets.

10. ***Assess and refertilize the site yearly for several years* to determine relative success or failure and to reapply amendments or seed in places when necessary.** Refertilization will almost certainly be required to further accelerate successional development of restored areas and to enhance survival and establishment of invading outside species. In addition, periodic soil sampling and analyses are recommended to assess nutrient deficiencies, requirements for additional liming, and other amendments.

Fencing may be required to minimize impacts by animals or people. (In our experience people can be far more destructive than most native animals.) Domestic livestock should be excluded from these sensitive areas, at least until the vegetation becomes well established.

References

Allen, E. B.; Chambers, J. C.; Conner, K. F.; Allen, M. F.; Brown, R. W. 1987. Natural development of mycorrhizae in disturbed alpine ecosystems. Arctic and Alpine Research. 19(1): 11–20.

Amacher, M. C.; Brown, R. W. 1999. Mine waste characterization. In: Barcelo, D., ed. Sample handling and trace analysis of pollutants: techniques, applications and quality assurance. Elsevier Science. B.V.: 585–622.

Amacher, M. C.; Brown, R. W.; Kotuby-Amacher, J.; Willis, A. 1993. Adding sodium hydroxide to study metal removal in a stream affected by acid mine drainage. Res. Pap. INT–RP-465. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 17 p.

Barber, S. A. 1984. Liming materials and practices. In: Adams, F., ed. Soil acidity and liming, second edition. Madison, WI: American Society of Agronomy. Agronomy. 12: 171–209.

Bartos, D. L.; Campbell, R. B., Jr. 1998. Decline of quaking aspen in the Interior West—examples from Utah. Rangelands. 20(1): 17–24.

Bermant, D.; Spackeen, S. 1997. Native species in the commercial seed industry. In: Shaw, N.; Roundy, B. A., comps. Using seeds of native species on rangelands: proceedings. Gen. Tech. Rep. INT-GTR-372. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 26–29.

Brown, D. 1954. Methods of surveying and measuring vegetation. Bull. 42. England: Commonwealth Agriculture Bureaux, Commonwealth Bureau of Pastures and Field Crops, Hurley Berks. 300 p.

Brown, D. 1995. The impact of species introduced to control invasion on the vegetation of an electrical utility right-of-way. Canadian Journal of Botany. 73: 1217–1228.

Brown, R. W.; Amacher, M. C. 1999. Selecting plant species for ecological restoration: a perspective for land managers. In: Holzworth, L. K.; Brown, R. W., comps. Revegetation with native species: proceedings; 1997 Society for Ecological Restoration annual meeting, November 12–15; Fort Lauderdale, FL. RMRS-P-8. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 1–16.

Brown, R. W.; Amacher, M. C.; Williams, B. D.; Mueggler, W. F.; Kotuby-Amacher, J. 1996a. Ecological restoration of acidic mine spoils at high elevations: long-term significance of revegetation and natural succession. In: High altitude revegetation workshop No. 12. Inf. Series No. 83. Fort Collins, CO: Colorado State University; Colorado Water Resources Research Institute:127–151.

Brown, R. W.; Amacher, M. C.; Williams, B. D.; Mueggler, W. F.; Kotuby-Amacher, J. 1996b. Revegetation of acidic mine spoils at high elevations: restoration of native plant communities. In: 18th annual conference of the Association of Abandoned Mine Land Programs; September 15–18; Kalispell, MT. Helena, MT: 23–33.

Brown, R. W.; Chambers, J. C. 1990. Reclamation practices in high-mountain ecosystems. In: Symposium on whitebark pine ecosystems: ecology and management proceedings. Gen. Tech. Rep. INT-GTR-270. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 329–334.

Brown, R. W.; Chambers, J. C.; Wheeler, R. M.; Neely, E. E.; Kelrick, M. I. 1988. Adaptations of *Deschampsia caespitosa* (tufted hairgrass) for revegetation of high elevation disturbances: some selection criteria. In: Proceedings: high altitude revegetation workshop No. 8. Inf. Series No. 59. Fort Collins, CO: Colorado State University, Water Resources Research Institute: 147–172.

Brown, R. W.; Johnston, R. S. 1976. Revegetation of an alpine mine disturbance: Beartooth Plateau, Montana. Res. Note INT-RN-206. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 8 p.

Brown, R. W.; Johnston, R. S. 1978a. Rehabilitation of disturbed alpine rangelands. In: Proceedings of the First International Rangeland Congress. Denver, CO: Society for Range Management: 704–706.

Brown, R. W.; Johnston, R. S. 1978b. Rehabilitation of high elevation mine disturbances. In: Proceedings: high altitude revegetation workshop No. 3. Inf. Series No. 28. Fort Collins, CO: Colorado State University, Water Resources Research Institute: 116–130.

Brown, R. W.; Johnston, R. S. 1979. Revegetation of disturbed alpine rangelands. In: Special management needs of alpine ecosystems. Denver, CO: Society for Range Management: 76–94

Brown, R. W.; Johnston, R. S. 1980a. An assessment of revegetation techniques for alpine disturbances. In: Proceedings: high altitude revegetation workshop No. 4. Inf. Series No. 42. Fort Collins, CO: Colorado State University, Water Resources Research Institute: 126–146.

Brown, R. W.; Johnston, R. S. 1980b. Bioassay of alpine mine spoils for plant growth and development. Res. Note INT-RN-285. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Brown, R. W.; Johnston, R. S.; Chambers, J. C. 1984. Responses of seeded grasses to repeated fertilization applications on acidic alpine mine spoils. In: Proceedings: high altitude revegetation workshop No. 6. Inf. Series No. 53. Fort Collins, CO: Colorado State University, Water Resources Research Institute: 200–214.

Brown, R. W.; Johnston, R. S.; Johnson, D. A. 1978a. Rehabilitation of alpine tundra disturbances. Journal of Soil Water Conservation. 33: 154–160.

Brown, R. W.; Johnston, R. S.; Van Cleve, K. 1978b. Rehabilitation problems in alpine and arctic regions. In: Reclamation of drastically disturbed lands. Madison, WI: American Society of Agronomy: 23–44.

Cairns, J., ed. 1995. Rehabilitating damaged ecosystems. Boca Raton, FL: Lewis Publishers. 425 p.

Crown Butte Mines, Inc. 1990. Environmental baseline study plan New World Project. Park County, Montana. Unpublished Report prepared by Hydrometrics, Inc., Helena, MT, for Montana Department of State Lands and USDA Forest Service.

Elliott, J. E. 1980. Geology and mineralization of the Cooke City Mining District. In: Nelson, W. H.; Prostka, H. J.; Williams, F. E. 1980. Geology and mineral resources of the North Absaroka Wilderness and vicinity, Park County, Wyoming. U.S. Department of the Interior, Geological Survey Bull. 1447: 57–59.

Elliot, J. E.; Kirk, A. R.; Johnson, T. W. 1992. Field guide: gold-copper-silver deposits of the New World District. U.S. Department of the Interior and Crown Butte Mines, Inc., joint-tour guide. 19 p.

Furniss, G. 1996. Age relationships of acid drainage water quality at the New World Mining District, Park County, Montana. Billings, MT: American Association of Professional Geologists, Round Table. July.

Haggas, L. R.; Brown, W.; Johnston, R. S. 1987. Light requirement for seed germination of Payson sedge. Journal of Range Management. 40: 180–184.

Hawley, J. R. 1972. The problem of acid mine drainage in the Province of Ontario. Special Projects. Toronto, Ontario: Section—Mining Industrial Wastes Branch, Ministry of the Environment. 338 p.

Hitchcock, C. L.; Cronquist, A. 1973. Flora of the Pacific Northwest. Seattle & London: University of Washington Press. 730 p.

Howard, P. L. 1978. Plant succession studies on subalpine acid mine spoils in the Beartooth Mountains. Logan, UT: Utah State University. 92 p. Thesis.

Jackson, L. L.; Lopoukhine, N.; Hillyard, D. 1995. Commentary—ecological restoration: a definition and comments. Restoration Ecology. 3(2): 71–75.

Johnston, R. S.; Brown, R. W.; Craven, J. 1975. Acid mine rehabilitation problems at high elevations. In: Watershed management symposium. Logan, UT: American Society of Civil Engineers, Irrigation and Drainage Division: 66–79.

Kirk, A. R.; Johnson, T. W. 1993. Geology and mineral deposits of the New World District, Park County, Montana. Montana Geological Society, 1993 guidebook: energy and mineral resources of central Montana. Billings, MT: Montana Geological Society: 227–235.

Lesica, P.; DeLuca, T. H. 1996. Long-term harmful effects of crested wheatgrass on Great Plains grassland ecosystems. Journal of Soil and Water Conservation. 51: 408–409.

Lovering, T. S. 1929. The New World or Cooke City Mining District, Park County, Montana. In: Loughlin, G. F.; Mansfield, G. R.; Burchard, E. F. Contributions to economic geology. Part 1—metals and nonmetals except fuels. U.S. Department of the Interior. Geological Survey Bull. 811: 1–87.

MacMahon, J. A.; Jordan, W. 1994. Ecological restoration. In: Meffe, G. K.; Carroll, C. R. Principles of conservation biology. Sunderland, MA: Sinauer Associates, Inc.: 409–438.

Majerus, M. 1999. Collection and production of indigenous plant material for National Park restoration. In: Holzworth, L. K.; Brown, R. W., comps. Revegetation with native species; 1997. Society for Ecological Restoration annual meeting. Ogden, UT. Proc. RMRS-P-8. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 17–21.

Mills, E. L.; Leach, J. H.; Carlton, J. T.; Secor, C. L. 1994. Exotic species and the integrity of the Great Lakes. BioScience. 44(10): 666–676.

O'Conner, G. A. 1988. Use and misuse of the DTPA soil test. Journal of Environmental Quality. 17(4): 715–718.

Perry, E. S. 1962. Montana in the geologic past. Bull. 26. Butte, MT: Montana Bureau of Mines, Montana School of Mines. 78 p.

Rapport, D. J.; Whitford, W. G. 1999. How ecosystems respond to stress. BioScience. 49(3): 193–203.

Simonin, H. A. 1988. Neutralization of acidic waters. Environmental Science Technology. 22(10): 1143–1145.

Sorensen, D. L.; Kneib, W. A.; Porcella, D. B.; Richardson, B. Z. 1980. Determining the lime requirement for the Blackbird Mine spoil. Journal of Environmental Quality. 9(1): 162–166.

Thomas, G. W.; Hargrove, W. L. 1984. The chemistry of soil acidity. In: Adams, F., ed. Soil acidity and liming, second edition. No. 12, Agronomy. Madison, WI: American Society of Agronomy: 3–56.

Williams, F. E. 1980. Cooke City Mining District: history. In: Nelson, W. H.; Prostka, H. J.; Williams, F. E. Geology and mineral resources of the North Absaroka Wilderness and vicinity, Park County, Wyoming. U.S. Department of the Interior, Geological Survey Bull. 1447: 54–55.

Young, J. A.; Young, C. G. 1986. Collecting, processing, and germinating seeds of wild land plants. Portland, OR: Timber Press. 236 p.

Appendix A: List of vascular plant species by life-form class by location in the New World Mining District. Occurrence of a species is indicated by a "1" at each location where found. Locations include the entire New World District, the demonstration area, six reference areas, and the natural successional areas located on untreated spoil within the Mine boundary.
(The number "1" in each cell indicates presence only and is not intended to imply abundance; other numbers are totals by life form for each area).

							Glengarry reference areas[c]			McLaren Mine succession areas			
		New World	McLaren Mine	McLaren reference areas[b]						Succ.	Succ.	Limestone	Spoil Piles
Scientific name	Common name	District	demo[a]	AA	AB	AC	AD	AE	AF	Strip	Hill	Hill	entire
Grasses:													
Agropyron caninum	bearded wheatgrass	1			1								
Agropyron scribneri	Scribner wheatgrass	1											
Agropyron trachycaulum	slender wheatgrass	1	1		1	1	1			1	1		1
Agrostis humilis	alpine bentgrass	1		1									
Bromus marginatus	mountain brome	1		1									
Danthonia intermedia	timber danthonia	1		1			1	1	1				
Deschampsia atropurpurea	mountain hairgrass	1		1	1		1						
Deschampsia caespitosa	tufted hairgrass	1	1	1	1	1	1		1	1	1	1	1
Phleum alpinum	alpine timothy	1	1	1	1	1	1		1	1	1	1	1
Poa alpina	alpine bluegrass	1	1	1	1	1	1			1	1	1	1
Poa compressa	Canada bluegrass	1	1										
Poa epilis	skyline bluegrass	1	1	1	1	1	1	1	1		1	1	
Poa nervosa	Wheeler bluegrass	1	1		1	1	1						
Poa reflexa	nodding bluegrass	1		1	1	1	1					1	
Poa rupicola	timberline bluegrass	1	1										
Trisetum spicatum	spike trisetum	1	1	1	1	1	1	1	1	1	1	1	1
Total grasses:		16	9	10	10	8	10	3	5	5	6	6	5
Sedges and Rushes:													
Carex haydeniana	cloud sedge	1	1	1									
Carex nigricans	black alpine sedge	1	1		1					1	1		1
Carex paysonis	Payson's sedge	1	1	1	1		1	1	1	1	1		
Carex phaeocephala	Dunhead sedge	1		1			1	1	1		1		
Carex rostrata	beaked sedge	1	1	1									
Juncus drummondii	Drummond rush	1		1	1		1	1	1	1	1		1
Juncus mertensianus	Merten's rush	1	1								1		1
Luzula parviflora	millet woodrush	1		1	1	1	1	1	1	1	1		1
Luzula spicata	spike woodrush	1		1	1		1	1	1				
Total sedges and rushes		9	5	7	5	1	5	5	5	4	6	0	4
Forbs:													
Achillea millefolium	yarrow	1	1		1								
Agoseris aurantiaca	orange agoseris	1	1	1									
Agoseris glauca	pale agoseris	1	1	1	1	1	1	1	1	1	1		1
Agoseris sp.	agoseris	1	1										
Allium Schoenoprasum	chive	1		1	1								1
Anaphalis margaritacea	pearl-everlasting	1	1										

Scientific name	Common name	New World District	McLaren Mine demo[a]	McLaren reference areas[b] AA	AB	AC	Glengarry reference areas[c] AD	AE	AF	McLaren Mine succession areas Succ. Strip	Succ. Hill	Limestone Hill	Spoil Piles entire
Forbs:													
Aquiligia flavescens	yellow columbine	1		1	1								
Antennaria alpina	alpine pussytoes	1	1	1									1
Antennaria lanata	woolly pussytoes	1	1	1	1		1	1	1				
Antennaria umbrinella	pussytoes	1		1					1				
Arabis furcata	rockcress	1	1										
Arabis lyallii	Lyall rockcress	1	1		1	1					1	1	1
Arenaria rubella	sandwort	1				1						1	
Arnica cordifolia	heartleaf arnica	1	1										
Arnica latifolia	broadleaf arnica	1	1	1	1	1	1	1	1	1	1		1
Arnica longifolia	longleaf arnica	1	1	1	1								
Arnica rydbergii	Rydberg arnica	1			1	1							
Aster alpigenus	aster	1	1	1	1	1		1	1	1			1
Aster foliaceus	alpine leafybract aster	1		1	1	1	1						
Astragalus alpinus	alpine milkvetech	1		?									
Besseya wyomingensis	Wyoming kittentails	1											
Caltha leptosepala	marshmarigold	1		1			1						
Castilleja pulchella	Indian paintbrush	1		1	1	1							
Cerastium berringianum	mouse-ear chickweed	1											
Claytonia lanceolata	lanceleaf springbeauty	1	1	1	1	1							
Dodecatheon pauciflorum	shootingstar	1		1	1								
Draba crassifolia	Whitlow-wort draba	1	1	1	1					1	1	1	
Draba incerta	Whitlow-wort	1	1	1	1								
Epilobium alpinum	alpine willoweed	1	1	1	1	1				1	1	1	1
Epilobium angustifolium	fireweed	1	1	1	1	1							
Equisetum palustre	marsh horsetail	1											
Erigeron sp.	fleabane daisy	1	1									1	
Erigeron peregrinus	peregrine fleabane	1	1	1	1	1	1	1	1	1	1		
Erigeron simplex	simplex fleabane	1		1			1	1	1				
Frasera speciosa	showy frasera	1		1									
Gaultheria humifusa	wintergreen	1						1					
Gentiana simplex	gentian	1	1	1			1						
Habenaria obtusata	habenaria	1		1									
Hieracium gracile	slender hawkweed	1	1	1	1		1	1	1	1	1		1
Helianthella quinquenervis	little sunflower	1		1									
Lewisia pygmaea	bitterroot	1		1		1							
Lupinus argenteus	silvery lupine	1		1	1	1	1						
Mertensia alpina	alpine bluebell	1	1	1	1								
Mertensia ciliata	mountain bluebell	1				1					1		
Mertensia paniculata	tall bluebell	1		1	1	1	1						

Scientific name	Common name	New World District	McLaren Mine demo[a]	McLaren reference areas[b] AA	AB	AC	Glengarry reference areas[c] AD	AE	AF	McLaren Mine succession areas Succ. Strip	Succ. Hill	Limestone Hill	Spoil Piles entire
Forbs:													
Mimulus lewisii	Lewis monkeyflower	1											
Myosotis alpestris	forget-me-not	1		1									
Oxyria digyna	mountain sorrel	1										1	
Oxytropis campestris	crazyweed	1											
Parnassia fimbriata	parnassia	1		1									
Pedicularis bracteosa	bracted lousewort	1		1	1		1						1
Pedicularis groenlandica	elephanthead	1		1			1						
Penstemon sp.	penstemon	1	1										
Phacelia sericea	silky phacelia	1											
Polemonium viscosum	skunk polemonium	1											
Polygonum bistortoides	American bistort	1	1	1	1	1	1	1	1	1			
Polygonum douglasii	Douglas knotweed	1		1	1	1	1						
Potentilla diversifolia	varileaf cinquefoil	1	1	1	1	1	1	1	1	1			1
Pyrola bracteata	wintergreen pyrola	1		1	1								
Rannuculus eschscholtzii	Eschscholtz buttercup	1	1	1	1	1	1		1				
Rumex paucifolius	mountain sorrel	1		1	1								
Saxifraga oregona	saxifrage	1		1									
Sedum lanceolatum	stonecrop	1		1					1				
Senecio crassulus	thickleaf groundsel	1		1	1	1				1		1	1
Senecio fremontii	Fremont groundsel	1	1	1								1	
Senecio serra	butterweed groundsel	1	1	1	1	1	1						
Senecio triangularis	arrowleaf groundsel	1									1		
Sibbaldia procumbens	sibbaldia	1	1	1	1	1	1	1	1	1	1		1
Solidago multiradiata	goldenrod	1	1		1	1							1
Spraguea umbellata	pussypaws	1				1							
Taraxicum officinale	common dandelion	1	1	1	1		1			1			1
Thalictrum occidentale	western meadowrue	1											
Trollius albiflorus	globeflower	1		1									
Valeriana edulis	edible valerian	1	1	1	1								
Veronica alpina	alpine speedwell	1	1	1	1								
Veronica wormskjoldii	American speedwell	1	1	1	1	1	1						
Viguiera multiflora	showy goldeneye	1	1										
Viola adunca	Hook violet	1	1	1	1								
Viola orbiculata	yellow violet	1	1	1	1	1							
Zygadenus elegans	mountain deathcamas	1		1									
Total forbs:		80	38	52	40	27	21	11	13	12	10	8	14

Scientific name	Common name	New World District	McLaren Mine demo[a]	McLaren reference areas[b] AA	AB	AC	Glengarry reference areas[c] AD	AE	AF	McLaren Mine succession areas Succ. Strip	Succ. Hill	Limestone Hill	Spoil Piles entire
Shrubs:													
Cassiope mertensiana	western mtn. heather	1											
Kalmia microphylla	swamp laurel	1						1					
Ledum glandulosum	Labrador tea	1											
Phyllodoce empetriformis	red mountain heath	1						1					1
Phyllodoce glandulifera	cream mountainheath	1											
Salix arctica	arctic willow	1			1			1					
Salix monticola	mountain willow	1		1	1								1
Salix wolfii	Wolf's willow	1											
Vaccinium scoparium	grouse whortleberry	1	1		1			1	1				1
Total shrubs:		9	1	1	3	0	0	4	1	0	0	0	3
Trees:													
Abies lasiocarpa	subalpine fir	1		1			1	1	1			1	1
Picea engelmannii	Engelman spruce	1	1	1									
Pinus albicaulis	whitebark pine	1	1	1		1	1	1	1				1
Pinus contorta	lodepole pine	1											
Total trees:		4	2	3	0	1	2	2	2	0	0	1	2
Total number of species observed:		118	55	73	58	37	38	25	26	21	22	15	28

[a]Species for the McLaren Mine Demonstration Area later than 1997 only.
[b]McLaren Mine reference areas are those within the Daisy Creek drainage only.
[c]Glengarry Mine reference areas are those in Fisher Creek drainage only.

Appendix B: Plant species frequency and ground cover on the demonstration area and on three native reference areas representing different level of productivity. (Frequency data are from 50 permanent plots on each area, and ground-cover data are from 300 points of intercept on each area.)

					Reference				
		Demonstration area			**High production**		**Medium production**		**Low production**
	Plot size	**1995**	**1997**	**1998**	**1995**	**1997**	**1995**	**1997**	**1995**
Ground cover data	*m*	- *Percent* -							
Bare soil		15	9	8	15	20	35	28	10
Gravel		26	21	26	8	7	49	49	80
Rock		2	8	4	0	0	0	2	1
Moss/liverwort		1	1	0	19	20	0	0	0
Litter		34	39	47	33	22	7	12	4
Basal vegetation		22	22	15	25	31	9	9	5
Frequency data									
Graminoids									
Agropyron trachycaulum	1/4	28	32	38			20	2	4
Agrostis humilis	1/4					10			
Carex haydeniana	1/4	30	28	34	66	76			
Carex paysonis	1/4	2	4	8	24	16			
Danthonia intermedia	1/4				6	8			
Deschampsia caespitosa	1/16	80	94	82	76	58		2	
Juncus drummondii	1/4		2	2	66	82			
Luzula parviflora	1/4				38	40	2		
Phleum alpinum	1/16	48	44	38	60	66	12	12	4
Poa alpina	1/8	66	72	58	22	16		2	
Poa epilis	1/4	14	8	6	24	56	68	60	60
Poa reflexa	1/4		10	12	8	12	24	20	24
Trisetum spicatum	1/4	52	62	74	62	44	16	26	6
Forbs									
Agoseris aurantica	1/4					10			
Agoseris glauca	1/4	6	30	32	62	56	80	70	74
Allium schoenoprasum	1/4				30	24	2		
Antennaria lanata	1/4				26	24			
Antennaria umbrinella	1/4				54	58			
Aquilija flavescens	1/4						2	2	
Arabis drummondii	1/4	18	24	12					
Arabis lyallii	1/4	22	18	42			4	24	4
Arabis sp.	1/4						2	2	
Arnica latifolia	1/4				4	4	6	4	
Arnica rydbergii	1/4						44	42	18
Aster alpigenus	1/4				6	12			
Aster foliaceus	1/16				78	74	10	16	14
Caltha leptosepala	1/4				56	48			
Castilleja pulchella	1/4				22	22	2		
Claytonia lanceolata	1/4					26		10	
Dodecatheon pauciflorum	1/8				68	84			
Draba spp.	1/4	12	12	2					
Epilobium alpinum	1/4		6	54	42	56	12	18	22
Epilobium angustifolium	1/4	8	14	12			38	34	
Eriogonum pyrolaefolium	1/4								4
Erigeron perigrinus	1/4	2	2	4	12	10			
Erigeron simplex	1/4				18	12			
Hieracium gracile	1/4	12	22	38	2	4			
Lupinus argenteus	1/4				34	38			6
Mertensia ciliata	1/4								2
Pedicularis groenlandica	1/4				6	4			
Polygonum bistortoides	1/4		2	2	60	62	4	2	

Appendix B (Con.)

		Demonstration area			Reference: High production		Reference: Medium production		Reference: Low production
	Plot size	1995	1997	1998	1995	1997	1995	1997	1995
Ground cover data	*m*	*Percent*							
Forbs									
Polygonum douglasii	1/16				80	76	14	14	
Potentilla diversifolia	1/4		6	2	6		36	48	60
Ranunculus eschscholtzii	1/4				62	78	2	2	
Rumex pauciflorus	1/4					6			
Saxifraga oregona	1/4				36	52			
Sedum spp.	1/4						10	2	
Senecio crassulus	1/4		2	2	2	6			
Senecio multiradiata	1/8						48	46	
Senecio spp.	1/4								52
Sibaldia procumbens	1/4	6	6	8	24	32	58	62	36
Taraxicum officinale	1/4	4	6	2					
Valeriana edulis	1/4				2	4	4	4	
Veronica wormskjoldii	1/4	20	52		36	58		2	
Viola obiculata	1/4						6	2	2
Shrubs									
Vaccinium scoparium	1/4						16	16	
Number of species encountered		**18**	**24**	**23**	**36**	**39**	**27**	**28**	**17**

NOTE: Considerable confusion in separating Epilobium alpinum and Veronica wormskjoldii in the vegetative stage. Apparantly most of this questionable species was called Veronica in 1995 AND 1997, but was identified as Epilobium in 1998 (when it flowered abundantly)!

Appendix C: Suggested seed mixture of native grass species for use in seeding disturbances on New World District acidic mine spoils and other disturbances. PLS (pure live seed percentage) provided is only an estimate and can vary widely depending on collection site, year, climatic conditions, and history of plant growth conditions.

				Spoil sites		Nonspoil sites	
Scientific name	**Common name**	**Number of seeds per pound**	**PLS percentage (estimate)**	**Desired number of viable seeds per ft^2**	**Number of lb seed required per acre**	**Desired number of viable seeds per ft^2**	**Number of lb seed required per acre**
Agropyron trachycaulum	Slender wheatgrass	177,000	75	100.00	32.81	75.00	24.61
Deschampsia caespitosa	Tufted hairgrass	1,750,000	75	100.00	3.32	75.00	2.49
Phleum alpinum	Alpine timothy	1,040,000	75	100.00	5.58	75.00	4.19
Poa alpina	Alpine bluegrass	1,430,000	75	100.00	4.06	75.00	3.05
Trisetum spicatum	Spiked trisetum	2,118,000	75	100.00	2.74	75.00	2.06
Total				**500.00**	**48.52**	**375.00**	**3.34**

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