Arctic and Alpine Research, Vol. 26, No. 4, 1994, pp. 354–363

Succession on Regraded Placer Mine Spoil in Alaska, U.S.A., in Relation to Initial Site Characteristics

R. V. Densmore

National Biological Survey, Alaska
Research Center, 1011 East Tudor,
Anchorage, Alaska 99503, U.S.A.

Abstract

This study evaluated the rate and pattern of natural succession on regraded placer mine spoil in relation to initial substrate characteristics. The study site was the Glen Creek watershed of the Kantishna mining area of Denali National Park and Preserve, Alaska. After regrading, twelve 0.01-ha plots were established and substrate characteristics were measured. Natural plant succession was evaluated after five growing seasons. Three successional patterns were identified on the basis of plant community characteristics using cluster analysis, and were related to substrate characteristics. First, a riparian plant community with vigorous *Salix alaxensis* and *Alnus crispa* grew rapidly on topsoil that had been spread over the regraded spoil. Second, a similar plant community with less vigorous *S. alaxensis* developed more slowly on unprocessed spoil and spoil amended with a small amount of topsoil. Third, processed spoil remained almost bare of vegetation, although *S. alaxensis* was able to establish and persist in a stunted growth form. In contrast, *Alnus crispa* had difficulty establishing on processed spoil, but the few established seedlings grew well. Several substrate variables, including the proportion of silt and clay vs. sand, total nitrogen, and water retention capacity, were good predictors of the rate and pattern of succession. Total nitrogen was the best single predictor for the number of vigorous *S. alaxensis*.

Introduction

Many subarctic riparian ecosystems have been severely disturbed by placer mining for gold. Placer mining involves removing riparian vegetation and topsoil, excavating gravel (usually down to bedrock) from the active floodplain, stream channel, and/or old terraces and channels, and processing the gravel to remove the gold. The result of placer mining is often a deranged and unstable stream bordered with poorly vegetated rock and gravel spoil piles. Recovery of these disturbed areas is important because subarctic riparian plant communities are areas of relatively productive vegetation. These plant communities support high wildlife densities and provide essential habitat for many species.

Current placer mine reclamation regulations require or recommend regrading to level and recontour the spoil piles, and stockpiling and replacement of topsoil and fines (U.S. Department of Interior Bureau of Land Management, 1985, 1989a, 1989b; State of Alaska, 1986, 1992; U.S. Department of Agriculture Forest Service, 1990; U.S. Department of Interior National Park Service, 1992). A major goal of the regulations is to reestablish riparian plant communities, preferably through natural succession (State of Alaska, 1986, 1992; U.S. Department of Interior Bureau of Land Management, 1989b; U.S. Department of Interior National Park Service, 1992). However, this goal may not be met, because even the best-designed reclamation grading does not correct major, long-term changes in the riparian ecosystem caused by placer mining. Changes which are likely to affect many aspects of ecosystem function and plant community structure include (1) elevation of spoil above the level of the active floodplain and (2) soil loss.

Deposition of the spoil above the active floodplain elevates the surface above the hydrological conditions that created the original floodplain environment. Although old terrace and channel areas were above the active floodplain before mining, their plant communities and soils were initiated when these areas were close to the water table and subject to flooding and sediment deposition. Furthermore, the elevation is increased relative to premining conditions because the volume of the excavated gravel is approximately one-third greater than the original volume.

The second change, soil loss, includes not only topsoil loss but also loss of fines (soil-sized particles, <2 mm) and organic material which are washed from alluvial gravels during processing. Recent regulations have reduced topsoil loss on some new mines, but topsoil has been lost on preregulation placer mines which are being remined or have been abandoned. On these sites, most of the topsoil was washed down the stream or buried under spoil.

Therefore, on regraded sites above the active floodplain where topsoil and fines have been lost or reduced, the rate of natural succession may be slow, and the plant communities that develop may differ from those originally present on the site. It is important that land managers be able to predict the rate and pattern of succession on placer-mined sites. An understanding of how fast natural revegetation will occur and what plant communities can be expected is necessary for ecologically sound reclamation plans and bonding requirements.

Previous studies have emphasized natural plant succession on placer-mined areas where the spoil piles have not been regraded. The major studies have focused on areas mined with the floating dredge method, which produced piles of coarse spoil interspersed with ponds (Rutherford and Meyer, 1981; Holmes, 1982; Durst, 1984). A few smaller studies have also addressed conditions in areas mined with the more common bulldozer/washplant method (Singleton et al., 1978; Halloran, 1986).

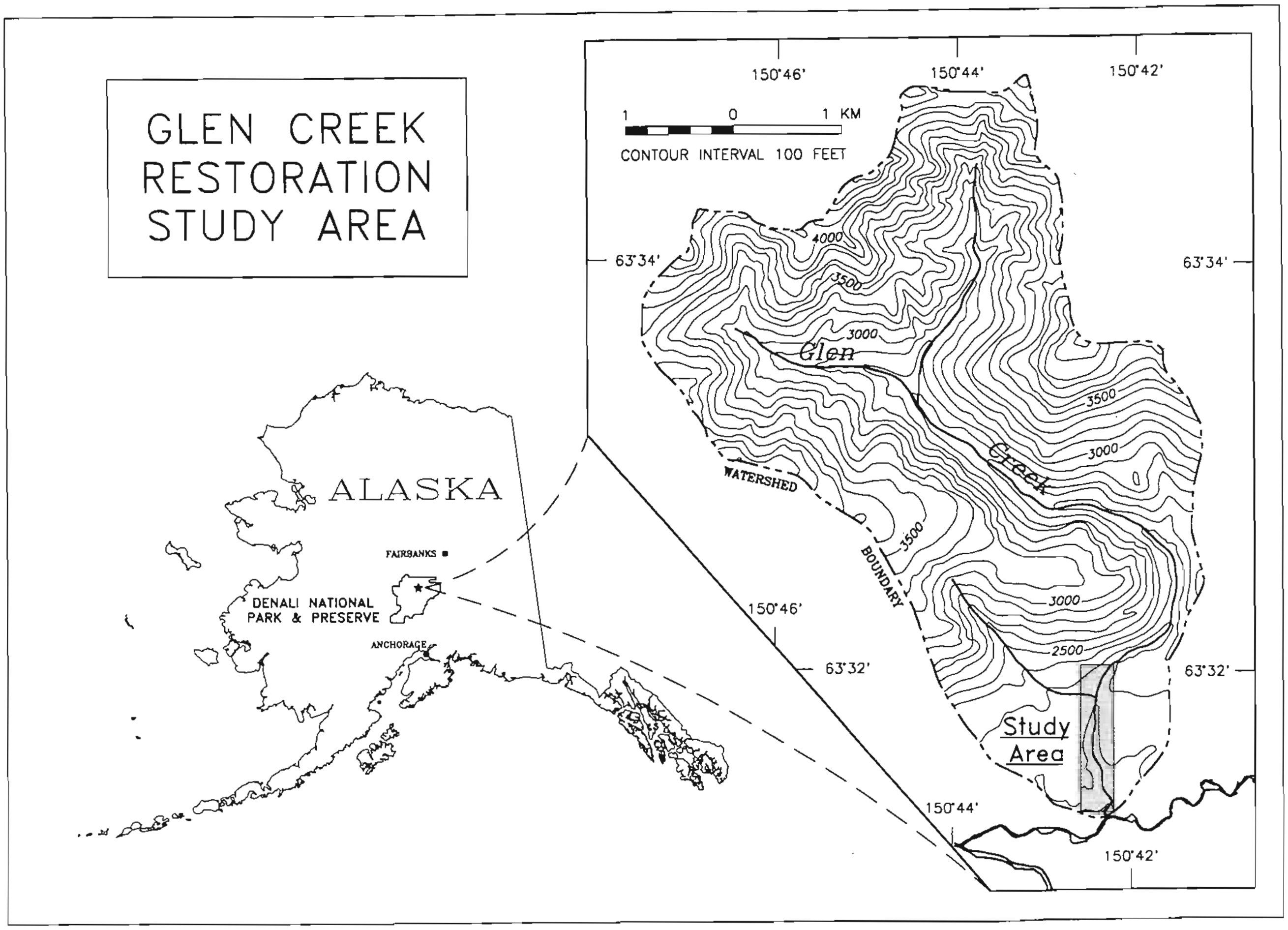

FIGURE 1. Map showing location of study area.

In general, these investigators found that the presence of topsoil ensured rapid succession dominated by riparian willows and herbs. Without topsoil, succession on spoil was dependent largely on (1) the proportion of subsand-size particles, and (2) substrate consolidation and stability. Slowest succession was on unconsolidated piles of processed spoil with few subsand-size particles, which remained largely barren even after 50 yr.

Current regulations requiring regrading are eliminating spoil piles on placer mined sites, but more information on natural plant succession on regraded spoil is needed. Furthermore, previous studies of the relationship between plant succession and substrate factors have been limited to qualitative observations, and quantitative measurements are lacking.

This study focuses on the establishment of native plant communities on placer-mine spoil that had been deposited above the active floodplain and regraded. The objectives of the study were (1) to evaluate the rate and pattern of natural succession on a variety of regraded spoil substrates, (2) to examine the relationship among the succession patterns and initial substrate characteristics, and (3) to evaluate the relative importance of nutrients and water as limiting factors.

Study Area

The Glen Creek watershed study area is located in the Kantishna mining area, a group of rugged hills within Denali National Park and Preserve (Fig. 1). The watershed is 16.7 km^2, with elevations ranging from 648 m at the mouth to 1372 m near Spruce Peak. The Glen Creek watershed is in the continental climatic zone of interior Alaska, but the continental pattern is modified by cooler summers and higher precipitation because of the maritime influence and a high elevation. July averages 12°C, while January averages −18°C. Precipitation averages 48 cm annually with 72% occurring from June through September.

The bedrock geology of the Glen Creek watershed is faulted and folded quartzite and hornblende schist of the Birch Creek formation. The study area on lower Glen Creek was covered in the middle Wisconsin with glacial ice from the Alaska Range, and gravel and rocks deposited by the glacier are mixed with bedrock material in the alluvial gravels.

The study area is at treeline, and trees are confined to favorable sites on alluvial terraces and south-facing slopes. Tall shrubs dominate riparian vegetation on the floodplain and younger terraces, and low shrubs and herbs form the tundra vegetation on colder, more exposed sites. The mining severely disturbed the vegetation on the study area, but the predisturbance vegetation can be inferred from remnants and adjacent less-disturbed watersheds. On these watersheds the floodplain is dominated by *Salix alaxensis* (feltleaf willow) (Viereck and Little, 1972) 3 to 4 m tall, mixed with varying amounts of *Alnus crispa* (American green alder) 1 to 2 m tall, and an understory that usually includes the low shrub *Potentilla fruticosa* (cinquefoil), the grass *Calamagrostis canadensis* (bluejoint reedgrass) (Hultén, 1968), and the forb *Epilobium latifolium* (dwarf fireweed). The floodplain is vegetated to the bankfull stream level; natural flood or ice events which remove vegetation and initiate riparian

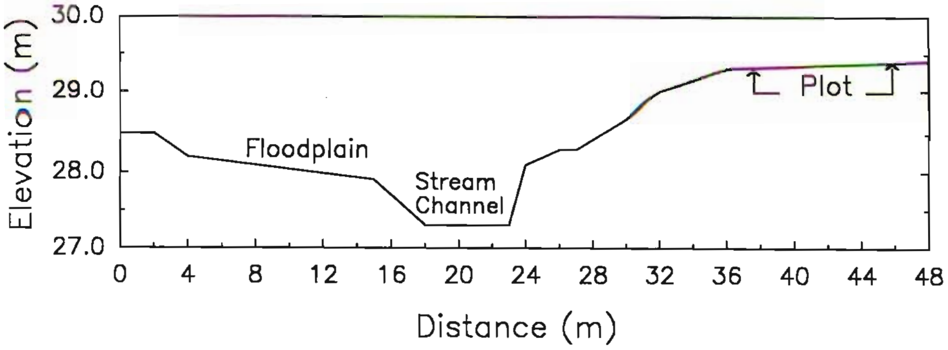

FIGURE 2. Typical cross section of the reclaimed Glen Creek valley showing the location of study plots on regraded spoil above the active floodplain.

succession are infrequent. Higher areas have *Populus balsamifera* (balsam poplar) and younger *Picea glauca* (white spruce), and old terraces have open stands of *P. glauca* with an understory of *Betula glandulosa* (dwarf birch) and *Salix planifolia* (diamondleaf willow).

This treeline plant community pattern is intermediate between the pattern of riparian succession in interior Alaska taiga (Viereck, 1970; Walker et al., 1986) and in northern tundra (Bliss and Cantlon, 1957; Moore, 1983). The general pattern of taiga succession is establishment of herbs and willows (primarily *Salix alaxensis*) as soon as the surface is sufficiently stable, development of a vigorous willow stand by 10 yr, followed by increasing importance of alder (*Alnus* sp.) and *Populus balsamifera* from 20 to 50 yr. Poplar dominates from 50 to 100 yr, after which the understory of *Picea glauca* gradually gains dominance. All of the tree and tall shrub species which dominate different successional stages may establish together early in succession; the slower-growing, long-lived species gradually replace the fast-growing, short-lived species (Walker et al., 1986). On tundra riparian areas, the willow/alder stage is followed by low willows and *Betula glandulosa,* with an eventual shift to herbaceous tundra.

The Glen Creek watershed was hand-mined from 1906 to 1941 (Hovis, 1991). The stream was diverted and dammed, and topsoil and fines were washed away, but the areal extent of disturbance was limited relative to later mining. In the 1970s, the study area on lower Glen Creek was extensively mined with the bulldozer/washplant method. In 1988, 9 to 15 yr after mining had ceased, the study area was dominated by unstable gravel and rock spoil piles 3 to 8 m tall. Spoil piles differed in particle size distribution, depending on whether the excavated alluvial material had been processed and on the type or stage of processing. The amount of natural revegetation also varied. Some piles were still unvegetated. On many piles natural revegetation was limited to scattered stunted *Salix alaxensis* and *Populus balsamifera* seedlings 8 to 9 yr old but only 5 to 20 cm tall, and few or no *Alnus crispa* seedlings. A few piles had scattered to complete cover of *A. crispa* 0.5 to 1 m tall interspersed with small *S. alaxensis.* Some small topsoil berms were present, but most of the topsoil was gone.

Reclamation of the study area began in August 1988, when the location and basic composition (topsoil, gravel, boulders, etc.) of spoil piles and excavations were mapped from aerial photographs and field observations, and recontouring of the area above the active floodplain was designed (Schramm, 1988). The recontouring redistributed spoil to reduce and stabilize slopes, covered spoil consisting of washed boulders and cobbles with finer spoil, and respread the available topsoil and fines. The stream channel and active floodplain were recontoured and stabilized in 1992, and the design and results of this part of the reclamation project are reported elsewhere (Karle and Densmore, 1994a, 1994b). A typical cross section of the recontoured area is shown in Figure 2.

Methods

EXPERIMENTAL DESIGN

Plant Succession

Twelve 0.01 ha (10 × 10 m) plots were established on the study site in June 1989, at the beginning of the first growing season after regrading of the area above the active floodplain. Each plot was located on a recontoured area which had been a spoil pile, and was as homogeneous as possible in elevation, aspect, slope, and substrate characteristics. The entire study site above the active floodplain (all recontoured spoil piles which were large enough for a homogeneous plot) was sampled. The position of the plots in relation to the active floodplain and the stream channel is shown in a typical cross section (Fig. 2). Substrate differences among plots were not preplanned treatments but reflected the variation in the distribution and type of spoil produced by the original placer mining operation on this site. For example, the site had only a few scattered piles of topsoil, so only a few plots could be established on respread topsoil. Plots were not located where spoil had been pushed over existing vegetation so that revegetation would not be affected by resprouting and growth from buried vegetation.

A transect was laid out diagonally across each plot, and foot traffic was confined to a designated area on one side of the transect to avoid disturbance to small seedlings and developing soil surface cryptogams.

Plant Succession with Nutrient Addition

Six plots were established in June 1990 to evaluate the effects of added nutrients on the number of species, vascular and nonvascular plant cover, and growth and density of *Salix alaxensis.* Each 5 × 5 m fertilizer plot was established downslope from one of the existing 10 × 10 m vegetation plots, and a 5 × 5 m subplot in the center of the 10 × 10 vegetation plot was used as the control for the fertilizer plot. All nutrient addition plots were located on relatively dry substrates without replaced topsoil.

Plots were fertilized with 14-14-14 NPK Osmocot at 350 kg ha^{-1}. Osmocot releases nutrients slowly from resin-coated beads over one or more growing seasons. Time-release fertilizer was used because previous work (Neiland et al., 1981) had shown that added nitrogen leached rapidly from very coarse substrates with little uptake by woody plants.

VEGETATION

Plant Succession

Vegetation was measured in August 1993, after five growing seasons. Cover was measured in 1-cm increments along the center 10 m of the transect in each plot. Vascular plant cover was measured by species, and ground cover was measured as rock, soil, cryptogamic crust, moss, or litter. To measure species composition, a plot 0.5 × 10 m was established adjacent to the transect on the side of the transect which had not been walked on. All vascular plant taxa present in this plot were recorded.

Woody plant density and growth were measured with two methods. The first method included all seedlings of any size in the measurements. For these measurements, the 0.5 × 10 m plot used to measure species composition was subdivided into twenty 0.25 × 0.25 m subplots. The height of the tallest *Salix alaxensis* seedling and the tallest *Populus balsamifera* seedling in each subplot was measured, and the density of all woody plant species was measured in eight randomly selected subplots. The second method measured woody plant density in a 50-m^2 subplot. For this method, only *S. alaxensis* and *P. balsamifera* seedlings which were >10 cm tall after 5 yr of growth were counted and the height of each measured. This criteria was chosen because seedlings which had not grown more than 10 cm in 5 yr were likely to remain stunted and not grow into vigorous, dominant plants.

Plant Succession with Nutrient Addition

Vascular plant cover was measured by species along a 5 m transect laid out diagonally across the plot, and ground cover was measured as rock, soil, moss, or litter. A subplot 0.5 × 5 m was established adjacent to the transect. All vascular plant taxa present in this plot were recorded. This plot was divided into ten 0.25 × 0.25 m subplots to measure woody plant growth. The density of all woody plant species and the height of the tallest *Salix alaxensis* seedling and the tallest *Populus balsamifera* seedling in each subplot was measured.

FACTORS AFFECTING VEGETATION RESPONSE

Substrate Characteristics

Soil from each plot was sampled in August 1989, during the first growing season following recontouring. Each textural sample was taken from a pit approximately 20 cm in depth and diameter. Three textural samples were taken from each plot and combined for particle size analysis. The proportions of sand, silt, and clay in the <2.0-mm fraction was determined by the Bouyoucos hygrometer method (Gee and Bauder, 1986). Each sample for all other parameters was taken from a pit 15 cm in depth and diameter. For each plot, nine samples were combined into one for analysis. The soil fraction (particle size < 2.0 mm) was analyzed for pH, organic matter, total nitrogen, and available phosphorus. Soil pH was measured with a pH meter in 1:1 soil/water paste. Organic matter content was estimated by loss of weight on ignition (for 7 h at 400°C) (Nelson and Sommers, 1982). Nitrogen content was determined by Kjeldahl analysis (Bremner and Mulvaney 1982). Available phosphorus was measured with Olsen's method (Olsen and Sommers, 1982).

Soil moisture was measured in each plot with installed thermocouples and a psychrometer, but many measurements were inaccurate because of numerous large rocks in the soil. Therefore, the data used in analyses were the relative field capacities, which were measured in July 1990. Samples were taken from pits approximately 15 cm in depth and diameter, and included all rocks. Pits were lined with plastic and filled with water to determine the volume of the excavated material. Each sample was watered, allowed to drain to field capacity, weighed, oven dried for 72 h, and reweighed. Field capacity was calculated as volume of water per unit volume of soil. Three samples were taken on the border of each plot (to avoid further soil disturbance), and the mean value was used in analysis.

Plant Moisture Stress

Xylem pressure potential was measured on feltleaf willow leaves using a PMS Model 600 portable pressure chamber. On 19 July 1990, leaves were measured from five 2-yr-old seedlings which were growing adjacent to the 10-m^2 plot with the lowest proportion of silt and clay and the lowest field capacity. This plot was approximately 2 m above the water table. For comparison, leaves were measured from five willow seedlings of the same age and size which were growing on a gravel bar on an unmined stream <10 cm above the water table. These comparison measurements were made only once because (1) seedlings were scarce on the mined site, (2) seedlings had only three or four leaves, and (3) measuring sites were over 1 h hiking time apart. Seedlings on the mined site were measured from 1400 to 1445 h at 28°C on the mined site and from 1600 to 1645 h at 26°C on the streamside gravel bar. Seedlings on both sites were growing in full sun on level ground.

To provide more measurements over a longer period of time, leaves were measured from planted 2-yr-old *Salix alaxensis* cuttings in the second year of growth and mature *Salix alaxensis* willows at intervals over a 44-h period 20–21 July 1990 at three sites. The three sites were (1) planted cuttings on the same mined plot where the seedlings were measured, (2) planted cuttings on regraded spoil with respread topsoil, and (3) mature, vigorous *S. alaxenis* plants growing adjacent to water. Leaves from three plants were sampled at each interval at each site, and air temperature was recorded at each measurement. Measurements were made during a period of sunny weather with above-normal temperatures. No rain had fallen for 1 wk.

DATA ANALYSIS

Data from the 10 × 10 m plots used in the analyses included the following vegetation variables: total vascular plant cover, moss cover, cryptogam cover, number of vascular plant taxa (species richness), *Salix alaxensis* and *Populus balsamifera* mean height and density for all seedlings and for seedlings >10 cm tall, and density of *Alnus crispa* and *Potentilla fruticosa*. Substrate variables used in the analyses included soil texture, pH, % organic material, total N, available P, and field capacity. Textural data from soil samples were broken down into two categories: total sample and fines. The total sample was divided into percentages of cobble, gravel, and fines equalling 100% of the total sample. The fines were further divided into percentages of sand, silt, and clay equalling 100% of the fines fraction of the soil sample. The Statistical Analysis System (SAS, 1988) was used for data analyses.

The data were first examined with scatterplots and a correlation matrix. Cluster analysis was then used to classify the plots into successional types on the basis of plant community characteristics. Variables used for clustering were cover of vascular plants, moss, and cryptogams; mean height of *Salix alaxensis* seedlings in 0.5-m^2 subplots, and density of *S. alaxensis* seedlings >10 tall in the 50-m^2 subplots. Data were standardized

TABLE 1

Correlation matrix of vegetation and substrate variables[a] *on regraded placer mine spoil, Denali National Park, Alaska*

	Vegetation						Substrate						
	1	2	3	4	5	6	1	2	3	4	5	6	7
Vegetation													
1. No. species	1.00												
Plant cover (%)													
2. Vascular	0.77	1.00											
3. Moss	0.87	0.83	1.00										
4. Cryptogamic crust	0.71	0.92	0.65	1.00									
Salix alaxensis													
5. Height (cm)	0.80	0.93	0.91	0.81	1.00								
6. Density[b]	0.72	0.92	0.73	0.97	0.89	1.00							
Substrate													
1. % sand[c]	−0.91	−0.81	−0.87	−0.70	−0.89	−0.75	1.00						
2. % silt	0.90	0.84	0.85	0.76	0.90	0.81	—	1.00					
3. % clay	0.76	—	0.75	—	0.68	—	—	—	1.00				
4. pH	−0.60	—	−0.62	—	—	—	—	—	−0.66	1.00			
5. % organic matter	0.74	0.95	0.81	0.79	0.91	0.82	−0.84	0.84	0.77	—	1.00		
6. Total N[d]	0.79	0.97	0.84	0.87	0.96	0.90	−0.89	0.90	0.79	—	0.96	1.00	
7. Field capacity[e]	0.73	0.98	0.76	0.96	0.90	0.96	−0.76	0.80	0.61	—	0.89	0.95	1.00

[a] The table includes only those substrate variables with one or more correlation values with vegetation variables significant to the level of $p < 0.05$. Dash indicates individual value not significant to the level of $p < 0.05$.

[b] Number of seedlings >10 cm tall per 0.005 ha.

[c] All substrate percentages are based on the fines (<2 mm) fraction of the soil sample.

[d] Values are g kg^{-1} of fines fraction of the soil sample.

[e] Values are ml water/cc soil.

to mean 0 and variance 1 and were examined for outliers which might skew the clusters. Plots were clustered using Ward's method. A three-cluster solution was obtained. This solution was tested by (1) testing for outliers in the data, as described above, and (2) by comparing the clusters obtained from Ward's method to clusters obtained from two alternative methods with different biases, complete linkage and average linkage. All three methods classified the same plot as an outlier. The first cluster had only one plot, the second three plots, and the third had seven plots. Clusters were identical for the Ward's and complete linkage methods, and the average linkage method classified 91% of the plots in the same clusters as the Ward's and average linkage methods.

For the two clusters with more than one plot, a MANOVA procedure was conducted on the original clustering variables to determine if the clusters were significantly different overall and by individual variable.

ANOVAs were used with substrate variables to evaluate and interpret cluster differences. Variables expressed as percentages were arcsine transformed to more closely conform to the assumptions of the model, but the transformations did not alter the results and the untransformed data was used instead.

Stepwise linear regression analyses was used to select the model which best described the relationships between substrate variables (% sand [relative to silt and clay], organic material, pH, total N, available P, field capacity) and density of *Salix alaxensis* seedlings taller than 10 cm and mean height of all *S. alaxensis* seedlings. The variable % sand was log transformed prior to analysis to meet the assumptions of the model. Residuals for equations were tested for heteroscedasticity.

Data from the nutrient addition plots were analyzed with a MANOVA procedure to determine if the treatments were significantly different overall and by individual variable.

For *Salix alaxensis* seedling plant moisture stress measurements, the mean and standard error of the three measurements taken for each site and sampling time was calculated, and for the repeated measurements the results were plotted and a curve was fitted to visually enhance the results.

Results

VEGETATION

The correlation matrix showed high correlations between some vegetation variables, between some substrate variables, and between vegetation and substrate variables (Table 1).

Plant Succession

Characteristics of the successional plant communities were examined by using hierarchical cluster analysis techniques to identify one outlier plot and three distinct types of plots. The two types with more than one plot were significantly differentiated ($p < 0.01$) by a MANOVA conducted on the original clustering variables (Table 2). The interpretation of these types was based on the mean values of the vegetation variables (Table 2). Interpretation was also based on more detailed information about these variables, specifically the vascular plant species contributing to species richness and cover (Table 3).

Some vegetation variables were similar among the types of plots. First, the woody plant species which dominate nearby unmined riparian areas were the most important colonizers. *Salix alaxensis,* the most important riparian species, colonized all of the plots at a relatively high density, and was a major contributor to cover (Table 2 and 3). *Populus balsamifera* and *Picea glauca,* the dominants of more stable riparian areas, were also present in most plots. The density of both *P. balsamifera* and *P. glauca*

TABLE 2

Vegetation characteristics on regraded placer mine spoil for the types of succession identified by cluster analysis

	Types of succession[a]				
	Rapid riparian	Slow riparian	Slow non-riparian	*F*	*p*
No. of species	21	17 ± 3	7 ± 1		
% plant cover					
Vascular	21.7	6.6 ± 3.3	0.5 ± 0.2	9.26	0.0160
Moss	4.8	3.0 ± 0.8	0.2 ± 0.2	27.26	0.0008
Cryptogamic crust	26.0	5.0 ± 1.2	1.1 ± 0.7	8.74	0.0183
Salix alaxensis					
All seedlings					
Seedlings/m²	22	17 ± 6	22 ± 6		
Height (cm)[b]	20.5	9.3 ± 2.4	1.7 ± 0.5	22.0	0.0016
Seedling ht >10 cm					
Seedlings/0.005 ha	188	62 ± 17		32.76	0.0004
Height (cm)[c]	54.0	31.3 ± 4.4	3 ± 1		
Populus balsamifera					
All seedlings					
Seedlings/m²	2	24 ± 16	5 ± 2		
Height (cm)[b]	8.0	9.6 ± 1.7	2.5 ± 0.5		
Seedling ht >10 cm					
Seedlings/0.005 ha	21	87 ± 43	2 ± 2		
Height (cm)[c]	24.9	25.7 ± 7.7	—		
Alnus crispa					
Seedlings/0.005 ha	32	14 ± 12	1 ± 1		
Potentilla fruticosa					
Seedlings/0.005 ha	18	3 ± 1	7 ± 6		
Wilks' Lambda for MANOVA				14.51	0.0113

[a] Values are mean ± SE. $n = 1$ for rapid riparian, $n = 3$ for slow riparian, and $n = 7$ for slow nonriparian. MANOVA compares clustering variables for two groups with $n > 1$. Dash = no data.

[b] Mean height of tallest seedling in 20 0.5-m² subplots.

[c] Mean height of all seedlings >10 cm tall in 50-m² subplot.

TABLE 3

Cover (mean ± SE) or presence (if cover <1%, = p) of plant species on regraded placer mine spoil for the types of succession identified by cluster analysis

	Rapid riparian ($n = 1$)	Slow riparian ($n = 3$)	Slow non-riparian ($n = 7$)
Woody plants[a]			
Alnus crispa	2.5	0.3 ± 0.3	p
Betula glandulosa			p
Dryas drummondii			p
D. integrifolia		p	p
D. octopetala		p	p
Picea glauca	p	p	p
Populus balsamifera	1.8	2.2 ± 1.8	0.3 ± 0.2
Potentilla fruticosa	p	0.1 ± 0.1	p
Salix alaxensis	8.3	1.0 ± 0.0	0.2 ± 0.1
S. reticulata			p
Salix sp.[b]	p	p	p
Shepherdia canadensis	0.1	p	p
Spiraea beauverdiana	p		
Total cover	12.7	3.6	0.5
Graminoids[c]			
Agropyron macrourum		p	
Agrostis scabra	0.1	p	p
Calamagrostis canadensis	7.5	0.9 ± 0.4	p
Carex sp.	0.3	p	
Festuca rubra	p	0.2 ± 0.2	
Festuca brachyphylla	0.5		p
Luzula multiflora		p	p
Poa arctica	0.2	0.1 ± 0.1	p
P. alpigena		p	
Trisetum spicatum		p	
Total cover	8.6	1.2	0.0
Forbs[c]			
Aster siberica		0.2 ± 0.2	
Artemisia tilesii		p	
Epilobium angustifolium	p	p	
E. latifolium	p	1.3 ± 0.6	p
Equisetum arvense	0.4		p
E. variegatum	p	0.4 ± 0.3	p
Hedysarum alpinum		p	
Minuartia stricta	p		
Oxytropis campestris		p	
Parnassia palustris	p	p	p
Wilhelmsia physodes		p	
Total cover	0.4	1.8	0.0

[a] Cover measured along 10 m line transect, presence measured in 50 m² subplot.

[b] Includes seedlings of the low-growing willows *Salix hastata, S. glauca, S. brachycarpa, S. lanata,* and *S. planifolia,* which could not be consistently identified.

[c] Cover measured along 10 m line transect, presence measured in 5 m² subplot.

was so strongly influenced by distance from a seed source (unlike *S. alaxensis,* for which distance to seed source was fairly uniform), that the relationship to substrate factors was obscured and was not analyzed in detail. The cryptogamic crust throughout the study area was dominated by two nitrogen fixers, the cyanobacteria *Microcoleus vaginatus* and the soil lichen *Collema tenax* (Belnap, pers. comm., 1993).

The first type included only one plot, which had high vascular plant and cryptogamic crust cover, and a high density of rapidly-growing *Salix alaxensis* seedlings. This successional type will be referred to as "rapid riparian" (Table 2 and 3). Seedlings of *Alnus crispa* and *Potentilla fruticosa* were common. Herb cover was dominated by vigorous *Calamagrostis canadensis* grass. Vegetation on the plot classified as an outlier by cluster analysis was very similar to this plot type, but the density of vigorous *S. alaxensis* seedlings was much higher (Table 2 and 3). This plot differed differed primarily because it was actually in the active floodplain of a tributary of Glen Creek, and it was removed from further analysis.

The second type had similar species richness, but lower vascular and nonvascular plant cover, and moderately slow growth of *Salix alaxensis* seedlings. This successional type will be referred to as "slow riparian" (Table 2 and 3). Seedlings of *Alnus crispa* and *Potentilla fruticosa* were common, as in the rapid successional type. Herb cover was dominated by *Epilobium latifolium,* a common riparian colonizer, and *Calamagrostis*

TABLE 4

Effects of nutrient addition with NPK time-release fertilizer on successional vegetation on regraded placer-mine spoil

	Unfertilized[a]	Fertilized	*F*	*p*
No. of species	9.2 ± 1.2	11.7 ± 1.5	1.02	0.3368
% plant cover				
Vascular	2.3 ± 1.2	7.4 ± 1.6	6.67	0.0273
Nonvascular	0.9 ± 0.6	13.6 ± 1.4	10.33	0.0093
Salix alaxensis				
Height (cm)	3.2 ± 0.5	7.8 ± 1.4	9.50	0.0116
Seedlings/m^2	12.7 ± 3.5	24.7 ± 8.7	1.64	0.2291
Wilks' Lambda for MANOVA			6.09	0.0240

[a] Values are mean ± SE. $n = 6$.

TABLE 5

Profile of substrate characteristics on regraded placer mine spoil for the types of succession identified by cluster analysis

	Types of succession[a]				
	Rapid riparian	Slow riparian mean, SE	Slow non-riparian mean, SE	*F*	*p*
Soil composition					
% cobble	20	27 ± 18	10 ± 3	2.23	0.1737
% gravel	50	54 ± 14	65 ± 2	1.34	0.2706
% fines	31	19 ± 4	24 ± 2	1.68	0.2307
Fines composition					
% sand	70	75 ± 1	81 ± 1	12.2	0.0082
% silt	23	19 ± 1	15 ± 1	12.3	0.0079
% clay	7	6 ± 1	5 ± 0	5.1	0.0542
pH	7.2	7.4 ± 0.3	7.7 ± 0.6	2.94	0.1249
% organic matter	3.2	1.7 ± 0.1	1.4 ± 0.1	2.05	0.1899
Total N (g kg^{-1})	0.8	0.3 ± 0.1	0.2 ± 0.0	8.93	0.0174
Available P, ppm	2.0	2.3 ± 0.3	1.4 ± 0.2	5.78	0.0430
Field capacity[b]	0.42	0.23 ± 0.0	0.20 ± 0.01	9.83	0.0139

[a] Values are mean ± SE. For n, see Table 2. ANOVA compares clustering variables for two groups with $n > 1$.

[b] Values are ml water/cc soil.

canadensis, which was not vigorous and showed signs of nutrient stress.

The third type of plots had only a few species, and very little vascular plant, moss, or cryptogamic crust cover. This successional type will be referred to as "slow nonriparian" (Table 2 and 3). *Salix alaxensis* seedlings were as numerous as on other types, but virtually all seedlings were stunted, growing at a rate of <10 cm in 5 yr, and the few seedlings that were taller than 10 cm were still growing very slowly. Seedlings of *Alnus crispa* and *Potentilla fruticosa* were rare, and were not found in all plots. Scattered herbs were present, but were too small and sparse to be measured as cover.

Plant Succession with Added Nutrients

Addition of time-release NPK fertilizer significantly increased vascular and nonvascular plant cover, and the growth rate of *Salix alaxensis* seedlings relative to controls (Table 4).

FACTORS AFFECTING VEGETATION RESPONSE

Substrate Characteristics

The substrate variables, which were not used as clustering criteria, were used to compare the substrate characteristics of the different successional types (Table 5). Several substrate variables were similar among all plots. The percentage of gravel and cobbles was high in all the types of plots (Table 5). The textural classification of the soil-size fraction (fines, <2 mm) varied only from loamy sand to sandy loam, and the pH was consistently high. Levels of available P were low in all plots.

Successional type profiles were based on the mean values of the substrate variables which differed among the types (Table 5). The rapid riparian succession type had relatively high levels of organic matter, total N, and field capacity. This type also had the least sand relative to silt and clay. The plots in this group had approximately 5 cm of topsoil spread over the top of and incorporated into the regraded spoil.

The slow riparian succession type was intermediate between the other two types, with less silt and clay relative to sand, and lower levels of organic matter, total N, and field capacity, than the first type. The plots in this type were located on material which either (1) had a small amount of topsoil incorporated into the spoil, or (2) had been excavated, but not processed.

The slow nonriparian successional type had significantly lower levels of silt relative to sand, organic matter, total N, available P, and field capacity than the slow riparian succession type. The substrate of this type was processed spoil, and the processing washed out some of the silt, clay, and organic matter.

The multiple regression models demonstrated a strong linear relationship between total soil nitrogen and (1) the growth rate of *Salix alaxensis* seedlings ($Y = -4.2 + 32.9X$, $r^2 = 0.89$, $p < 0.001$) and (2) the density of vigorous *S. alaxensis* seedlings ($Y = -52.5 + 302.4X$, $r^2 = 0.90$, $p < 0.001$) (Fig. 3). Since the procedure eliminated highly correlated variables that did not improve the model, the resulting model represented the variable or combination of variables which best predicted the dependent variable.

Plant Moisture Stress

Plant moisture stress did not differ between 2-yr-old *Salix alaxensis* willow seedlings growing on an unmined stream gravel bar <10 cm above the stream (mean ± SE = −18.4 ± 1.7 MPa) and seedlings of the same age growing on regraded spoil with very low field capacity (−17.3 ± 1.5 MPa). Plant moisture stress also did not differ over a 44-h period among 2-yr-old feltleaf cuttings planted on the same regraded spoil, feltleaf willow cuttings planted on regraded spoil with respread topsoil, and mature, vigorous feltleaf willow plants growing next to water (Fig. 4).

Discussion

The rate and pattern of natural succession on regraded spoil above the active floodplain varied substantially, from areas with relatively rapid restoration of vigorous riparian vegetation to areas which were essentially bare after 5 yr. These successional differences were closely associated with substrate characteristics. Interpretation of these results was assisted by hierarchical cluster analysis, which identified three types of plots differing in key characteristics of the successional plant communities and associated substrate characteristics (Tables 2 and 3).

On regraded spoil with added topsoil (rapid riparian suc-

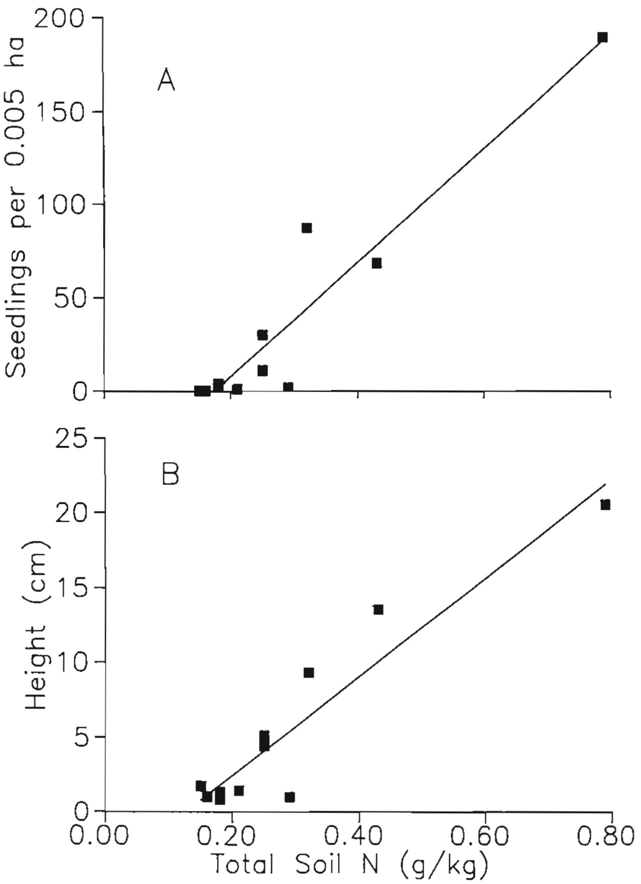

FIGURE 3. Regression equations relating (a) number of vigorous (>10 cm tall after 5 yr) Salix alaxensis *seedlings per 0.005 ha, and (b) mean height of tallest* S. alaxensis *seedling in 0.5 m^2 subplot* (n = *20 per plot), to total soil nitrogen.*

cession type), the rate and pattern of succession was similar to that observed on nearby unmined riparian areas (Densmore, unpublished data) and on other interior Alaska riparian areas (Viereck, 1970; Walker et al., 1986), even though the site was elevated above the active floodplain. The growth rate and vigor of *Salix alaxensis* were similar to that observed in vigorous *S. alaxensis* stands on nearby unmined riparian areas (Densmore, unpublished data). The understory included *Alnus crispa* and *Potentilla fruticosa,* both very common shrubs in riparian plant communities in the study area. Herbaceous cover was dominated by vigorous *Calamagrostis canadensis* grass, which is usually found in mesic sites with higher nutrient levels, and which is common in mature riparian *S. alaxensis* stands on higher areas with infrequent flooding.

These results suggest that natural succession will restore a vigorous mixed stand of *S. alaxensis* and *A. crispa* on these sites, and that absence of frequent flooding has led to accelerated development of the understory. These results agree with Singleton et al. (1978), Rutherford and Meyer (1981), and Durst (1984), who also found rapid recovery of riparian vegetation on piles of overburden.

On regraded spoil with a small amount of topsoil incorporated, and on unprocessed spoil (slow riparian succession type), the species composition was similar to the rapid riparian succession type, but plant growth was much slower and provided less cover. The growth rate of *Salix alaxensis* was at the low end of the growth rate observed on adjacent unmined areas, and was similar to the growth rate measured on tundra riparian sites in northern Alaska (Moore, 1982), but the seedlings were healthy. *Alnus crispa* seedlings were present and growing vigorously. This type had more *Populus balsamifera* seedlings than other types, but much of the variation was due to proximity to the seed source, and could not be attributed to substrate characteristics.

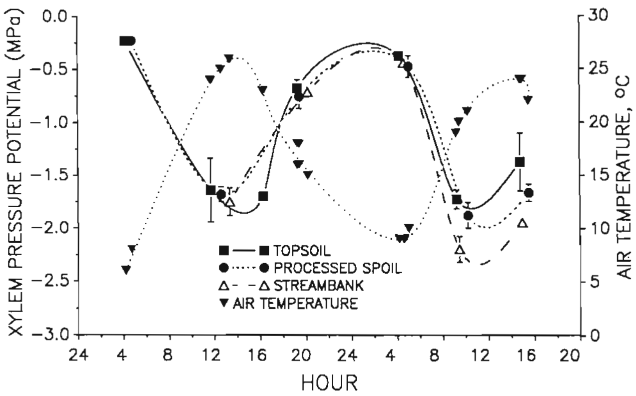

FIGURE 4. Plant moisture stress measurements (mean ± SE, n = *3, not all error bars are visible) on leaves of* Salix alaxensis *growing on regraded spoil with and without added topsoil, and on unmined streambank (control).*

These results suggest that the direction of succession on these sites is toward a slow-growing stand of *Salix alaxensis,* with varying amounts of *Populus balsamifera, Alnus crispa,* and *Potentilla fruticosa.* The *A. crispa* is likely to overtop the slow-growing *S. alaxensis,* and may dominate these stands. The results for both riparian succession types disagree with Cooper and Van Haveren (1994), who found that *S. alaxensis* seedlings died on test plots where 5 cm of topsoil had been respread over regraded spoil on Birch Creek in interior Alaska. Seedlings died because their roots were concentrated in the topsoil layer, which dried out rapidly. However, there were important differences in topsoil composition and application between this study and Cooper and Van Haveren's experiments. The topsoil used in the Birch Creek study contained 23 to 33% organic material and was not mixed into the underlying spoil, while the topsoil in this study was mostly mineral soil to begin with, and was mixed with the spoil to produce a substrate that was only 3% organic material (Table 5).

On the processed spoil (slow nonriparian succession), the plant community was limited to stunted seedlings of a few woody species and herbs. All plants were so small and scattered that they did not show up on cover measurements on several plots. *Salix alaxensis* seedlings were able to establish, but almost all 5-yr-old seedlings were less than 10 cm tall (Table 2), and are likely to remain stunted and fail to develop into a mature stand. *Alnus crispa* seedlings were sparse or absent altogether, although the few seedlings present were vigorous, indicating that substrate conditions limit establishment but not growth of this nitrogen-fixing species. Rutherford and Meyer (1981), Durst (1984), and Halloran (1986) also reported that alder did not establish on processed spoil with a low proportion of soil-sized particles.

If alder does not colonize these sites, they are likely to remain as stands of stunted riparian species which are gradually vegetated with lichens (particularly *Stereocaulon* sp.) and vascular plants characteristic of well-drained, rocky tundra (including *Dryas* sp. and *Shepherdia canadensis,* which have already established in some plots). This type of plant community is found on similar old (>40 yr) disturbances around the area, and resembles the successional plant community described by Viereck (1957) on outwash terraces of the nearby Muldrow Glacier (approximately 25 km south). Similar plant communities have been documented on old dredge spoil with a low percentage of fines (Holmes, 1982; Durst, 1984).

Several substrate characteristics, including the proportion of sand relative to silt and clay, the amount of organic material, total nitrogen, and field capacity differed among the three types of plots (Table 5). With the exception of available phosphorus, these substrate characteristics were highly correlated (Table 1), as would be expected from their interrelated roles in the ecosystem. Soil texture is important as soils with more silt and clay retain more nutrients and water, while soil organic material is highly correlated with total soil nitrogen and also increases field capacity. Water availability, in turn, influences nitrogen uptake.

These interrelationships made it difficult to identify and quantify the effects of individual factors. Nevertheless, some factors were better predictors of succession than others. The multiple regression models indicated that total soil nitrogen was the best predictor for the number of vigorous *Salix alaxensis* plants on a site and for the overall growth rate of *S. alaxensis* (Fig. 3). Available phosphorus was undoubtably also important, but was less useful as a predictor of succession, probably because levels were low throughout the site, and the range of variation among types of succession was small. The results of nutrient addition and of the plant moisture stress measurements also indicated that nutrients, particularly nitrogen, were more limiting than water to the development of vigorous vegetation on this site (Table 4 and Fig. 4). Time-release fertilizer stimulated vigorous growth of woody, herbaceous, and nonvascular plants on even the driest plots. Low nitrogen levels have been recognized as a primary substrate factor limiting plant community development on many severely disturbed sites (Bradshaw, 1987).

In contrast, plant moisture stress for *Salix alaxensis* was similar on wet streamside sites and elevated sites with low field capacity, in spite of the fact that plant moisture stress was measured under the highest air temperatures and lowest soil moisture conditions of the 1990 growing season (Fig. 4). These measurements were supported by observations in small pits, which were dug adjacent to the driest plots during most of the dry periods throughout the 5-yr evaluation period. In all cases, the soil was visibly moist below the top few centimeters of soil.

However, Cooper and Van Haveren (1994) found that water availability limited establishment of *Salix alaxensis* on regraded placer mine spoil on Birch Creek in interior Alaska. In tests of revegetation methods for *S. alaxensis* on this site, density of *S. alaxensis* was 2 seedlings/m^2 on unwatered plots and 28 seedlings/m^2 on artificially watered plots after 2 yr. Seedling density on unwatered plots was lower than on any substrate type at Glen Creek, even though the Birch Creek study site was unprocessed spoil, similar in soil texture to the substrates at Glen Creek which had the highest nitrogen and field capacity levels. The reason for the difference is that the Birch Creek site receives approximately one-half as much annual precipitation as the Glen Creek site.

In summary, a riparian plant community with vigorous *Salix alaxensis* developed rapidly (within 5 yr) on regraded spoil with respread topsoil, while a similar plant community with less vigorous *S. alaxensis* developed more slowly on unprocessed spoil and spoil amended with a small amount of topsoil. Processed spoil, on the other hand, remained almost bare of vegetation after 5 yr. *Salix alaxensis* was able to establish, but growth was stunted, while *Alnus crispa* had difficulty establishing, but the few established seedlings grew well. Several correlated substrate variables, including the proportion of silt and clay vs. sand, total nitrogen, and field capacity, were good predictors of the rate and pattern of succession on regraded placer mine spoil. Soil nitrogen levels were the best single predictor for the number of vigorous *S. alaxensis*. However, on other subarctic sites with less rainfall, lack of moisture may inhibit establishment of *S. alaxensis* even where substrate conditions would permit growth.

Acknowledgments

This work was supported by funding and logistical support from the National Park Service, Alaska Regional Office, Minerals Management Branch, with special assistance from A. R. Carter and P. Spencer. D. Schramm designed and directed the spoil regrading. J. Van Horn, M. Pope, M. Emers, M. and A. Vander Meer, J. Forbes, and T. Ledwidth provided field assistance, and K. Karle prepared the figures. Special thanks go to D. Cooper, J. Fox, and S. Wesser for critical review.

References Cited

Belnap, J., 1993: Personal communication. National Park Service, Southeast Utah Group, Moab, Utah 84532-2995.

Bliss, L. C. and Cantlon, J. E., 1957: Succession on river alluvium in northern Alaska. *American Midland Naturalist,* 58: 452–469.

Bradshaw, A. D., 1987: The reclamation of derelict land and the ecology of ecosystems. *In* Jordan, W. R., Gilpin, M. E., and Aber, J. D., (eds.), *Restoration Ecology, a Synthetic Approach to Ecological Research.* Cambridge: Cambridge University Press, 53–83.

Bremner, J. M. and Mulvaney, C. S., 1982: Nitrogen-total. *In* Page, A. L., Miller, R. H., and Keeney, D. R., (eds.), *Methods of Soil Analysis. Part 2. Chemical and Microbial Properties.* Agronomy Monograph 9. Madison, Wisc.: Agronomy Society of America, 595–624.

Cooper, D. J. and Van Haveren, B. P., 1994: Establishing feltleaf willow from seed: an approach for restoring interior Alaska floodplains. *Arctic and Alpine Research,* 26: 42–45.

Durst, J. D., 1984: Small mammals in relation to natural revegetation of gold dredge tailings at Nyac, Alaska. M.S. thesis, University of Alaska, Fairbanks. 105 pp.

Gee, G. W. and Bauder, J. W., 1986: Particle size analysis. *In* Klute, A. (ed.), *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods.* Agronomy Monograph 9. Madison, Wisc.: Agronomy Society of America, 383–412.

Halloran, J. E., 1986: *A study of the natural revegetation of placer tailings.* Report, U. S. Department of Interior, Bureau of Land Management, Alaska State Office, Anchorage, Alaska.

Holmes, K. W., 1982: Natural revegetation of gold dredge tailings at Fox, Alaska. M.S. thesis, University of Alaska, Fairbanks. 197 pp.

Hovis, L. W., 1991: *Historic sites, cultural isolates, and other concerns, Upper Glen Creek, Denali National Park and Preserve.* Unpubl. preliminary report. Available at National Park Service Alaska Regional Office, Anchorage, Alaska. 12 pp.

Hultén, E., 1968: *Flora of Alaska and Neighboring Territories.* Stanford, Calif.: Stanford University Press. 1008 pp.

Karle, K. F. and Densmore, R. V., 1994a: Stream and floodplain restoration in Glen Creek, Denali National Park and Preserve. Technical Report NPS/NRWRD/NRTR-94/17, U.S. Department of Interior National Park Service. 33 pp.

Karle, K. F. and Densmore, R. V., 1994b: Stream and floodplain restoration in a riparian ecosystem disturbed by placer mining. *Ecological Engineering,* 3: 121–133.

Moore, N. J., 1982: Pioneer *Salix alaxensis* communities along the Sagavanirktok River and adjacent drainages. M.S. thesis, University of Alaska, Fairbanks. 189 pp.

Neiland, B. J., Zasada, J. C., Densmore, R., Masters, M. A., and Moore, N., 1981: *Investigations of techniques for large-scale reintroduction of willows in arctic Alaska.* Technical research report, University of Alaska-Fairbanks Agricultural and Forestry Experiment Station. 448 pp.

Nelson, D. W. and Sommers, L. E., 1982: Total carbon, organic carbon, and organic matter. *In* Page, A. L., Miller, R. H., and Keeney, D. R., (eds.), *Methods of Soil Analysis. Part 2. Chemical and Microbial Properties.* Agronomy Monograph 9. Madison, Wisc.: Agronomy Society of America, 539–552.

Olson, S. R. and L. E. Sommers, 1982. Phosphorus. *In* Page, A. L., Miller, R. H., and Keeney, D. R., (eds.), *Methods of Soil Analysis. Part 2. Chemical and Microbial Properties.* Agronomy Monograph 9. Madison, Wisc.: Agronomy Society of America, 403–430.

Rutherford, C. and Meyer, K., 1981: *Revegetation on gold dredge tailings, Nyac, Alaska.* U.S. Bureau of Land Management, Anchorage District Office. 51 pp.

SAS, 1988: *SAS/STAT User's Guide.* Cary, N.C.: SAS Institute, Inc., 1028 p.

Schramm, D., 1988: *Environmental assessment, Glen Creek reclamation project, Denali National Park and Preserve.* National Park Service Alaska Regional Office, Anchorage, Alaska. 59 pp. plus maps and photographs.

Singleton, G. A., Steen, O. A., Weagle, K., and Weir, D., 1978: *Fish and Wildlife Habitat Recovery in Placer Mined Areas of the Yukon.* Department of Indian Affairs and Northern Development, Serial no. OSU80-00045. 131 pp.

State of Alaska, Department of Fish and Game, 1986: *Best Management Practices for Placer Mining: Reference Manual.* Alaska Department of Fish and Game, Division of Habitat, Box 3-2000, Juneau, Alaska. 209 pp.

State of Alaska Department of Natural Resources Division of Mining, 1992: *Mining Reclamation Regulations.* 11 AAC Chap. 97.

U.S. Department of Agriculture Forest Service, 1990: *Code of Federal Regulations.* 36 CFR Ch. II 228 (7-1-90 Edition), Minerals.

U.S. Department of Interior Bureau of Land Management, 1985: *Surface Management Regulations for Mining Claims under the General Mining Laws.* Code of Federal Regulations, 43 CFR Ch. II 3809.

U.S. Department of Interior Bureau of Land Management, 1989a: *Placer Mining in Alaska: A Guide to Mitigation and Reclamation.* Document BLM-AK-GI-89-021-3809-918, Bureau of Land Management, Alaska State Office, Anchorage, Alaska. 50 pp.

U.S. Department of Interior Bureau of Land Management, 1989b: *Birch Creek Placer Mining: Record of Decision.* Document BLM-AK-ES-89-015-3809-918, Bureau of Land Management, Alaska State Office, Anchorage, Alaska.

U.S. Department of Interior National Park Service, 1992: *Reclamation Requirements.* Code of Federal Regulations, 36 CFR Ch. I 9.11 (7-1-92 Edition).

Viereck, L. A., 1957: Plant succession and soil development on gravel outwash of the Muldrow Glacier, Alaska. *Ecological Monographs,* 36: 181–199.

Viereck, L. A., 1970: Forest succession and soil development adjacent to the Chena River in interior Alaska. *Arctic and Alpine Research,* 2:1–26.

Viereck, L. A. and Little, E. L., 1972: *Alaska Trees and Shrubs.* U. S. Department of Agriculture, Forest Service. Agricultural handbook No. 410. 265 pp.

Walker, L. R., Zasada, J. C., and Chapin, F. S., 1986: The role of life history processes in primary succession on an Alaskan floodplain. *Ecology,* 67: 1243–1253.

Ms submitted November 1993