Red Dog Mine
Closure and Reclamation Plan

SD F3: Revegetation Plan for the Red Dog Mine (ABR Inc., 2007)

REVEGETATION PLAN
FOR THE RED DOG MINE, ALASKA

Final Report

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INTRODUCTION

The Red Dog Mine is located in the DeLong Mountains, approximately 82 miles north of Kotzebue in northwest Alaska. The climate of the mine site is transitional, with a mean summer temperature of 49.9 °F and an average winter temperature of -2.3 °F (Western Regional Climate Center). The mine is located within the zone of continuous permafrost. Mean annual precipitation is low (18–21 in) and mostly occurs in summer and fall. The vegetation surrounding the mine site is predominantly open low willow (*Salix* spp.) and alder (*Alnus* spp.) scrub and mesic graminoid herbaceous communities composed of sedges such as tussock cottongrass (*Eriophorum vaginatum*) and bigelow sedge (*Carex bigelowii*). Scattered patches of shrub birch (*Betula* spp.) also are present as well communities dominated by evergreen shrubs, such as Labrador tea (*Ledum palustre*), four-angled cassiope (*Cassiope tetragona*), and white mountain-avens (*Dryas octopetala*) . In some areas, especially along stream drainages, vegetation is sparse due to exposed gravels.

A Reclamation Plan was prepared for the mine in 1983 (Cominco Engineering Services Ltd.), with revisions in 1986 (Cominco Alaska Incorporated 1986) and 1994 (Dames and Moore 1995). This Revegetation Plan is being prepared as part of a larger Closure and Reclamation Plan, which is required for a Solid Waste Management Permit, issued by the Alaska Department of Environmental Conservation (ADEC) in accordance with 18 AAC 60, solid waste regulations. The Revegetation Plan also is designed to satisfy the reclamation guidelines outlined in Article 9 of the NANA-Cominco Agreement. The specific objective of this Revegetation Plan is to develop revegetation strategies for the mine that achieve the goals of 1) establishing plant communities (where appropriate) that are self-sustaining; 2) assisting in protecting water quality by controlling erosion and preventing acid rock drainage (ARD); and 3) contributing to the proposed land use(s) of the mine after closure.

This Revegetation Plan should be considered an interim document. Changes in mine operations and construction activities may warrant revision of the plan in the future. In addition, the results of revegetation testing may indicate that some of the treatments outlined herein will need to be modified. Some terms in this document may not be familiar to all readers; thus, a glossary of terms is provided in Appendix A.

DATA REVIEW

EVALUATION OF COVER MATERIALS

OVERBURDEN STOCKPILE

Overburden and unmineralized or lightly mineralized rock have been stockpiled along the southern margin of the tailings pond (Figure 1). This material is primarily a mixture of calcareous shale (Kivalina Shale), limestone, some coarse material, and organic-rich topsoil. The shale weathers relatively rapidly to a soil-like texture, and is representative of other similar material that will be mined in large quantities from the future Aqqaluk pit. It is one candidate for use in covering of reclamation areas.

The primary concerns associated with using the material in this stockpile as cover are high salinity and leaching of some metals. Soil analyses in 1993 indicated that electrical conductivity (EC) was > 4 dS/m, a level that may inhibit the growth of some plant species. Most plants grow best in soils with EC < 2 dS/m. However, natural colonization has occurred on the stockpile (Table 1). It also appears that at least some of the shale in this stockpile is inter-mixed with more mineralized rock, which could be the source of salinity and metals. If upon further study, the material is found not to be a concern in terms of leaching of contaminants, this material may have potential for use as a cover material for supporting vegetation. Although nitrogen and phosphorous concentrations are low, the organic matter content and high percentage of fines will help retain soil moisture and promote biological activity, which is important for nutrient cycling to support plant growth.

SIKSIKPUK AND IKALUKROK SHALE

Revegetation test plots were set up on the Siksikpuk and Ikalukrok shale by the Alaska Plant Materials Center (PMC) in 1987 and 1988 (see below). Although the soil characteristics of the shale generally were poor for supporting plant growth (low nitrogen, phosphorus, potassium, and organic matter), no phytotoxic concentrations of metals were present (Cominco Alaska, Inc. 2000). The pH was slightly acidic (5.5–5.9), but soils in this range will not inhibit the growth of most plants. Siksikpuk shale is available from the Airport and DD2 material sites.

QUARRY MATERIAL

In the event that the tailings impoundment and main waste, oxide ore, marginal ore, and overburden stockpiles need to be capped to prevent ARD, several million yards of material will be needed to cover these sites. To address this potential need, two existing and two new quarry sites are being evaluated as potential sources of cover material. The existing quarries were developed within the Middle Siksikpuk Formation, which is composed of siliceous shale. The material is attractive as a cover because it will not require crushing after blasting and is not acid generating. It may be too coarse to support plant growth, however, unless it is amended with finer-grained material. A sufficient volume of material is available to cap the tailings impoundment and stockpiles.

The potential quarry sites are located at the head of Sulfur Creek, in the Kivalina formation, and east of the south end of the Main Waste pile, in the Okpikruak Formation (Figure 1). The Kivalina formation is composed of calcareous shale with acid neutralization material, although metal leaching may be of concern due to the presence of orange sphalerite. Similar to the existing quarries, it has been estimated that a sufficient volume of material is available to cap the tailings impoundment and stockpiles.

The Okpikruak material also is shale with traces of pyrite but contains no other metals. It is neutral in terms of acid generating/consuming potential. This shale weathers quickly to a fine texture, which should be beneficial for supporting vegetation. The volume of material available is unknown.

Units of Okpikruak and Kivalina shale have also been identified in the remaining Main Pit and the future Aqqaluk pit. Some of these units are large enough to be extracted “clean” and stockpiled to provide a source of cover material, without the need for additional quarrying.

UNCONSOLIDATED MATERIAL

Two types of unconsolidated material have been considered for use as cover material: talus from nearby hillsides and sand and gravels associated with floodplains. The feasibility of using the talus is dependent on appropriate slope angles (up to 35°) and proximity to the mine site.

Only the upper slopes of Deadlock Mountain have a sufficient volume of material and are located within 2 miles of the mine site.

The Ikalukrok and Robinson Creek drainages were identified as potential sources of sand and gravel. However, Ikalukrok Creek contains lead- and zinc-bearing detritus, which could raise a concern about the possibility of metal leaching. The alluvial deposits associated with Robinson Creek do not contain high concentrations of heavy metals, and thus are probably the closest source of uncontaminated sand and gravel. This creek is located 5 miles east of the mine. The main limitation of this material is the alluvium is coarse gravel, with little organic matter, making it a poor substrate for supporting plant growth.

REVEGETATION EFFORTS

VARIETAL TEST PLOTS

In 1987, the PMC established a series of test plots to evaluate the germination and growth of a variety of forbs and grasses at the mine site (Wright 1990). The study was conducted as part of PMC's North Latitude Revegetation and Seed Project, which researches and identifies new plant varieties for use in erosion control and mine land rehabilitation. The test plots were designed to 1) identify those species and varieties that would perform best in future Red Dog Mine revegetation efforts, and 2) assess the effectiveness of dormant seeding in the Arctic. The following is a summary of the revegetation studies; the details of the studies can be found in the report entitled *1990 Final Report of Data and Observations Obtained from the Red Dog Mine Evaluation and Demonstration Plots* (Wright 1990).

Two test plots were established at the mine site: one in tundra that had been scraped down to bare soil, and the other in highly compacted gravel fill. Seed from up to 49 plant species or varieties was planted in treatment blocks within each of the plots at a rate of 40 lb/acre and 20-20-10 (N-P-K) fertilizer was applied to the plots at 450 lb/acre. The species were either native-grass cultivars or agronomic varieties that have been used for revegetation in the lower forty-eight states and are also being tested elsewhere in Alaska. Plant performance was evaluated by assessing plant vigor (on a scale of 1–9) and percent cover.

Between the two plots, 12–20 species were still present after three growing seasons. The best performers in terms of cover and vigor included tundra bluegrass (*Poa glauca*), ‘sourdough’ bluejoint (*Calamagrostis canadensis*), ‘Egan’ American sloughgrass (*Beckmannia syzigachne*), and ‘Alyeska’ polargrass (*Arctagrostis latifolia*). Other varieties that had somewhat lower ratings in terms of vigor, but still had high percentages of cover (60–80%) included tufted and ‘Nortran’ tufted hairgrass (*Deschampsia caespitosa*), ‘Norcoast’ Bering hairgrass (*D. beringensis*), ‘Gruening’ alpine bluegrass (*Poa alpina*), and rough fescue (*Festuca* sp.). Additional species that performed well included ‘Arctared’ and ‘Boreal’ creeping red fescue (*Festuca rubra*), several varieties of wheatgrass (*Agropyron* sp.), big bluegrass (*Poa ampla*), and the forb, tilesy sage (*Artemisia tilesii*). The plots were assessed again in 1992 and 1993 and continued to support high percentages of plant cover.

New plots were set up at three locations by PMC in 2004 to test some of the species included in the original 1987 test plots, as well as additional native species (total of up to 62 species per plot). The sites were selected to test germination and growth in soils developed on rock types considered for reclamation use. Initial results show that the species with the highest cover and vigor were mostly grasses, although a few forbs, such as tall Jacob’s ladder (*Polemonium acutiflorum*) and false mayweed (*Tripleurospermum maritima*) also showed potential. Kivalina Formation and Okpikruak Formation soils supported better growth than the Siksikpuk soils. A greenhouse study was subsequently initiated in March 2006 to further investigate a subset of the species in the field trials (PMC, in preparation).

DEMONSTRATION PLOTS AND RIPARIAN REVEGETATION

In addition to the test plots, the PMC also set up a demonstration plot at the mine site’s solid waste disposal site north of the port (1988) and assisted in the revegetation of several stream crossings (1989). These studies were designed to demonstrate practical methods of revegetation using native-grass cultivars and forbs. With the exception of *D. beringensis,* the seed stocks came from collections along the Dalton Highway and Sagwon Bluffs in northern Alaska, but were cultivated in southcentral and interior Alaska to increase seed production. The *D. beringensis* is a coastal species that was collected in southwestern Alaska. It is closely related to *D. caespitosa,* which occurs in mesic environments in the Arctic. The other native species were collected in western, southcentral, and interior Alaska for commercial production. The seeding and fertilizing specifications were the same as those described for the test plots above. An area of tundra adjacent to the pit that was disturbed by vehicle tracks also was fertilized (200 lb/acre) and seeded (20 lb/acre); the rates were reduced because the disturbance was relatively minor. In addition to the seed, sprigs of beach wildrye (*Elymus arenarius*) were transplanted on a portion of the waste disposal area that has reconnected with a dune adjacent to the pit. This area also was seeded with a mixture of 'Norcoast' Bering hairgrass and 'Arctared' fescue. Fertilizer (20-20-10) was applied at 600 lb/acre. A mixture of native-grass cultivars and tilesy sage was also planted at each of the six river crossings at 40 lb/acre. Fertilizer (20-20-10) was applied at 450 lb/acre.

Results for the demonstration plots at the waste disposal site after three growing seasons showed a high percentage (95%) of plant cover, with all species planted performing well. A powerful storm surge destroyed the stand of transplanted beach wildrye sprigs, as well the entire natural dune formation. The preliminary results of the transplant effort were favorable, however, suggesting this treatment may be appropriate for other areas in the future; although the species naturally occurs only in coastal areas. Successful transplanting of beach wildrye also has been demonstrated in the Alpine Oilfield, in the Colville River Delta on the Arctic Coastal Plain (Bishop et al., in preparation). The seeding of the six river crossings also was successful, with all sites well vegetated after two growing seasons.

OVERBURDEN STOCKPILE

Over a period of several years (1997–2001), portions of the Overburden Stockpile at the south end of the tailings pond were fertilized and seeded with native-grass cultivars, following recommendations outlined by the PMC. The success of the revegetation effort was evaluated in July 2004 (Table 1). Vegetation cover was relatively high, although this may be due to multiple seeding efforts. Total live vascular plant cover was 50% and was dominated by the native-grass cultivar Arctared fescue (36%). The most abundant natural colonizer was the forb Bering chickweed (*Cerastium beeringianum*). A natural colonizing area on the stockpile had considerably less total live vascular cover (6%) (Table 1), but included a higher number of species than the seeded areas.

OTHER MINE DISTURBANCES

A number of mine disturbances have been fertilized and seeded over the past several years to reduce the potential for erosion of these areas (Figure 1). Three of these areas were monitored for vegetation cover in July 2004 an area next to the road just south of the overburden stockpile; an area adjacent to the tailings impoundment, and small area on the west side of the road near the airport (Table 1). Total live vascular cover in the area south of the overburden stockpile had a percentage of cover (42%) comparable to that measured on the stockpile, but cover was only 24% adjacent to the impoundment. Vegetation response may have been poor due to acidity coming from upslope runoff, although no soil chemistry data was available to confirm this. Total live vascular cover was lower at the site near the airport (22%), but included a high number of natural colonizers. The results for this site are important because it was only fertilized and seeded once (in 1997), whereas the other seeded sites had been fertilized at least twice. The results from the airport site suggest that vegetation cover can persist several years after treatment (in this case, 7 years).

NATURAL RECOVERY

The natural vegetation recovery that has occurred at mine disturbances was assessed in 1993, as part of an overall analysis of the revegetation potential of the Red Dog Mine (Dames and Moore 1995). This study provided important information on the rate of natural recovery that can be expected at the mine, and identified species that may have potential for use in revegetation efforts in the future. Five areas were surveyed for the presence of natural colonizers: 1) the overburden stockpile at the tailings pond, 2) Material Site 7, 3) a material site at Buddy Creek, 4) several access roads to material sites along the haul road that were abandoned in 1988, and 5) the area surrounding the revegetation test plots established by the PMC that are described above.

On the overburden stockpile, total live plant cover was 10–25%, and consisted primarily of tall fireweed (*Epilobium latifolium*) and bluejoint (*Calamagrostis canadensis*), with smaller amounts of Jacob's ladder (*Polemonium boreale*), short-stalk sedge (*Carex podocarpa*), and groundsel (*Senecio lugens*). A description of the soil characteristics was presented above.

At Material Site 7, cover was 10–20% and consisted of tall fireweed, bluejoint, and scattered willows. Cover was mostly restricted to the margins of the site, as a result of recent vehicle traffic elsewhere. The soil was composed of predominantly coarse, angular rocks.

Vegetation at the Buddy Creek material site was confined to a bench that experienced limited traffic disturbance. In this area, cover was 15–20% and consisted of fireweed, mustard (*Draba hirta*), chickweed (*Stellaria longpipes*), wormwood (*Artemisia campestris*), and willows. The soil consisted of coarse fill with some angular rocks.

The cover of natural colonizers varied widely among the abandoned roads surveyed, ranging from 5 to 30%. Species included tall mustard (*Lesquerella* sp.), milk vetch (*Astragalus* spp.), willows, arctic bluegrass (*Poa arctica*), bluejoint, and tall fireweed. Colonizing species adapted to mesic and wet sites, such as sedges, rushes (*Juncus* spp.), tall cottongrass (*Eriophorum angustifolium*), and field horsetail (*Equisetum arvense*) were found in swales present in some areas. The soils were gravelly with some weathered shale material. Plant cover was lowest in areas where the soil was highly compacted.

Native species that have colonized the area surrounding PMC's revegetation test plots include shrub birch (*Betula glandulosa*), anemone (*Anemone drummondii*), blueberry (*Vaccinium uliginosum*), spike trisetum (*Trisetum spicatum*), and tufted hairgrass (*Deschampsia caespitosa*). No natural colonizers were noted inside the test plots, but they likely were limited because of the dense grass cover.

Additional colonizing species identified during the July 2004 site visit included feltleaf willow (*Salix alaxensis*), Altai fescue (*Festuca altaica*), bluegrass (*Poa* spp.), arctic wormwood (*Artemisia arctica*), *Oxytropis borealis* (boreal locoweed), and river beauty (*Epilobium latifolium*) (Table 1).

SITE COMPONENTS FOR REVEGETATION

The following areas are currently being considered for revegetation:

- Waste piles (Main Waste, Oxide, Low Grade Ore, Main Pit)
- Overburden stockpile
- Material sites and borrow areas

- Water diversion systems
- Camp pads and roads (including mill site)
- Tundra disturbances

The feasibility of revegetation for each unit will depend on the suitability of the physical growing environment; the likelihood of successful revegetation without long-term maintenance; cost; the need to satisfy other mine reclamation goals (e.g., protecting water quality); and post-mining land use(s).

WASTE PILES

The Main Waste stockpile is located above and to the east of the tailings pond. The Oxide Ore stockpile is located along the ridgeline immediately above the Main Waste stockpile. The Main Pit stockpile does not exist yet, but will eventually fill the Main Pit.

Together the Main Waste, Oxide Ore and Main Pit stockpiles contain or will contain almost all of the mineralized waste rock generated by mining. The geological composition and geochemical properties of the waste rock are discussed in detail elsewhere. In brief, the material is dominated by components that oxidize to release metals, salinity and acidity, and is essentially completely unsuitable as a basis for revegetation. The Closure and Reclamation Plan therefore calls for all of this material to be covered prior to revegetation.

The Main Waste, Oxide and Main pit stockpiles will also be re-graded prior to cover construction. It may be possible to arrange some of the re-grading to enhance soil moisture retention, as low soil moisture is one of the main limitations to plant growth (Daubenmire 1947).

Portions of the Overburden stockpile are a potential source of cover material. Preliminary results from revegetation testing of this material suggest that the physical and chemical characteristics of the soil are suitable for supporting plant growth. The main potential limitations of this material are moderate salinity and elevated metal concentrations, which were detected in water samples taken immediately downstream from the stockpile. The moderate salinity may inhibit the plant growth of some species and high metal concentrations could lead to a requirement that all surface runoff be collected for water treatment.

The Low Grade Ore Stockpile is located at the north end of the Main Waste stockpile. If the stockpile is not processed through the mill (with the tailings deposited in the tailings impoundment), then it will be regraded, capped and vegetated along with the Main Waste, Oxide and Main Pit stockpiles.

OVERBURDEN STOCKPILE

The Overburden Stockpile is located at the south end of the tailings impoundment. It is composed of weathered Kivalina shale, salvaged topsoil, and material excavated from the mill site and tailings impoundment. Since 1997, portions of the stockpile have been fertilized and seeded to assess its revegetation potential. Colonization by native species already has been observed (see Natural Recovery section above). Possible concerns are potentially elevated EC (> 2 dS/m) and the concentrations of some metals (as evidenced in seepage and soil samples [see Data Review above]).

A portion of the stockpile will be incorporated into construction of the Back Dam. The remainder may be available for use as cover material elsewhere. The results of studies to determine the thickness of the cover are still pending, so the volume of overburden material that will remain after capping is complete is uncertain. If a portion of the stockpile remains at mine closure, this material will be contoured as described above to enhance plant establishment and growth.

MATERIAL SITES

Currently, there are two material sites associated with the mine. The DD-2 material site is located west of Diversion Ditch No. 2 and northwest of the overburden stockpile (Figure 1). Initially there were two sites in this area, but suitable material (non-mineralized rock) was exhausted in the southern site and this area is now used to store surplus equipment. The other site (MS-14) is located southeast of the airport runway (Figure 1). Other sites currently under investigation as potential sources of cover are described above.

The physical and chemical characteristics of soil at the two active material sites are likely to be poor for supporting plant growth (lack of fines and organic matter); thus, active revegetation is not proposed. Instead, natural colonization of these sites will be monitored to help identify plant materials that are adapted to poor soils. If recovery does not appear to be progressing over time, more active revegetation efforts may be implemented, if deemed appropriate.

WATER DIVERSION SYSTEMS

RED DOG CREEK AND PARALLEL DIVERSION SYSTEMS

The primary diversion channel begins south of the main pit and the oxide and main waste storage areas. The channel diverts water from the upstream Middle Fork of Red Dog Creek and tributaries (Connie, Shelly, Rachel, and Sulfur creeks) along the north side of the mine site area and then empties back into the Middle Fork of Red Dog Creek just above the tailings dam.

A deeper channel (mine water channel) was constructed parallel to the primary diversion channel to route runoff from the mine area. At the downstream end of the channel, a sump was excavated to collect the water, which is then pumped into the tailings impoundment.

Plans for closure of the diversion system are still in the development stage. The area around the pit originally consisted mainly of gravel, thus revegetation will not be necessary. The downstream portion of the area will need to be monitored for natural colonization. If enhancement of natural recovery is recommended, transplanting shrub (willow) cuttings or native-forb seeding may be possible, depending on the availability of local collection areas or seed stock from PMC.

DIVERSION DITCHES

Diversion ditches have been constructed on the northwest side of the tailings impoundment (DD-4) and west of the overburden stockpile area (DD-2 and DD-3). The ditches divert natural runoff away from the tailings impoundment and other development areas to minimize contamination of this natural surface water. If the ditches are not needed after closure, they could be left to recover naturally. Some natural colonization already has been observed along portions of the ditches.

CAMP PADS AND ROADS

An airstrip, access roads, and facility and storage pads are other disturbances that may be considered for revegetation, although this will depend in part on the post-mining land use of the area. As the land owner, NANA may choose to retain some of the roads and facilities (including the air strip) after mine closure. Revegetation of these areas may be difficult because of the compacted surfaces and poor soil properties for plant growth. To enhance revegetation potential, roads and pads that are abandoned at closure will be recontoured and scarified to break up the compacted surface. Re-establishing natural drainages (by removing culverts and contouring the roads to promote cross-drainage) will help promote natural recovery of these areas. Natural colonization of abandoned access roads along the haul road already has been documented (see Natural Recovery section above). If any areas are contaminated by fuel spills or because of other mine activities, the contaminated material will be removed. The excavated areas would either be backfilled with clean material or monitored for natural recovery, similar to other areas.

If it is determined that a more active revegetation effort is warranted, fertilizing and seeding with a mixture of native legumes and native-grass cultivars would be the most effective planting regime. Preliminary results of a companion planting of these species indicate the legumes help sustain the plant cover of the grasses after nutrients from fertilizer have been depleted (ABR, Inc., unpublished data).

TUNDRA DISTURBANCES

MINE OPERATIONS

Tundra disturbances that may result directly from mine operations include vehicle tracks, minor deposition of fill (e.g. from snow removal or road washouts), and contaminant spills. For sites where disturbance has resulted in substantial loss of plant cover (> 50%), a light application (100–200 lb/acre) of fertilizer (20-20-10 NPK) will be applied to promote vegetation recovery. This balanced fertilizer is appropriate for tundra disturbances, as all major nutrients are typically present at low concentrations in tundra soils (Chapin et al. 1975, Ulrich and Gersper 1978). No seed or other plant materials will be applied to these sites, as conditions are expected to be relatively favorable for natural recovery. In some cases, site remediation may be necessary as an initial treatment (e.g., contaminant spill). For these areas, decisions regarding revegetation treatment will be made on a case-by-case basis. Whenever possible, however, treatments will be selected to promote the recovery of the native tundra plant community, rather than the establishment of vegetation cover using other plant materials (e.g., native-grass cultivars).

FUGITIVE DUST

In addition to physical disturbance of tundra by mine operations, plant tissue damage (and in some cases mortality) has been observed in areas in downwind of the mine site. These impacts are likely due to the deposition of dust derived from blasting, load-haul-dump activities, ore stockpiles, crushing activities, the main waste pile, and exposed mill tailings. This dust is rich in metal sulfides (iron, zinc, and lead) and produces sulfuric acid during oxidative decomposition. Excess availability of these metals can impair plant growth and development (Williams and Schuman 1987).

In 2006, a study was initiated to better understand the source and nature of these impacts and to develop a remediation plan. Damage assessments were conducted at several locations where vegetation impacts had been observed, and samples of plant tissue and soil were collected at each location for analysis. The parameters measured included selected metals (aluminum, iron, manganese, lead, zinc, cadmium), sulfate, and plant macronutrients (nitrogen, phosphorus, and potassium). Preliminary results suggested that the vegetation impacts were primarily due to direct acid precipitation and the input of iron sulfate from fugitive dust. Plots were established at each sampling location for application of pelletized dolomitic lime, to test the effectiveness of this treatment in reducing the effects of acid precipitation. Additional plots were established and left untreated as controls, or possibly for applying a different treatment, pending results from further analysis of the soil and plant tissue data. The plots will be monitored for the next two years (2007 and 2008) to measure vegetation response.

In addition to the treatment plots described above, long-term monitoring plots also were established along nine 4-km long transects radiating out from the mine facilities (Figure 2). These plots will be monitored semi-annually over the next 10 years to provide information on changes in the plant community, both within and outside the dust shadow. This long-term study will help determine whether recovery of sensitive plant species within the affected area is occurring, in response to ongoing efforts to reduce fugitive dust emissions from mine facilities and direct remedial efforts.

REVEGETATION SPECIFICATIONS

FERTILIZER

With few exceptions, fertilizer is required to promote the establishment and growth of both planted species and natural colonizers on mine disturbances. In some cases, ammonium nitrate is present for a limited period from blasting, but the blasted material is typically so coarse that nutrients readily leach out. Even fine-grained material is low in nutrients because organic matter content is low (< 10%). Consequently, those mine development units that will be reclaimed to promote natural recovery or as part of an active revegetation effort will need to be fertilized. The fertilizer will be a balanced combination of elemental nitrogen (N), phosphorous pentoxide (P_2O_5), and potash (K_2O); a typical mixture is 20:20:10 (N-P-K). The appropriate rate of fertilizer application depends to some extent on substrate characteristics, but a typical rate is 400–450 lb/acre. For large areas, fertilizer will be broadcasted aerially. In cases where a seed mix also will be broadcasted, fertilizer and seed will be combined in a slurry, which will more effectively broadcast the seed over the target areas. For smaller areas (< 5 acres), applying fertilizer and seed probably will be done using a hydroseeder or manual chest and push spreaders.

PLANT MATERIALS

NATIVE-GRASS CULTIVARS

The development of native-grass cultivars for revegetating land disturbances in arctic Alaska began about 20 years ago, in response to the poor performance of most agronomic cultivars (Appendix B). Grass species were collected throughout northern and western Alaska and brought to the University of Alaska’s agricultural experimental stations at Palmer and Fairbanks to evaluate their potential as commercial sources of native grass seed. Over the years, several Alaska farmers began growing some varieties and currently there are at least eight species in commercial production, although their availability varies from year to year (Table 2).

The native-grass cultivars provide some important advantages over the agronomic species that were previously used, but their long-term performance is variable in poor soils such as those commonly associated with mine disturbances. Although the cover of several of these species was high in PMC test plots at the Red Dog Mine after three years, little information is available regarding their status 5–10 years after seeding. Studies on revegetation of thick gravel fill and gravelly sand in the North Slope oilfields and at the EKATI Diamond Mine in the Northwest Territories, Canada, found that cover of native-grass cultivars declined over time, with total cover typically peaking 3–5 years after seeding (Jorgenson and Joyce 1994, Jorgenson et al. 1995, 2003; Kidd and Max 2001). The decline probably was in response to depletion of nutrients (the sites were fertilized only at the time of seeding). At sites where the soil is higher in organic matter or is amended with a complex fertilizer, such as sewage sludge (biosolids), the long-term performance of the native-grass cultivars is improved.

It will be necessary to use native-grass cultivars in the revegetation program at the Red Dog mine, as they are the only species native to northern Alaska for which seed is consistently available in bulk from commercial growers. Efforts will be made to improve site conditions for sustaining their growth over the long term, including companion plantings of legumes (see below), which contain nitrogen-fixing bacteria. The native-grass cultivars proposed for vegetating the various mine development units are presented in Table 2. The two species listed as secondary species, Arctared fescue and Bering hairgrass are not recommended unless no other sources of seed are available. The sod-forming habit of the Arctared fescue may inhibit colonization by local species and the Bering hairgrass is not native to the Red Dog Mine area; it occurs principally along the southern and southwestern coasts of Alaska. A relatively low seeding rate (20 lb/acre) is recommended for all seed mixes, so that the seeded species will not impede natural colonization by local species. In general, seed and fertilizer will be applied in the fall (September) to take advantage of the soil moisture gained from snowmelt the following spring. If this is not possible, than seeding will be done early in the spring, following snowmelt.

NATIVE FORBS

To increase species richness on disturbed sites and help sustain the cover of native-grass cultivars, research into the germination and growth potential of legumes and other forbs has been conducted over the past 15 years (Jorgenson and Kidd 1991, Wright et al. 1993, McKendrick et al. 1992, Bishop et al. in preparation). Although commercial sources currently exist for bulk seed of indigenous legumes, several species are abundant as natural colonizers and have been collected manually along the Trans Alaska Pipeline System corridor, 60–80 km south of Prudhoe Bay and along roadsides in the Fairbanks area. In addition, several growers are in the process of cultivating some legume species for use on a commercial scale (APMC 2005). The species that may be used at the Red Dog Mine Site include *Astragalus alpinus* (alpine milk vetch), *Hedysarum mackenzii* (liquorice root), *Oxytropis deflexa* (deflexed oxytrope), *O. borealis* (boreal locoweed), *O. campestris* (field locoweed), and *O. maydelliana*. The selection of these species is based on both availability and the results of germination testing performed by PMC. These species also have been used successfully in vegetating disturbed sites in alpine areas in Denali National Park (Densmore and Holmes, 1987; Densmore et al., 1990) and in the Kuparuk Oilfield (Kidd et al. 1997, Bishop and Max 2002).

Depending on the feasibility of obtaining seed by hand collection and by purchasing seed from growers, legumes may be included in seed mixtures for several of the mine development units. If erosion sensitivity is limited, the seeding of grasses will be delayed for two growing seasons following sowing of legumes. This will allow the legumes to establish without competition from the grasses, which are capable of rapid growth in response to fertilizer application. Another (non-legume) forb that is available onsite (tilesy sage) and through PMC also will be included in seed mixes for revegetation of stockpiles and roads and pads, where appropriate. Tilesy sage is not only valuable as a species adapted to disturbed soils, but also is a preferred forage species for caribou (Kidd, pers. obs.). Other forbs that may be included in seed mixes are listed in Table 2. Seed will be broadcast in the fall, as described above for the native-grass cultivar seed.

LOCALLY COLLECTED SPECIES

The survey of natural colonization that was conducted at the Red Dog Mine in 1993 (Dames and Moore 1995) identified a number of natural colonizers that have the potential to serve as seed sources for revegetation efforts. Additional testing, perhaps with onsite test plots, will be conducted for species for which sufficient quantities of seed can be collected. Species that may be particularly promising include wormwood, spike trisetum, milk vetch, and shrub birch. A field survey in July 2004 also identified two legumes that have been successfully used for revegetation elsewhere: alpine milk vetch and boreal locoweed. Areas that are successfully revegetated with local species could serve as seed sources for other areas for future revegetation efforts. The main limitation to using local seed sources is the lack of sufficient stands for efficient seed collection. Relatively large populations of local species will be needed because the percentage of viable seed is likely to be considerably lower than for cultivated species. For most forbs, seed will be collected in late July and early August, but seed of most grasses and sedges are not be mature until mid September. Seed will be broadcast in the fall as described for forbs and native-grass cultivars.

SHRUB CUTTINGS

Planting of shrub cuttings, specifically willow, will only be considered for the Diversion Channel System or in other areas where there is sufficient soil moisture. The cuttings will be collected in late spring (while dormant) and stored frozen onsite till planting (early June). Species that have performed favorably as transplanted cuttings elsewhere include feltleaf willow, diamondleaf willow, and Richardson willow.

REVEGETATION RESEARCH

To aid in the development of effective revegetation approaches for the Red Dog Mine, TCAK is developing a revegetation research plan that includes 1) a pilot vegetation study on the main waste rock stockpile, 2) evaluation of large scale vegetation efforts through progressive reclamation, 3) plant materials development, and 4) development of a reclamation database. Results from initial testing of plant materials and vegetation monitoring were described above under *Data Review*. A monitoring program for future revegetation efforts also has been developed (see Supporting Document I), to ensure objectives are being met and to identify deficiencies or areas requiring further investigation or treatment. The results from research efforts will help refine some of the strategies described above and potentially identify new techniques or plant species that promote recovery of the mine site area after closure.

PILOT VEGETATION STUDY

Reclamation of the waste rock piles at the Red Dog Mine will require developing a cover that encapsulates the waste and prevents the generation of ARD. Establishing a productive plant community will help promote stability of the waste rock cover surface. In summer 2007, TCAK and O'Kane Consultants Inc. will test several treatment combinations of non-compacted overburden and waste rock in 50 ×50 ft cells on the main waste rock pile (see Supporting Document F). The study will focus primarily on the performance of the cover in terms of water content, percolation, temperature, and negative pore-water pressure. One treatment cell, however, will be set aside for vegetation testing.

Seed (200 per species) of at least three plant species will be sown in the experimental cell in fall 2007. Species will be sown in separate rows (1 m spacing between rows) so that germination, growth, and plant health can be measured for each species. A balanced fertilizer (20-20-10 NPK) will be applied at 400 lbs/acre (23 lbs). Species selected will depend on availability, but may include the native-grass cultivars *Poa alpina* (alpine bluegrass), *P. glauca* (tundra bluegrass), and *Trisetum spicatum* (spiked trisetum). If local populations are adequate, indigenous forb species also may be tested, including *Artemisia arctica* (arctic wormwood), *Epilobium angustifolium* (tall fireweed), *Astragalus alpinus* (alpine milk vetch), *A. umbellatus* (tundra milk vetch), and *Aster sibericus* (Siberian aster). Other species may be added to the study, based on results from PMC's North Latitude Revegetation and Seed Project or from data collected from other revegetation studies at the mine.

For any locally collected seed, subsamples will be tested for viability using tetrazolium chloride dye. Tetrazolium chloride reacts with dehydrogenase enzymes and produces a red stain when live tissue is present in the seed. Using this test to assess percent seed viability is much less time-consuming than performing germination tests, and also provides better accuracy. Seed that fails to germinate when tested may simply require an extended dormant period, but might germinate eventually in a field setting. In some species, it is not unusual for seed to remain dormant for more than a year (Schütz 1998).

Initial monitoring (August 2008) will consist of recording percent germination and collecting soil samples (n = 3) for analysis of physical and chemical characteristics important for plant growth. In the following year (2009), the plots will be photo-documented and qualitatively assessed. After three growing seasons (2010), plant densities will again be quantitatively recorded, and overall plant health will be assessed. Plant tissue samples also will be collected for analysis of selected metals, to ensure that concentrations are not phytotoxic or potentially harmful to grazing wildlife. The plant species that show the strongest survival and growth will be selected for sampling and analysis.

PROGRESSIVE RECLAMATION

The pilot study described above will be valuable in identifying those plant species with the ability to survive on the cover material used to cap the waste rock stockpile. Additional research will be required, however, to provide information on the degree of revegetation success that can be expected for a larger area, on the scale of the revegetation effort that will be required for mine closure. To assist in this effort, progressive reclamation of those portions of the waste rock stockpile no longer receiving material will begin as soon as possible. This will allow for the testing of a variety of landscaping techniques and plant materials, and developing effective methods to promote the establishment of a stable land surface and a productive and sustainable plant community.

Lack of adequate soil moisture is one of the main limiting factors for establishing productive vegetation cover in the Arctic (Billings 1987). Results from cover system field trials and from early reclamation of closed areas will help determine to what extent soil moisture can be retained close to the surface with limited percolation into the underlying waste rock. If the risk of ARD downstream is limited, the feasibility of creating surface conditions that promote snow capture and other features that increase soil moisture will be evaluated. A more detailed plan for a larger-scale vegetation effort on the waste rock stockpile will be submitted once a location has been identified and the analysis of the pilot cover and vegetation studies is complete.

PLANT MATERIAL DEVELOPMENT

Previous efforts to identify plant materials with the potential to establish and develop a sustainable plant cover on disturbances at the Red Dog Mine were summarized above (see Revegetation Specifications). Although a number of plant species have been identified as promising candidates for revegetation efforts in the Arctic (Appendix A), limited information is available on successful revegetation efforts at sites with similar conditions to the Red Dog Mine. Thus, on-site testing of candidate plant species is necessary. This will include both small-scale test plots such as those set up by the PMC in 2004, and the pilot study proposed for the waste rock stockpile. In addition, monitoring of progressive reclamation will provide data on how various species perform on a landscape scale. Based on preliminary results from previous revegetation efforts and PMC test plots, several plant species (both native and non-native) were identified as potential candidates. However, NANA and park representatives from the nearby Noatak National Preserve have expressed concern over the introduction of non-native species. Thus, none of the agronomic species that were included in PMC's test plots will be used for mine revegetation efforts.

The results of a long term vegetation monitoring study at the mine will be reviewed, to determine whether other indigenous plant species should be considered as candidates for use in revegetation. This study was initiated in July 2006 to provide information on changes in cover by species and life form of vegetation within, and outside of, the dust shadow of the mine (Figure 1) (ABR, Inc. in preparation). The transects traverse a variety of habitats, providing a database that can be used to screen (based on habitat requirements) for species that may be adapted to disturbed environments.

RECLAMATION REGISTRY

As part of TCAK's commitment to conduct progressive reclamation throughout the life of the Red Dog Mine, a mechanism for tracking the success of reclamation efforts is needed. By tracking the scheduling, implementation, and results of reclamation activities, important information will be obtained about the effectiveness of various reclamation strategies in an area where land rehabilitation has largely been untested. To provide this information in an accessible format, a reclamation registry will be developed. The registry will integrate a variety of databases into a comprehensive datafile listing that will allow the user to learn about the types of mine disturbances that have been reclaimed, the techniques that were used at the site(s), and the progress of reclamation efforts. In some cases, the data may be from small-scale experiments testing new plant materials, topdressings, or site manipulation techniques (e.g., cover experiment on the waste rock pile). In other instances, the data may summarize large-scale reclamation efforts, with data on plant cover, soil characteristics, and habitat use.

The structure of the database is still under development, but likely will include such variables as location, site characteristics, treatments applied, plant species and cover values, soil properties, and wildlife use. The registry will be updated every 1–2 years as new sites are added and/or additional monitoring data are collected, and will be linked to Red Dog's GIS database so that acreages of reclaimed areas can be regularly updated. The GIS integration also will help in planning future reclamation efforts and understanding their potential effects on mining activities. Variables such as locations of cover sources, volumes of material available, and associated soils data also may be included in the database.

Since the Red Dog reclamation program is still in its early stages, most of the results from revegetation efforts are preliminary. Nevertheless, incorporating these data into a registry now will help provide the framework on which to build as sites respond to treatment and additional reclamation work is completed. The registry also will aid in tracking the history of reclamation treatments applied at various sites (grading, fertilizing, seeding) and provide assistance in planning future activities.

REVEGETATION PERFORMANCE STANDARDS

Under ADNR's Mining Laws and Regulations (2002), land reclamation performance standards include leaving an area in a "condition that can reasonably be expected to return waterborne soil erosion to pre-mining levels within one year after the reclamation is completed, and that can reasonably be expected to achieve re-vegetation, where feasible, within five years after the reclamation is completed, without the need for fertilization or reseeding." (p.35, AS 27.19.100, 11 AAC 97.200). The statute goes on to say, however, that this standard is not required if it is incompatible with the post-mining land use approved for the mine (e.g. commercial). Furthermore, most of the site is on land that is privately owned, and the post-mining land use will be determined by NANA.

Nonetheless, Teck Cominco Inc. (TCAK) will try to develop more precise site specific performance standards for revegetation at the Red Dog Mine for two main reasons. First, performance standards provide regulatory agencies with the assurance that reclamation is being conducted that is compatible with mine closure goals and objectives. Second, developing specific standards will allow TCAK to focus on specific end-point targets that are not subject to interpretation. Because ecosystems are complex and influenced by numerous external and internal factors, it is impossible to assign specific performance standards to all indicators of ecosystem development. Nevertheless, many ecosystem components are measurable and can be used to indicate whether reclamation efforts are moving toward the creation of a diverse, self-sustaining ecosystem.

A review of performance criteria for other mine sites in Canada, Alaska, and for selected mines in the lower forty-eight found that few mines have developed a systematic approach to evaluating the performance of revegetation efforts. The approaches used to evaluate revegetation success varied widely. Some regulations and closure plans provided specific target end-points, including percent plant cover, species diversity (taxonomic richness and evenness), plant density, and life form composition (e.g., grasses and shrubs). In contrast, other plans described success in much more general terms; for example, requiring that plant species must be compatible with native species, that plant communities must be self sustaining, or that plant cover must be productive. Despite the variety of approaches, most recommendations and/or requirements included 1) establishing plant communities dominated by native species and with a diversity and productivity similar to pre-mining conditions, and 2) establishing plant communities that are sustainable and are compatible with the land uses proposed for the area after mine closure.

Since the Red Dog Mine is still in the active mining phase (with few areas ready to be reclaimed), only selected areas have been revegetated. Consequently, few data are yet available on the success of revegetation efforts at the mine site. Thus, it is difficult to develop performance standards that are meaningful (and achievable) at this time. As more data become available from revegetation efforts (and rates of natural recovery) at the mine, TCAK will develop, in consultation with ADNR, a list of goals and objectives for revegetation efforts that can serve as the basis for evaluating performance. This approach will help ensure that the performance standards developed are achievable within a reasonable time frame (both in terms of bond release and regulatory oversight) and are sustainable over the long term. Since the long term sustainability of vegetation establishment at the Red Dog Mine is unknown, however, it likely will require at least 10 years before standards can be developed that will accurately reflect the potential for vegetation recovery of the mine site.

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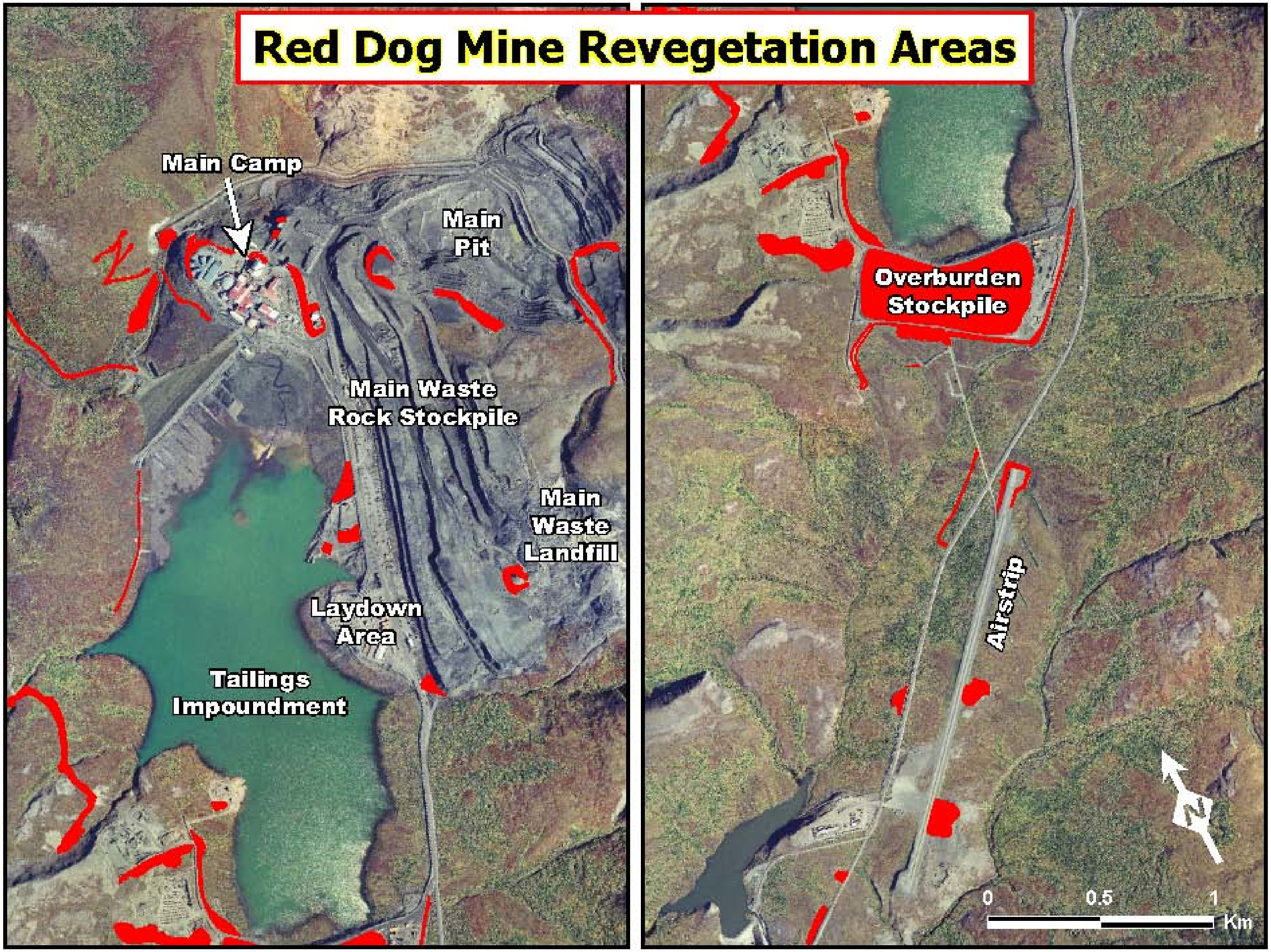

Figure 1. Map of areas where fertilizer and seed have been broadcast at the Red Dog Mine, Alaska, 2004.

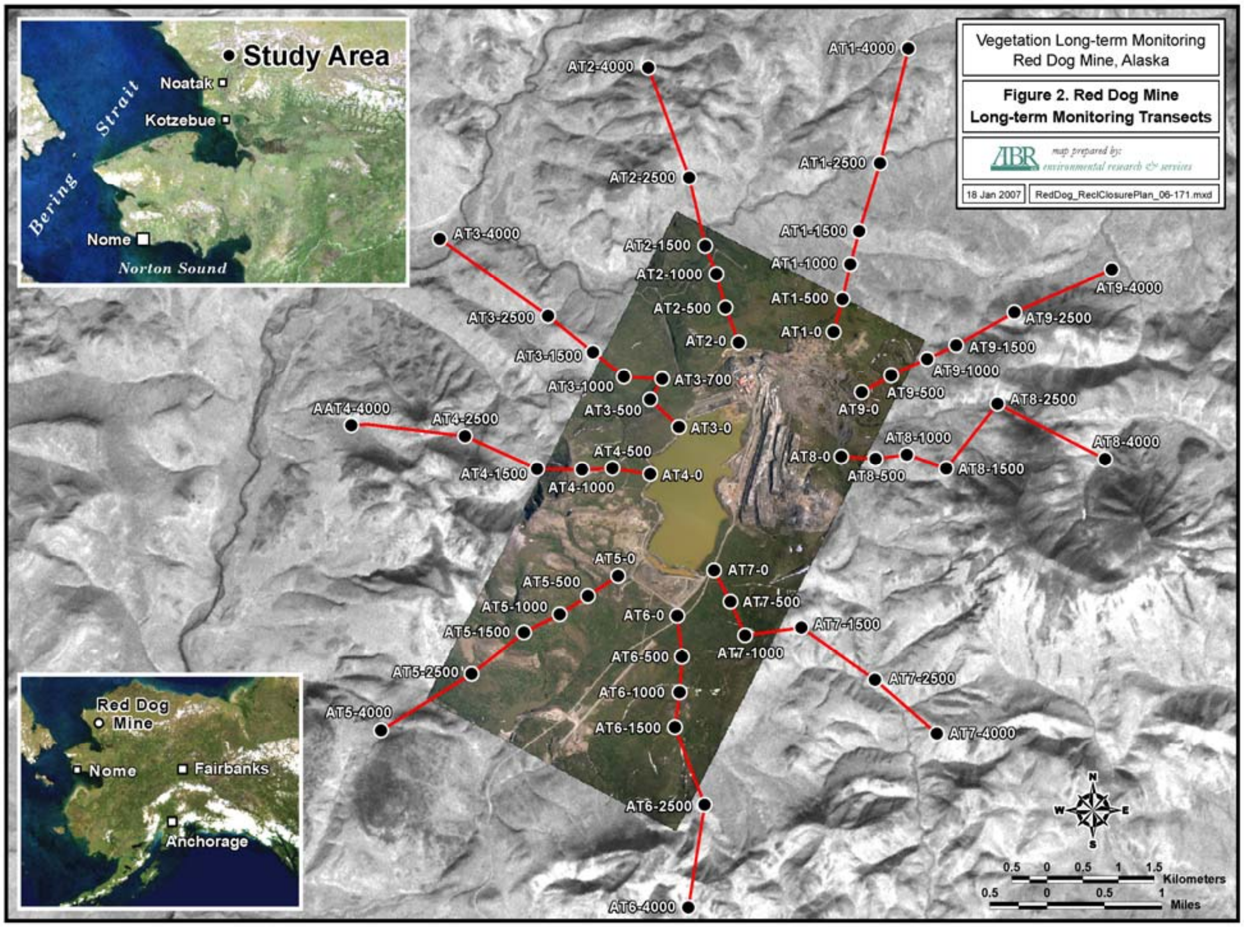

Figure 2. Locations of plots along transects established in July 2006 for long-term monitoring of vegetation in the vicinity of the Red Dog Mine, Alaska.

Table 1. Percent plant cover of seeded and naturally colonizing areas in the vicinity of the Red Dog Mine, Alaska, July 2004. Taxonomy follows Hultén (1968); common names derived from Viereck et al. (1992) or the Natural Resources Conservation Service Plant Database.

	Fertilized and Seeded				
	Overburden Stockpile	South of Overburden Stockpile	Adjacent to Tailings Impoundment	Near Airport	Natural Colonization (Overburden Stockpile)
Bare Ground	15	40	77	61	64
Plant Litter (standing dead)	7	9	7	8	1
Total Live Cover	102	73	24	36	37
Total Live Vascular Cover	50	42	24	22	6
Graminoids (sedges and grasses)					
Seeded native-grass cultivars					
Alopecurus pratensis (meadow foxtail)		tr[a]			
Arctagrostis latifolia (polargrass)	1		tr		tr
Deschampsia beringensis (Bering hairgrass)	13	26	21		1
Festuca rubra (Arctared fescue)	36	tr		20	5
Poa glauca (tundra bluegrass)	tr	16		tr	tr
Non-seeded				1	
Carex bigelowii (bigelow sedge)				tr	
Deschampsia. caespitosa			2		
Poa alpina (alpine bluegrass)		tr			tr
Poa arctica (arctic bluegrass)		tr			tr
Poa alpina (alpine bluegrass)				tr	
Poa sp. (bluegrass)				1	tr
Trisetum spicatum (spike trisetum)					tr
Forbs				1	
Arnica sp.				tr	
Artemisia arctica (boreal sagebrush)				tr	
Cerastium beeringianum (Bering chickweed)		tr	1		tr
Epilobium angustifolium (tall fireweed)		tr		1	tr
E. latifolium (river beauty)					tr
Dryas octopetala (Alaska mountain-avens				tr	
Oxytropis borealis (boreal locoweed)					tr
Erysimum cheiranthoides (wormseed wallflower)	tr				tr
Minuartia arctica (arctic stitchwort)				tr	
Petasites frigidus					tr
Saxifraga tricuspidata (three-toothed saxifrage)				tr	
Senecio congestus (marsh fleabane)					tr
Silene acaulis (moss campion)				tr	
Shrubs				tr	
Betula nana (dwarf birch)				tr	
Populus balsamifera (seedling) (balsam poplar)				tr	tr

Table 1. continued.

	Fertilized and Seeded				Natural Colonization (Overburden Stockpile)
	Overburden Stockpile	South of Overburden Stockpile	Adjacent to Tailings Impoundment	Near Airport	
Potentilla fruticosa (shrubby cinquefoil)				tr	
Salix alaxensis (feltleaf willow)				tr	tr
S. glauca (grayleaf willow)				tr	tr
S. phlebophylla (skeletonleaf willow)					tr
Salix sp.				tr	tr
Total Live Non-vascular Cover		31	tr	14	31
Bryophytes	52	31	tr	14	31
Unidentified moss	51	31	tr	14	31
Polytrichum juniperinum	1				

[a] tr = trace.

Table 2. List of plant species that may be used to revegetate mine development units at the Red Dog Mine, Alaska.

Plant Species		Planting Specifications	Disturbance Type
Native-grass cultivars Primary List Nortran hairgrass Tundra bluegrass Alpine bluegrass Spike trisetum Thickspike wheatgrass Polargrass Bluejoint	Secondary List Bering hairgrass Arctared fescue	Seeding Rate 20 lb/acre (final mixture) Ratio of species will depend on availability, but mix may include predominantly tundra bluegrass and alpine bluegrass for drier areas and Nortran hairgrass, polargrass, and bluejoint for mesic sites.	Thick gravel or mineral fill—stockpiles of waste rock, overburden, and marginal and oxide ore; airstrip, roads and gravel pads
Native forbs Tilesy sage Alpine milkvetch Alpine sweetvetch Boreal sweetvetch Field Oxytrope Boreal yarrow	Other potential species[a] Tall fireweed Siberian aster Arctic bladderpod	50 seeds/m^2 for each species Ratio of species will depend on availability, but mix may include alpine milkvetch, field oxytrope, Arctic bladderpod, and Siberian aster for dry areas; and tilesy sage, boreal sweetvetch, alpine sweetvetch, tall fireweed for mesic areas.	Thick gravel or mineral fill—stockpiles of waste rock, overburden, and marginal and oxide ore; diversion channel system
Shrub cuttings and seedlings Diamondleaf willow Feltleaf willow Richardson willow Shrub/dwarf birch[a]		For willows, 1 cutting on 1-ft centers For birch seed, 100 seeds/m^2	Diversion channel system, moist depressions at other locations

[a] No data on germination success.

APPENDIX A. GLOSSARY OF TERMS

Table A1. Glossary of terms.

Term	Definition
Acid rock drainage	Discharge of acid that is formed when sulfide-bearing rock is oxidized as a result of being exposed to air and water.
Agronomy	A branch of agriculture dealing with crop production and soil management.
Alluvial	Created or deposited by running water.
Bulbil	Small bulb-like body, usually formed in the leaf axil of a plant, that can physically separate from the parent plant to form a new individual.
Capillary rise	The upward movement of ground water, as a result of surface tension, through small pours in the soil.
Cation exchange capacity (CEC)	A measure of the mobility in the soil (and therefore the availability to plants) of nutrient ions such as potassium, calcium, magnesium, and sodium.
Companion planting	Cultivation of different varieties of plants in the same area, usually for the benefit of one or more of the varieties.
Cuttings	Sections of shrub stem capable of rooting and sprouting into independent plants when placed in appropriate media.
Dehydrogenase	An enzyme that oxidizes a substrate by transferring one or more protons and a pair of electrons to an acceptor, which are commonly helper molecules that assist in chemical reactions.
Dormant	A naturally occurring state in plants during which metabolic processes slow, and plants are less susceptible to mechanical and temperature damage.
Electrical conductivity (EC)	An indirect measure of soil salinity; higher EC measures indicate higher concentrations of total salts in the soil..
Enzyme	A protein that initiates (commony accelerates) chemical reactions
Exchangeable cations	Plant nutrients (e.g. potassium, calcium, magnesium, sodium) adsorbed onto soil particles.
Forb	A non-woody plant other than grasses, sedges and rushes.
Germination	The process by which a seed or spore begins to sprout.
Graminoid	Grasses (Poaceae family) and grass-like plants, such as sedges (Cyperaceae family) and rushes (Juncaeae family).
Habitat	The physical environment in which an organism lives
Herbaceous	Non-woody plant that dies back at the end of the growing season.
Hydrophylic	Something that is attracted to, or thrives in the presence of water.
Indigenous	Originating or occurring naturally in an area.
Invertebrate	Any of many groups of animals lacking bony spinal column (e.g., insects).
Leaching	Process by which soluble materials, such as metals or contaminants, in rocks and soil are dissolved and washed away by water.
Legume	Plants in the bean family (Fabaceae) favored in revegetation projects because of their relationship with nitrogen-fixing bacteria (commonly *Rhizobium* sp.)
Littoral	Pertaining to the shore zone of a water body.

Table A1 continued.

Term	Definition
Loam	A textural class of soil containing moderate amounts of sand, silt and clay, often considered ideal for plant growth.
Mesic	Habitat that is moderately moist or temperate.
Microbial flora	The microorganisms that are associated with a particular area.
Mitigation	Measure taken to reduce, prevent or correct the impact of an action.
Mulch	A natural (e.g. ground up plant material) or artificial layer of material applied to the soil surface.
Mycorrhizae	Beneficial associations between plants and fungi that occur at the plants roots.
Native forbs	Forbs which grow naturally in the study area.
Native-grass cultivars	Grass species which grow naturally in the study area, but are cultivated for commercial production
Natural colonization	The process of revegetation of a disturbed area by naturally dispersed seeds, spores or vegetative propagules from local plant populations.
Natural Recovery	Ecosystem components that establish on disturbed land unassisted. With respect to vegetation, refers to the natural colonization of species on a site disturbance.
Nitrogen-fixing bacteria	Bacteria that converts atmospheric nitrogen into a form of nitrogen that can be used by plants.
Overburden	Soil or rock layers that are removed during the mining process to access desired minerals.
Pedologic	Of or related to soils.
Permafrost	Permanently frozen layer of ground that occurs commonly in arctic and sub-arctic regions.
Phytotoxic	Poisonous to plants.
Plant cover	The percentage of substrate in any area that is covered by living plant biomass.
Progressive reclamation	Reclamation that occurs while a mine is still operational. As mining progresses, those areas recently abandoned are reclaimed as soon as possible, instead of at mine closure.
Propagules	Any part of a plant that can be used for sexual or asexual reproduction.
Reclamation	Process by which mined land is re-contoured, vegetated (in some cases), and chemically stabilized to ensure that the structures that remain after mine closure do not impose a long-term hazard to public health and safety and the environment, which includes ensuring that the land and watercourses are returned to a safe and environmentally sound state and to and acceptable end use.
Rehabilitation	The process of returning a mined or otherwise disturbed area to a state of full ecological functioning. The process may involve establishing appropriate vegetation, hydrologic conditions and wildlife habitat.
Remediation	Alleviation of problems associated with environmental disturbances through land rehabilitation (e.g., revegetation), site clean-up (e.g., contaminants), and/or engineering practices (e.g., site stabilization measures).

Table A1 continued.

Revegetation	The process of establishing a cover of live plants on a formerly disturbed area via any of a number of techniques
Riparian	Habitat along the banks of streams or rivers.
Scarify	To break up or loosen a surface.
Scrub	An area where shrubs are the dominant lifeform.
Sodium adsorption ratio (SAR)	Describes the concentration of sodium ions relative to calcium and magnesium ions in millequivalents per liter. Used to assess whether a soil has excess sodium (sodic)
Sprigs	Sections of grass plants capable of establishing independent plants when placed in appropriate media.
Tailings pond / Tailings impoundment	Body of water used to store waste material removed during the mining process.
Talus	Rock debris, such as that which accumulates at the base of a cliff or hillside.
Thermal regime	Temperature distribution and how it changes over time.
Transitional climate	Climate characterized by long, cold winters and cool summers.
Unconsolidated material	A sediment whose particles are not cemented together. Examples include clay, silt, sand and gravel.
Vascular plant	Plant that has a well developed system of tissue, such as xylem and phloem, used to transport water and nutrients from one part of the plant to another. This group includes most plants, except mosses and lichens.
Xerophylic	Something that is well adapted to arid areas.

APPENDIX B. LITERATURE REVIEW OF MINE RECLAMATION RESEARCH IN THE ARCTIC

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INTRODUCTION

Traditionally, mine reclamation efforts have focused on controlling soil erosion resulting from the removal of natural vegetation, in order to maintain water quality (Bolstad 1971, McKendrick et al. 1984). In permafrost areas, revegetation was promoted to minimize thermal erosion (thermokarst) associated with disturbing ice–rich soils (MacKay 1970, Bureau of Land Management 1973, Dabbs et al. 1974, Hernandez 1973a, Haag and Bliss 1973, Lawson 1986). More recently, however, the objectives of revegetation have expanded to include the establishment of plant communities that are productive, self-regulating ecosystems integrated with the landscape in which they occur. Aesthetics, biological diversity, and wildlife habitat are all factors commonly considered in the development and implementation of revegetation plans (Densmore et al. 1987, Walker et al. 1987, Helm 1992, Jorgenson and Joyce 1994).

The severe environment of the Arctic poses many limitations to the rehabilitation of disturbed lands. The growing season is very short, the number of warm days is limited, and frosts can occur at any time during the summer. Low temperatures result in low rates of organic matter decomposition and nutrient cycling; limited and inconsistent seed production; and slow colonization of disturbed areas by plants (Haag 1974, Billings 1987). In areas where hard–rock mining occurs, the soil frequently is poorly developed and contains little organic matter, so the availability of topsoil for amending disturbed sites is limited. In addition, mining typically produces waste rock and creates a disturbed land surface that has few physical and chemical characteristics conducive to promoting plant establishment and growth. Unless precipitation is abundant, raised disturbed surfaces such as gravel pads and roads are very dry, because they are disconnected from the natural water table. However, revegetation can be successful if techniques are appropriate to the conditions at a particular site.

Since the early 1970s, numerous studies have been conducted to develop techniques for revegetating disturbed areas to facilitate long-term ecosystem recovery. This report reviews many of these studies in an attempt to synthesize the status of reclamation research in the Arctic and to provide background and justification for the proposed reclamation plan of the Red Dog Mine. The report describes the plant cultivation, soil conditioning, fertilization, and surface manipulation and preparation treatments that have been evaluated, and the prospects and limitations associated with each treatment.

SURFACE MANIPULATION

BERM AND BASIN CONSTRUCTION

Thick gravel fill, which is one of the most extensive types of disturbance at mine sites, presents a severe environment for plant growth. One of the factors limiting plant growth is soil moisture. Berms can be constructed perpendicular to prevailing winds to capture drifting snow during winter and increase water input during snowmelt, thus compensating for low precipitation in summer and low soil moisture on thick gravel fill (Jorgenson and Cater 1991, Jorgenson et al. 1992). In areas with fine-grained soils, such as overburden stockpiles, meltwater can be impounded permanently to create wetlands (Jorgenson et al. 1992). Moderately sized berms (~1 m high) and shallow basins (≤0.5 m) constructed on thick gravel fill at a drill site in the Prudhoe Bay Oilfield (Jorgenson and Cater 1991) resulted in substantial snow capture and, after three years (1994), soil was moist within the basins through the end of summer (J. Kidd, pers. comm.).

Large (~4 m) berms were constructed to capture snow and smaller berms (~2 m) were constructed to impound the meltwater within an overburden stockpile in the Kuparuk Oilfield (Jorgenson et al. 1992). Fine-grained soil and permafrost beneath the shallow active layer (seasonally thawed ground) resulted in water levels increasing in the basin from 1990 to 1993 (Jacobs et al. 1994). Transplanted sprigs of *Arctophila fulva* and the presence of aquatic invertebrates in the impounded basin have made this site attractive to numerous waterbirds.

FILL REMOVAL

Removal of gravel fill to facilitate the development of pedologic and hydrologic conditions similar to those found in adjacent undisturbed tundra has been investigated at several sites in the Prudhoe Bay Oilfield (Kidd et al. 2004, 2006). Without the removal of gravel and the associated increase in the availability of water and nutrients, the growth of plants on thick gravel fill is poor. Jorgenson (1988) found plant growth to be negligible on gravel thicker than 1 m and attributed the response to the low rate of capillary rise of groundwater as a result of the thickness of the fill.

Determining how much gravel should be removed from roads and pads is difficult because tundra soils typically are underlain by ice-rich permafrost; removing overlying gravel can initiate thaw settlement as permafrost adjusts to the new thermal regime. Some gravel can be left in place to compensate for thaw settlement, but tundra soil will remain buried. If gravel is removed completely to expose the buried tundra soil, excessive thaw settlement may cause the site to become flooded permanently, and water movement in the adjacent tundra may be altered, which occurred at one of the study sites in the Prudhoe Bay Oilfield (Kidd et al. 2006). The impounded water provides an opportunity to create aquatic habitats, but it also restricts the types of plant materials that can be used.

FLOODING OF MINE SITES:

Abandoned gravel mine sites can be flooded with water and connected to nearby drainages to support overwintering fishes (Hemming 1989, Hemming 1990, Hemming 1991). Natural colonization by fishes has been rapid in mine sites that have been flooded and connected to adjacent streams with access channels. Eleven species of fishes have been found at these sites: arctic cisco (*Coregonus autumnalis*), broad whitefish (*C. nasus*), least cisco (*C. sardinella*), round whitefish (*Prosopium cylindraceum*), burbot (*Lota lota*), ninespine stickleback (*Pungitius pungitius*), rainbow smelt (*Osmerus mordax*), Dolly Varden char (*Salvelinus malma*), arctic grayling (*Thymallus arcticus*), slimy sculpin (*Cottus cognatus*), and fourhorn sculpin (*Myoxocephalus quadricornis*).

Portions of mine sites also have been backfilled with overburden to create islands for nesting waterbirds and shallow, littoral areas for establishing wetland vegetation (Jorgenson et al. 1992, ABR, Inc. 2002). These mines typically do not have stream connections; thus, rehabilitation efforts are more focused on creating habitats favorable for terrestrial wildlife (e.g., caribou) and waterbirds including geese, ducks, loons, and shorebirds.

SURFACE PREPARATION

Surface preparation techniques include compaction, contouring, raking or dragging, scarifying, surface roughening, and mulching. Compaction was done on an abandoned spur road in the Kuparuk Oilfield with a large, rubber-balloon-tired vehicle (Rolligon) to improve contact between the applied sod and the underlying thin layer of gravel (Cater and Jorgenson 1994a). Scarifying has been done at many sites by using a grader equipped with chisel teeth or by pulling a pipe equipped with tines (Jorgenson et al. 1990; Jorgenson and Cater 1991, 1992b), and raking or dragging has been conducted to improve soil-seed contact (Jorgenson and Cater 1992b). In windy, low-precipitation areas, the placement of rock structures or boulders can provide wind protection for young seedlings, prevent sheet flow of runoff, and improve soil moisture by capturing snow. Plants at scarified sites typically are most abundant in the bottom of furrows, suggesting that scarification increases seed germination by providing favorable microsites. Finally, mulch has been applied to thick gravel fill to reduce the rate of evaporation of soil moisture with limited success. Although seed germination was improved in the mulched areas, soil temperatures and moisture were lower than in the unmulched plots because the mulch intercepted solar radiation and precipitation (Jorgenson and Cater 1992a).

SOIL AMENDMENTS

FERTILIZATION

Many of the disturbed areas targeted for vegetation rehabilitation do not have sufficient levels of nutrients for promoting plant establishment and growth (Walker et al. 1987). In addition, some undisturbed tundra communities have depressed levels of soil nutrients, particularly nitrogen, because decomposition is slow and much of the soil nitrogen is tied up in undecomposed plant material (Dadykin 1958, Haag 1974). To compensate for the lack of nutrients, fertilizer usually is added to increase soil nutrient status and facilitate more rapid establishment of cover on disturbed soils. The rate of fertilizer to be applied is dependent on the composition of the soil substrate and on the types of plant species targeted for revegetation. Graminoids and forbs prefer fairly high rates of fertilizer (McKendrick et al. 1978, Chapin and Shaver 1985), whereas some shrubs respond more positively to lower levels of nutrients (Russell 1973, Henry et al. 1994).

The question of multiple versus single applications of fertilizer has not been completely resolved. In cases where the plant species used are grasses and they attempting to establish on thick gravel, multiple fertilizations usually are necessary to maintain plant productivity (Kidd and Jorgenson 1992). If the soil is loamier in origin and has some organic material, a single application of fertilizer may be all that is necessary. A single fertilization also may be warranted if trying to encourage colonization of native shrubs is a priority.

SOIL CONDITIONERS

Depending on the origin and composition of the disturbed soil substrate, the addition of soil conditioners may be necessary to ameliorate acidic or alkaline conditions, sodium toxicity, improve the soil microbial flora, or increase the soil-water storage capacity. Most of these amendments are site specific and require an assessment of site conditions to determine the rate and amount of conditioner to apply.

PH ADJUSTMENT

One of the concerns associated with reclaiming mine soils is the generation of acid rock drainage (ARD) that results from the oxidation of iron (Fe) sulfides (e.g., pyrite and sphalerite). This oxidation reduces soil pH, thereby increasing the bioavailability of some heavy metals and affecting nutrient availability for plant growth. High concentrations of available Al (aluminum), and Mn (Manganese), for example, have been shown to be major sources of plant toxicity (Tucker et al. 1987). Although most mines try to develop covers on mine waste to prevent the generation of ARD, neutralizing agents such as lime, calcium carbonate, and sodium or magnesium hydroxide have been used to increase soil pH (Johnson and Hallberg 2005). Although typically very effective, this type of treatment has high operating costs and disposal problems.

Remediation of highly alkaline soils is less common than neutralizing acidic soils, although alkaline soils can similarly increase the solubility of metals such as boron (B), molybdenum (Mb), and selenium (Se) to toxic levels (Tucker et al. 1987). In contrast, however, the solubility of some important plant micronutrient metals such as Fe and zinc (Zn) is reduced in alkaline soils. In some cases, a simple application of fertilizer that includes ammonium (NH_4-N) can increase soil pH by stimulating bacteria to transform the ammonium to nitrate (NO_3-N), thereby releasing hydrogen ions (Horneck et al. 2004). Alternatively, elemental sulfur can be used, although soil texture, moisture, and temperature are important factors to consider (Mitchell and Adams 2000). When elemental sulfur (and sulfuric acid) was added to small plots on an alkaline overburden stockpile in the Kuparuk Oilfield of Alaska (Jorgenson et al. 1990), the application appeared to have little effect on soil alkalinity or plant growth. This may have been attributable to low soil moisture and temperature.

GYPSUM

Gypsum has been applied to reduce the sodium hazards in tundra that was damaged by fire-extinguishing agents (primarily sodium bicarbonate) used during fire-fighting training on a gravel pad in the Kuparuk Oilfield of Alaska (Cater and Jorgenson 1994b). After one month, the sodium adsorption ratio decreased from 3.1 to 2.5, and germination tests indicated that sodium levels (mean = 290 mg/L) were no longer toxic to plants.

MICROORGANISMS

Soil microorganisms have been applied in a soil-water slurry on small germination test plots to inoculate the roots of legumes with nitrogen-fixing *Rhizobium* bacteria (Cater and Jorgenson 1994a). No results are yet available on the effectiveness of this technique, but if nitrogen-fixing bacterial populations can establish in disturbed soils, the need for frequent fertilization could be moderated to some degree. The use of soil transfer for introducing mycorrhizal bacteria also has been tested at a coal mine site in south-central Alaska (Helm and Carling 1992). That study found that *Populus balsamifera* (balsam poplar) cuttings grew taller in plots treated with soil transfer in combination with a phosphorus fertilizer than cuttings in plots treated with fertilizer alone. Mycorrhizae have been shown to be important to plant productivity because they increase soil nutrient availability and moisture by increasing the surface area of plant roots (Linderman 1994). Some evidence also indicates that mycorrhizae help guard against plant pathogens (Duchesne 1994).

WATER ABSORBANTS

Inadequate soil moisture is one of the primary factors limiting establishment of vegetation on mine soil. Mine soil frequently is made up of predominantly coarse gravels, which have little capacity to hold water and promote high rates of evaporation. To increase the water storage capacity of coarse gravel soils, soil amendments such as starch-based polymer absorbents or sandy overburden (which would increase soil moisture by retaining additional water during snowmelt) have been tested on plots in the Kuparuk Oilfield in Alaska (Cater and Jorgenson 1994a). Initial results indicate mean values for soil moisture in the absorbent treatment and overburden were similar to those in an unamended control, but over time these treatments may result in increased benefit.

TOPSOIL ADDITION

To increase the water-storage capacity, nutrient status, and biological activity of disturbed soils, topsoil (a mixture of organic and mineral horizons from tundra soil) has been applied as a soil amendment in several studies (Jorgenson and Cater 1991, Jorgenson and Cater 1992a, Cater and Jorgenson 1994a). Topsoil significantly increased vegetation cover and plant productivity over controls in all of these studies. Unfortunately, topsoil is very limited at most mine sites in the Arctic.

SEWAGE SLUDGE ADDITION

Domestic sewage sludge from mine camp facilities has the potential to improve soil properties on thick gravel fill. Like topsoil, it is composed primarily of organic matter and, thus, has many of the same beneficial properties. In experimental plots, sewage sludge was applied to a thick gravel pad at three different tonnage rates in the Kuparuk Oilfield (Cater and Jorgenson 1994a). Although differences in total organic carbon, and nitrogen and phosphorus were pronounced immediately after application when compared to the control, soil properties did not appear to be improved substantially on a long-term basis. The lack of improvement appeared to be due to application rates that were too low. Factors limiting the application rates of sludge include the low cation-exchange capacity of gravel and concerns over applying excessive amounts of nitrate that can leach into adjacent wetlands. Although groundwater below the plots had concentrations of fecal coliform bacteria and heavy metals that were similar to background levels, nitrate concentrations were three times higher under the sludge-amended plot. Given the lack of topsoil available, sludge could provide an alternative source of organic matter. However, potential adverse impacts of pathogens, heavy metals, and nitrates associated with application of sludge on gravel fill needs to be further evaluated.

VEGETATION ESTABLISHMENT

NATURAL COLONIZATION

Colonization of disturbed sites by species from adjacent undisturbed plant communities has been monitored at a number of locations (Hernandez 1973b, Kershaw and Kershaw 1987, Taylor and Gill 1974, Chapin and Chapin 1980, Jorgenson et al. 1990, Chapin and Shaver 1981, Abele et al. 1984, Everett et al. 1985, Gartner et al. 1983, 1986, Carghill and Chapin 1987, Ebersole 1987, McKendrick 1987, Felix and Reynolds 1989, Kidd et al. 2006), the success of which is dependent on factors such as the nature and type of disturbance, soil characteristics, and the species composition of potential source plant communities. When only the organic tundra mat is disturbed, natural colonization is fairly successful, and can include a variety of herbs, graminoids, and shrubs. On thin (<25 cm thick) gravel fill, natural colonization occurs at a slower rate than on disturbed tundra, but still can comprise a variety of species, primarily herbs (e.g., *Draba* and *Braya* sp.) and graminoids (e.g., *Carex aquatilis* and *Eriophorum* sp.) (Jorgenson et al. 1990). On gravel-fill depths greater than 80 cm, natural revegetation is negligible. If the disturbance is only minor, natural colonization may be preferable over plant cultivation for revegetating disturbed sites where soil properties are favorable, because the colonizing species come from adjacent areas and thus should be better adapted to arctic conditions than are cultivated species.

PLANT CULTIVATION

Research into developing a suite of plant materials for revegetating disturbed lands in the Arctic has been ongoing since the early 1970s (Johnson and Van Cleve 1976; Johnson 1981; Hernandez 1973a; Mitchell and McKendrick 1974a, 1974b), and has undergone considerable evolution over the years since (Vaartnou 1988, Helm 1991, Jorgenson and Cater 1991, Jorgenson and Joyce 1994, Jorgenson et al. 1990, Wright 1990, Wright et al. 1993, Jacobs et al. 1994, Kidd and Jorgenson 1994).

AGRONOMIC CULTIVARS

Many of the first attempts to actively revegetate disturbed areas used commercially available cultivated grasses and legumes as the primary plant material source (Johnson and Van Cleve 1976; Johnson 1981; Hernandez 1973a; Mitchell and McKendrick 1974a, 1974b). A study in the Prudhoe Bay Oilfield evaluated over 100 varieties based on positive laboratory tests (Mitchell and McKendrick 1974b) to determine what species may be applicable. Although many of the species germinated and showed rapid growth, most did not persist beyond the first season. This die-off was primarily due to winter kill. Several grass species, however, did persist up to three years or more and were used through the 1980s (Johnson 1981, Wishart 1988, Evans and Kershaw 1989). These species included *Poa pratensis* (Kentucky bluegrass), *Festuca ovina* (sheep fescue), *Agropyron trachycaulum* (revenue slender wheatgrass) and *Phleum pratense* (climax Timothy). The principal attraction of these species was their ability to establish a rapid cover, their tolerance to low moisture conditions, and their adaptability to short summers and cold winters.

Despite some success, several limitations are associated with using agronomic cultivars for revegetating disturbed lands in the Arctic. First, because agronomic cultivars are not part of the native flora (usually cultivated in more southern latitudes), they tend to be less adapted to the harsh environmental conditions of the Arctic. Second, they generally are dependent on a fairly high level of nutrients and tend to require repeated fertilizations, particularly if they are on gravelly soils with little organic matter (Johnson and Van Cleve 1976, Klebesadel 1966, Jorgenson and Joyce 1994). If repeated fertilization does not occur, the grasses tend to die back, leaving a large amount of above-ground biomass remaining that does not readily decompose. Finally, because they can establish a rapid cover and are very effective at sequestering nutrients, agronomic cultivars tend to competitively exclude natural colonizers (Native Plants 1980, Densmore et al. 1987, Younkin and Martens 1987, Densmore 1992, McKendrick et al. 1993). In situations where the disturbance involves thick gravel fill, however, few native species are able to colonize these areas and competition with cultivars may not be a concern (Jorgenson and Joyce 1994).

NATIVE-GRASS CULTIVARS

The concern over introducing exotic species into the Arctic, and the variable success associated with using agronomic cultivars, has prompted researchers to investigate the use of native-grass cultivars for vegetation rehabilitation (Gill 1974, Vaartnou 1988, Mitchell and McKendrick 1974b, Jorgenson and Joyce 1994). Mixtures of native grasses have been used for several experimental (Klebesadel 1966, Mitchell 1972) and full-scale applications in Alaska oilfields and mine sites (Jorgenson et al. 1990, Wright 1990, Helm 1991, Jorgenson and Cater 1991, Wright et al. 1993, Kidd and Jorgenson 1994, Jacobs et al. 1994), and at mine sites in the northern Yukon and Northwest Territories (Wilson 1987, Hutchinson and Kuja 1988, Dabbs et al. 1989, Maslen and Kershaw 1989) (Table 1). Preliminary results have shown a productive cover can develop fairly rapidly. Results have been best on thick gravel fill where organic topsoil has been applied (Jorgenson and Cater 1991), and on overburden stockpiles where the soil has a high percentage of fines and where permafrost under the thin active layer prevents leaching of nutrients (Jorgenson et al. 1990, Jacobs et al. 1994). Growth of grasses on thick gravel fill without any manipulation of the site or topsoil application has been slower; even after fertilizer was applied the first and third years (Jorgenson and Cater 1992a).

Although native-grass cultivars are more adapted to arctic conditions than their agronomic cousins, the problem of declining productivity over time and the inhibitory effect on natural colonizers are still problems yet to be resolved. However, native-grass cultivars still are a useful tool for establishing rapid cover on disturbed soils, and they may help improve soil properties by increasing soil biological activity, soil moisture, and capturing wind-dispersed plant propagules. To minimize competition with native colonizers, seeding rates at some sites have been reduced to establish a more open cover, thereby encouraging species from adjacent undisturbed areas to colonize.

INDIGENOUS SPECIES

In an effort to more closely restore the plant communities that have been disturbed as a result of mining activities, effort has been put into collecting indigenous plants for use in revegetation experiments (Wein and MacLean 1973, Maslen and Kershaw 1989, Jorgenson and Joyce 1994, PMC 2005, Kidd et al. 2006). With the exception of some grasses, only a few native plants are available at a commercial scale and, thus, most collections tend to be small, localized, and site-specific. The types of plant materials collected include seed, containerized seedlings, cuttings, sprigs, and plugs of the vegetation mat, which generally comprise more than one species (Table 1).

SEED

Seed collection efforts have focused primarily on hydrophylic grasses and sedges (Wein and MacLean 1973, Jorgenson and Kidd 1991, Jorgenson et al. 1992) xerophylic legumes and Wormwood (*Artemisia* sp.) (Moore 1993, Kidd and Jorgenson 1994), and willow (*Salix*) species (Cooper and Beschta 1993, Cooper and Haveren 1994). Preliminary observations of seed germination of these plant groups indicate that the technique is feasible, although germination rates are low (Gartner 1983), growth rates of seedlings are slow, and availability of seed is dependent on how successful seed production is during any one year. Data have not been collected yet, however, to assess adequately the results of those applications, and much needs to be learned about this technique, including: seed handling and storage requirements for optimizing germination, potential germination rates, annual variability in seed production for harvesting, effect of site conditions on germination and growth, and interspecific variation among species.

Two plant groups that are of particular interest to revegetation specialists are legumes and *Artemisia* species (Moore 1993, Kidd and Jorgenson 1994). Legumes are appealing for their association with nitrogen-fixing bacteria and potential contribution to long-term productivity. They also appear to be well adapted to gravelly soils with low soil moisture and little organic matter. *Artemisia* also tolerates xeric soils and is an attractive food source for caribou and arctic ground squirrels (J. Kidd, per comm.). Tilesy sage (*Artemisia tilessi*) is currently available through PMC for breeding and field testing.

To address the growing need for the availability of native species on a commercial scale, the Alaska Plant Materials Center (PMC) initiated a project in 1999 referred to as the Native Plant Commercialization Evaluation Project (PMC 2005). The project was designed to evaluate the feasibility of producing a variety of native species at a scale available for landscaping and revegetation needs associated with transportation and resource extraction projects. Species being

Table 1. Plant species planted by various methods for rehabilitating disturbed lands in the Arctic. Taxonomy follows Hultén (1968); common names derived from Viereck et al. (1992) or the Natural Resources Conservation Service Plant Database.

Species (common name)	Natural Colonization	Seed	Stem Cuttings /Bulbils	Sprigging	Sod Transplanting
Graminoids					
Native Grass-cultivars[a]					
Arctagrostis latifolia (polargrass)	*	*			
Bechmannia syzigachne (sloughgrass)		–			
Calamagrostis canadensis (bluejoint)	*	–			
Deschampsia caespitosa (tufted hairgrass)	*	*			
D. beringensis (Bering hairgrass)		–			
Elymus macrourus (thickspike wheatgrass)		?			
Festuca rubra (red fescue)	*	*			
Poa alpina (alpine bluegrass)		*			
P. glauca (tundra bluegrass)	–	*			
Puccinellia borealis (boreal alkaligrass)		–			–
Trisetum spicatum (spike trisetum)	*	*			
Indigenous					
Alopecurus alpinus (alpine foxtail)	*	–			
Arctophila fulva (Arctic pendant grass)	*			*	
Carex aquatilis (water sedge)	*	*			*
Dupontia fisheri (Fisher's tundra grass)	–	*			–
Elymus arenarius (dunegrass)	–	?		–	
Eriophorum angustifolium (tall cottongrass)	*	*			*
E. scheuchzeri (white cottongrass)	*	*			*
Festuca altaica (fescue grass)		?			
F. baffinensis (Baffin fescue)	*				
Luzula arcuata (curved woodrush)		?			
Luzula sp. (woodrush)	–				
Poa alpigena	*				
Poa arctica (arctic bluegrass)	–				
Puccinellia langeana (tundra alkaligrass)	*	–			–
P. phryganodes (creeping alkaligrass)	–				
Forbs					
Artemisia arctica (Arctic wormwood)	*	*			
A. tilessi (tilsey sage)		?			
Astragalus alpinus (alpine milk vetch	–	*			
Braya purpurascens (rockcress)	*				
Cerastium beeringianum (Bering chickweed)	–				
Cochlearia officinalis (scurvy grass)	*				
Descurainia sophioides (northern tansymustard)	–				
Draba sp. (mustard)	*				
Epilobium latifolium (river beauty)	–	–			
E. angustifolium (tall fireweed)	–	–			
Hedysarum alpinum (alpine sweet-vetch)	*	*			

Table 1 continued.

Species	Natural Colonization	Seed	Stem Cuttings /Bulbils	Sprigging	Sod Transplanting
H. mackenzii (northern sweet-vetch)	*	*			
Oxyria digyna (mountain sorrel)		?			
Oxytropis borealis (boreal oxytrope)	*	*			
O. campestris (field locoweed)	-	–			
O. deflexa (deflexed oxytrope)	*	*			
O. nigrescens (blackish oxytrope)	–	–			
O. viscida (viscid oxytrope)	*	*			
Polemonium acutiflorum (tall Jacob's ladder)		?			
Polygonum viviparum (alpine bistort)			?		
Sagina intermedia (snow pearlwort)	–				
Saxifraga oppositifolia (purple mountain saxifrage			?		
Solidago multiradiata (goldenrod)		?			
S. decumbens (dwarf goldenrod)		?			
Tripleurospermum phaeocephalum (false mayweed)	–	?			
Shrubs					
Arctostaphylos uva-ursi (kinnikinnik bearberry)			?		
Cassiope tetragona (four-angled cassiope)			?		
Dryas integrifolia (entire-leaf mountain-avens)	-	?			–
D. octopetala (white mountain-avens)		?	?		
Empetrum nigrum (crowberry)			?		
Salix alaxensis (feltleaf willow)	–		*		
S. arctica (Arctic willow)	–		–		–
S. ovalifolia (ovalleaf willow)					
S. planifolia (diamondleaf willow)	-		–		–
S. polaris (polar willow)			?		
S. richardsonii (Richardson's willow)			*		
Vaccinium vitis-idaea (mountain-cranberry)			?		

[a] Species that are natural colonizers are indigenous stock
* Commonly found or used, - uncommon, ? under evaluation.

evaluated include grasses, sedges, forbs, and shrubs that occur throughout the state, in a variety of habitats. As a result of this effort, several native grasses and forbs are available through the PMC as breeder and foundation seed (for testing) and/or the Alaska Seed Growers, Inc. (for application).

CONTAINERIZED SEEDLINGS

Germinating seeds and growing seedlings in a greenhouse before planting has not generally been used as a revegetation technique because of the expense in maintaining a greenhouse and the logistical constraints associated with most sites requiring rehabilitation in arctic Alaska and Canada. A study conducted in Denali National Park evaluated ten species (grasses, forbs, and shrubs) for use in revegetating areas in the Park disturbed by construction activities (Densmore and Holmes 1987). Survival after one year was high for all species planted, but their long-term survival is yet to be determined. For small-scale disturbances or critical habitat areas, containerized seedlings may be warranted, but because little research has been done on their potential as compared to other methods, they probably would not be practical for large areas.

CUTTINGS AND SPRIGS

Revegetation with cuttings only has been done for woody shrubs and a few tree species (Epps 1973, Densmore et al. 1987, Jorgenson and Cater 1991, Kidd and Jorgenson 1994, Helm 1994). Their potential for use in revegetation studies has not been fully evaluated but initial results are encouraging. Some of the factors affecting establishment and long-term survival of cuttings are season of collection, plant competitors, planting media, and climatic conditions. Survival appears to be greater when cuttings are obtained as early in the spring as possible, which allows them enough time to develop overwintering buds (Densmore et al. 1987). A moderate-to-high cover of cultivated grasses affects survival, as the grasses are more effective at capturing soil nutrients than the cuttings (Densmore et al. 1987, Helm 1994). A gravel substrate in a low precipitation area also may affect cutting survival, especially during initial establishment. Finally, if cuttings are planted in windy areas that lack snow cover in winter, mortality may occur from wind desiccation (Kidd and Jorgenson 1994).

For sprigs, *Arctophila fulva* (Arctic pendant grass) has been used for experiments in establishing wetland vegetation (Moore 1991, Moore 1993, Jorgenson et al. 1992, Kidd et al. 2004), and has proven to be highly amenable to transplanting, even into fairly nutrient-poor, gravelly substrate (Jorgenson et al. 1993). At most study sites where *Arctophila* has been planted, additional tillers are present usually within the same growing season. The main limiting factor is the intense grazing some of the young plants experience, which includes both removal of biomass and uprooting (Jorgenson et al. 1992). Although more expensive than seeding, this technique has proven to be reasonably cost-effective because of the colonizing ability of this species. Further research with other wetland species may identify additional candidates for sprig transplants.

PLUGS AND TUNDRA MATS

Revegetation using plugs and tundra mats of undisturbed vegetation has been tested at several sites and has appeal because usually more than one species is contained in a single plug. Thus, the potential for colonization of a disturbed area by a variety of species is much greater. Several studies using tundra plugs have conducted in the Prudhoe and Kuparuk oilfields of Alaska as part of wetland restoration and land rehabilitation efforts (Jorgenson and Joyce 1994, Kidd et al. 2004, 2006). The species present in plugs come primarily from moist and wet tundra and include *Carex aquatilis* (water sedge), *C. bigelowii* (Bigelow sedge), *Eriophorum* sp. (cottongrass), and *Salix* sp. (willows). The plugs usually were planted in an organic substrate, although shallow depths of gravel were present at the surface. At one location, plugs were planted in a thick gravel substrate (Jorgenson and Joyce 1994). Survival of the plugs has been quite high, but lateral expansion has been limited.

Transplant of tundra mats has been tested in the Kuparuk and Prudhoe Bay oilfields in Alaska, Tuktoyuktuk in Northwest Territories, and Rae Point, Melville Island, Canada. The first attempt in Alaska (in the Kuparuk Oilfield) was a complete failure as the tundra was in a frozen state and was very difficult to excavate (Jorgenson 1992). The attempt was aborted after the excavating equipment was severely damaged. Preliminary results from a more recent effort implemented for promoting tundra recovery following an oil spill in the Prudhoe Bay Oilfield are more encouraging (ABR, Inc. and BP Environmental Studies Group 2006). The experiment at

Tuktoyuktuk also was more successful, with vegetation recovery accelerated in those areas where the tundra mat was placed as compared to those areas where the mineral substrate was left to be colonized naturally (Younkin and Martens 1985). However, composition of the soil in the disturbed area was such that natural recovery was still possible, albeit at a slower rate. Tundra replacement at Rae Point was largely unsuccessful because the mat was placed in a very wet area, resulting in much of it becoming submerged. In addition, the area where the tundra was removed had subsided and vegetation was composed primarily of mosses. Because of expensive logistical costs and limited areas available for excavating tundra mats, it is unlikely this method will become more commonplace. Like containerized seedlings, however, it may be recommended when specific habitats are targeted for restoration. In addition, logistical costs can be lowered if the tundra surface is stockpiled as part of construction efforts. Stockpiled material was the source used for successful revegetation of the tundra disturbed by an oil spill in the Prudhoe Bay Oilfield.

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