Site Characteristics and Plant Community Development Following Partial Gravel Removal in an Arctic Oilfield

Authors: Kidd, Janet G., Streever, Bill, and Jorgenson, M. Torre

Source: Arctic, Antarctic, and Alpine Research, 38(3) : 384-393

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2006)38[384:SCAPCD]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 38, No. 3, 2006, pp. 384–393

Site Characteristics and Plant Community Development Following Partial Gravel Removal in an Arctic Oilfield

Janet G. Kidd‡*
Bill Streever† and
M. Torre Jorgenson§*

*ABR, Inc.—Environmental Research & Services, P.O. Box 80410, Fairbanks, AK 99708, U.S.A.
†BP Exploration (Alaska), Inc., P.O. Box 196612, Anchorage, AK 99519-6612, U.S.A.
streevbj@bp.com
‡jkidd@abrinc.com
§tjorgenson@abrinc.com

Abstract

This paper describes the results of a revegetation experiment involving partial removal of gravel fill followed by various revegetation treatments on five sites in the Prudhoe Bay Oilfield on Alaska's Arctic Coastal Plain. Gravel fill was removed to a residual thickness of approximately 25 cm. Revegetation treatments were transplanted tundra plugs and fertilizer; seeding with indigenous graminoids and fertilizer; seeding with native-grass cultivars and fertilizer; fertilizer only; and no treatment. We monitored surface stability, soil characteristics, and vegetation response from 1990 to 2003. Thaw settlement of 17–40 cm occurred over most areas (with >1 m over areas with ice wedges) between 1990 and 1997; sites had mostly stabilized by 2003. Soil properties important for plant growth generally were poor. The establishment of vegetation dominated by indigenous species was similar when adding only fertilizer as compared to also adding plant materials. Although total live vascular cover was similar among fertilized, tundra-plug transplant, and indigenous graminoid seed treatments (26.1–38.3%), species richness was highest for the indigenous graminoid seed and tundra-plug transplant treatments. The results from this study will drive decisions about planting and fertilization schemes for future North Slope rehabilitation projects.

Introduction

The Arctic Coastal Plain on Alaska's North Slope is covered by tundra that ranges from dry to very wet, with numerous lakes and ponds. Poor drainage is a result of the impermeable layer of permafrost that underlies the tundra at depths of about 1 m or less. Vegetation is dominated by wetland plant communities. Development facilities are typically built on a 1.5-m-thick layer of gravel fill that minimizes heat transfer to the underlying permafrost and reduces thermokarst (Walker et al., 1987). More than 3640 ha of gravel fill have been placed for roads, runways, and pads that support infrastructure in the North Slope oilfields (Aeromap, 2002; National Research Council, 2003).

As the oilfields age, some exploratory well sites, gravel roads, and other gravel-fill areas are no longer needed and are being decommissioned. Over the past 30 years, research has been conducted to develop ways to rehabilitate these decommissioned sites to support vegetation or serve other ecosystem functions (e.g., Mitchell, 1979; Moore and Wright, 1991; Jorgenson, 1997; Jorgenson and Joyce, 1994; Jorgenson et al., 1995; McKendrick, 1997, 2000; Streever et al., 2003; Kidd et al., 2004). Techniques assessed include planting on top of thick gravel, total gravel removal followed by planting, partial gravel removal followed by planting, and contouring of gravel to form snow berms and wind breaks followed by planting (e.g., McKendrick, 1991; McKendrick et al., 1992; Jorgenson et al., 1993, 2003).

Two of the principal challenges to establishing wetland plant communities after gravel removal are (1) limiting the extent to which thermokarst occurs, and (2) developing techniques for facilitating establishment of plant communities dominated by indigenous plant species. In undisturbed settings, tundra vegetation maintains a reasonably stable thermal regime through a combination of insulation, reflectance, and evapotranspirative cooling. As a result, removal of gravel that exposes tundra where vegetation has been killed often leads to thermokarst. Also, because the weight of gravel fill often compresses underlying tundra soil (Kidd et al., 2004), when the gravel is removed a depression remains that promotes the impoundment of water, which accelerates thermokarst by conducting and convecting heat away from the ground (Hopkins, 1949).

This paper describes surface elevation changes, soil characteristics, and plant community development on two to five plots at each of five sites where gravel fill approximately 1.5 m thick was partially removed, leaving a residual thickness of 25 cm, and where three planting methods were tested, along with fertilization. Following planting in 1990, we monitored in 1991, 1997, and 2003 (1) changes in surface topography and permafrost depth; (2) physical, chemical, and biological characteristics of the soil; (3) cover of vascular and non-vascular vegetation and spread of transplanted tundra plugs; and (4) taxonomic richness of indigenous plant species.

Materials and Methods

STUDY AREA

The five study sites are located in the Prudhoe Bay Oilfield, which is located on the eastern coastal plain of the North Slope of Alaska (Fig. 1). The landscape in the Prudhoe Bay area has been greatly influenced by permafrost processes, eolian deposition of silts and sands derived from the Sagavanirktok River delta, and coastal erosion and deposition (Walker, 1985). Permafrost has resulted in numerous lakes (commonly referred to as "thaw" lakes) interspersed with patterned-ground features such as high- and low-center polygons, frost boils, and pingos, as well as relatively uniform, undifferentiated flat plains. The vegetation is dominated by wet sedge meadows, *Arctophila* marshes, and moist sedge–dwarf shrub tundra. The five study sites were built between 1968 and 1977 by placing gravel pads about 1.5 m thick on top of tundra using gravel from the floodplain of the Sagavanirktok River and from two nearby mine sites.

TREATMENT LAYOUT

Gravel was partly removed from the five study sites in winter (1988–1989), leaving a residual gravel thickness of approximately

1523-0430/06 $7.00

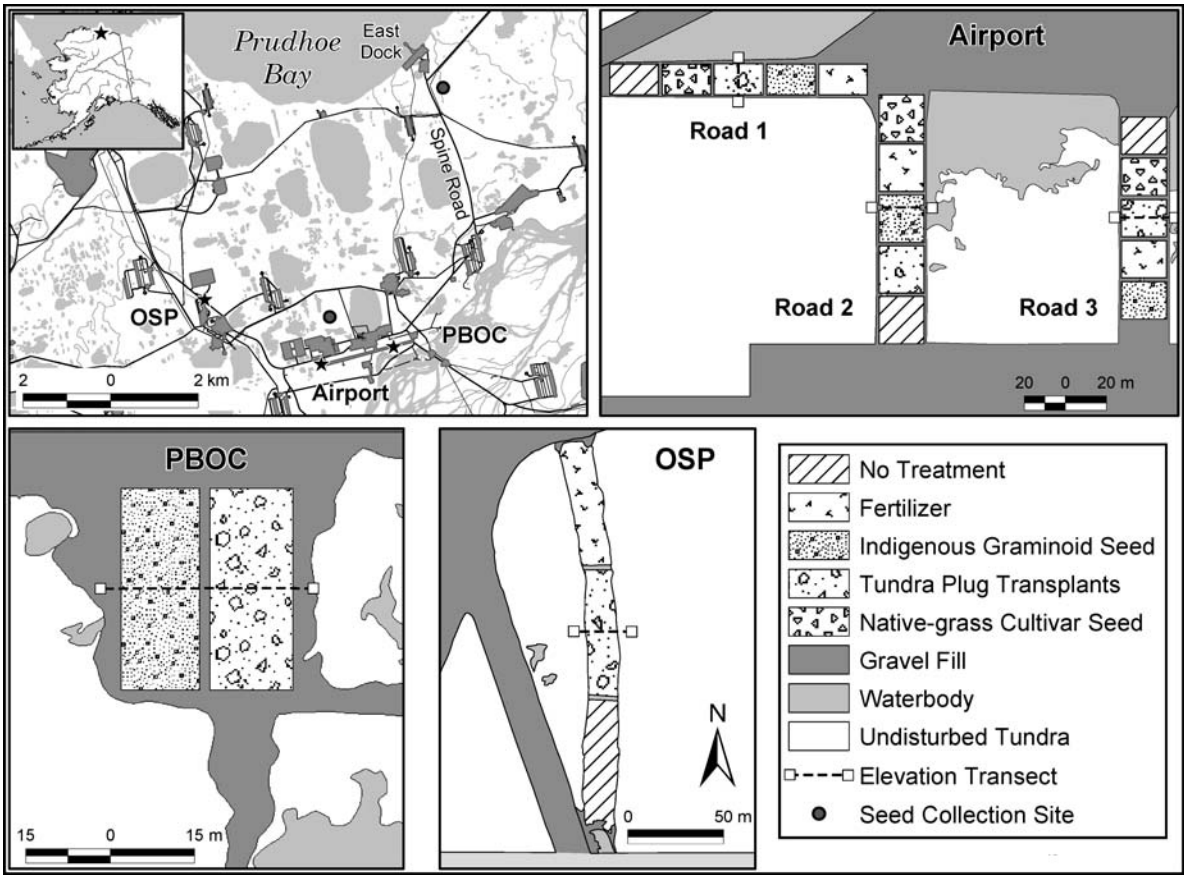

FIGURE 1. Layout of plant cultivation treatments at five gravel removal sites, Prudhoe Bay Oilfield, Alaska, 2003.

25 cm. To test the effectiveness of plant cultivation in promoting the establishment of wetland plant communities following partial gravel removal, three to five plots were established on each of the five sites. One of the following treatments was applied on each plot (Fig. 1): (1) fertilization only; (2) tundra plug transplants and fertilizer; (3) seeding with indigenous graminoids and fertilizer; (4) seeding with commercially available native-grass cultivar seeds and fertilizer; and (5) no treatment.

All of the plots at the Airport site had comparable dimensions (~22×26 m; 0.06 ha), with slight differences due to the total length of each road (120–160 m); the five treatment plots were divided equally within each road. Only two treatment plots (14×36 m; 0.05 ha) were applied to the Prudhoe Bay Operations Center PBOC site (Fig. 1). The three plots established at the OSP site were 15×57 m in size (0.09 ha). Differences in area of plots and the unbalanced application of treatments reflect differences among sites in the area available and conditions after gravel removal. For example, flooding in the spring following gravel removal at the OSP site precluded applying the treatments involving seed mixes. For those plots treated with fertilizer, a mixture of 8-32-16 (N-P-K) was applied at a rate of 400 kg ha^{-1} in mid-June 1990 using a hand spreader.

The tundra plug transplants were collected from wet sedge meadow tundra adjacent to the sites in mid-June 1990. The plugs consisted predominantly of the wetland sedges *Carex aquatilis* and *Eriophorum angustifolium*, although the shrubs *Salix planifolia* and *S. reticulata* also were commonly present. The plugs (dimensions approximately $15 \times 15 \times 30$ cm [$l \times w \times d$]) were collected using a post-hole digger and spade and were planted in plots approximately 1 m apart. The objective of transplanting the tundra plugs was to provide islands of tundra vegetation that would expand to fill in adjacent areas and serve as seed sources for establishing indigenous species.

The indigenous graminoid seed mixture was collected in late August 1990 from a wet sedge meadow approximately 80 km south of Prudhoe Bay (next to the Dalton Highway at MP 367), and from coastal graminoid and wet sedge meadows behind PBOC and along the Spine Road going toward East Dock in the Prudhoe Bay Oilfield, respectively (Fig. 1). To enhance seed production prior to harvesting in August (Chapin and Chapin, 1980), the Dalton Highway and East Dock seed collection sites were fertilized in June 1990 with a 10:1 mixture of 8-32-16 and 20-20-10 (N-P-K) applied at 200 kg ha^{-1}. We suspected the PBOC site received nutrients from an adjacent sewage lagoon, so this area was not fertilized before seed collection. The dominant species in the seed mixture were *Carex aquatilis*, *Eriophorum angustifolium*, *Dupontia fisheri*, and *Hierochloë pauciflora*. The seeds were harvested using a portable gas-powered weed trimmer equipped with an aluminum collecting chamber and cotton bag (Grin Reaper™, Environmental Survey Consulting, Austin, Texas). The seed and chaff of each species were combined and air-dried before they were manually applied to the plots in late August 1990. We did not quantify the percentage of each species; rather, we broadcast approximately equal volumes of seed and chaff (approximately 10 kg) in each designated plot.

The native-grass cultivar seed was a mix of species obtained from commercial growers in Alaska and had the following component percentages by weight: 28% *Festuca rubra* (Arctared Fescue–Palmer), 29% *Poa glauca* (Tundra Bluegrass–Fairbanks), 13% *Arctagrostis latifolia* ("Alyeska" Polargrass–Trapper Creek), and 11% *Beckmannia syzigachne* ("Egan" American Sloughgrass–Palmer), and 19% *Deschampsia beringensis* ("Norcoast" Bering Hairgrass–Fairbanks). With the exception of *D. beringensis*, the seed stock came from collections along the Dalton Highway and Sagwon Bluffs in northern Alaska, but was cultivated in south-central and interior Alaska to maximize seed production. The *D. beringensis* is a coastal species and was collected in southwestern Alaska. It is closely related to *D. caespitosa*, which occurs in mesic environments in the Arctic but was not available commercially when this study was initiated.

Seed mix was broadcast in mid-June 1990 at 33 kg ha^{-1}. Although the long-term goal of this study is to establish plant communities dominated by indigenous wetland species, there are no commercial sources for seed of such species. At a minimum, we expected that the grass cover would improve organic matter content over time through decomposition, improve soil biological properties, help trap seed of adjacent tundra wetland species, and provide habitat for wildlife in the short term. Over the long term, we expected the grasses to facilitate establishment of vegetation dominated by wetland tundra species.

MONITORING

Ground Surface Elevations

We monitored the elevation of the ground surface within the gravel removal areas by surveying along permanent transects oriented east-west across each pad or road and extending 5 m into the tundra on either side (Fig. 1). We recorded the elevations at 1-m intervals using an autolevel and survey rod, and calculated the elevation relative to the mean elevation of the adjacent undisturbed tundra at each site. The elevations were recorded in 1990, 1997, and 2003. Thaw depths also were recorded along the transects in 1997 and 2003 at 2- and 5-m intervals, respectively, using a metal probe. In 1991, thaw depths were recorded in the vegetation sampling quadrats. Thaw depths also were recorded in 1991 in undisturbed wet sedge meadow tundra adjacent to the Airport sites to compare with the gravel removal areas.

Soil Properties

In 1991, we collected a total of four soil samples (at two of the three Airport sites and at each of the other sites) to assess the baseline physical and chemical characteristics of the residual gravel substrate. We did not collect soil samples from the individual treatments because there was no reason to expect differences among treatments in this initial phase of the study. In 1997 and 2003, we collected samples within each treatment (three to five samples, depending on the number of treatment blocks). Each sample was a composite of three "grab" samples collected at a depth of 4 to 10 cm below the gravel surface. Based on personal observation, this was the primary rooting zone. In addition, one sample was collected for descriptive purposes in 2003 from the upper 2 to 3 cm of the soil column (just below the moss layer) in the fertilized treatment at the Road 1 Airport Site.

The soil samples were air-dried at room temperature and ground through a sieve to separate the coarse fraction (>2 mm diameter) from the fine-earth fraction (<2 mm diameter). Parameters measured included total organic matter and carbon, pH, electrical conductivity, cation exchange capacity, and available nutrients and cations. Laboratory analyses are reported on an oven-dried basis (105°C) using only the fine-earth fraction (silt, sand, and clay), but final results for most chemical properties (except pH, electrical conductivity, cation exchange capacity) are expressed on a whole sample basis including the gravel fraction, which is assumed to be inert. The analyses were performed using standard methods (Page et al., 1982; Klute, 1986) by the Soil, Water, and Plant Testing Laboratory, Colorado State University, Fort Collins, in 1991, and by the Agricultural & Forestry Experiment Station, University of Alaska, Palmer Research Station, in 1997 and 2003.

As an indirect measure of soil biological productivity in each plant cultivation treatment, we collected three soil samples within each treatment at each location in 1997 and 2003 to assess total fungal and bacterial biomass. These samples were collected in a manner similar to that described for the physical and chemical analyses. To minimize changes to the microbial populations during transit, the samples were immediately shipped under refrigeration to the laboratory for analysis. In addition, five samples were collected for comparison from undisturbed tundra adjacent to the sites near the Airport. Fungal biomass was determined by measuring hyphal length and diameter, while bacterial biomass was measured using plate counts (Schmidt and Paul, 1982). Soil Foodweb, Inc., Corvallis, Oregon, processed the samples.

Vegetation Response

To monitor vegetation response, we sampled vegetation cover in five permanent 1-m^2 quadrats placed randomly in each treatment plot at each of the five gravel-removal sites. Vegetation cover was estimated in the quadrats in 1991, 1997, and 2003 generally using the point-frame method (Barbour et al., 1980). Plant species were recorded at 20-cm intervals below cross-hairs within a 1-m^2 point-frame, for a total of 50 points per quadrat. Thus, each point within a quadrat represented a cover value of 2%. If several plant parts of one or more species overlapped at a given point, each occurrence was recorded, thus generating a repetitive cover value that could exceed 100%. In 1997, cover of submerged aquatic forbs at the OSP site had to be recorded using ocular estimates; the water became too turbid upon approaching the quadrats to record hits using a point-frame. Species found within the treatment plots but not recorded as a point also were recorded as trace cover. Taxonomic identification was primarily for vascular plants and the nomenclature follows Hultén (1968).

To determine whether the transplanted tundra plugs expanded in size over time, we measured the total area (length × width) of plugs either inside of, or within 0.5 m of vegetation quadrats in 1997. The initial mean plug area (1990) was assumed to be 0.02 m^2, based on transplanting plug dimensions of 0.15 × 0.15 m. Meaningful plug-area measurements could not be collected in 2003 because many plugs had coalesced at the Airport and PBOC sites.

Results and Discussion

Changes in surface elevation of the gravel removal areas were highly variable across the five sites, ranging from virtually no change between 1990 and 2003 at the OSP site to the development of deep troughs and surface settling typically ranging from 17 to 40 cm at PBOC and Road 2 of the Airport sites (Fig. 2). Overall mean thaw settlement was 20 cm, with a maximum of 136 cm (1.4 m). The mean ground-surface elevation of the Road 2, OSP, and PBOC sites was 3–9 cm below tundra grade in 2003, but the two remaining sites were slightly above tundra grade (9–10 cm). Comparing the 1997 and 2003 profiles, it appears that most of the thaw settlement occurred between 1990 and 1997, although a few troughs that were slightly visible in 1997 deepened considerably by 2003, particularly on Road 2 and at PBOC. The mean depth of the active layer for all sites increased from 87 ± 1 cm in 1991 (n = 116) to 96 ± 7 cm (n = 31) in 2003, although thaw depth was highly variable among sites (Fig. 2). At the OSP site, the mean active layer depth was thinner in 2003 (66 ± 10 cm, n = 4) than in 1997 (84 ± 3 cm, n = 7), suggesting the thermal regime has started to stabilize at this site. Nevertheless, the active layer depth of all the sites in 2003 was typically more than twice that found in undisturbed wet sedge meadow tundra (44 ± 3 cm, n = 14).

The thinner layer of gravel fill and subsequent thaw settlement and deepening of the active layer in the gravel removal areas has had at least three hydrological effects that probably influence vegetation response. First, the settlement of sites below tundra grade has made them more susceptible to flooding, so that with the exception of Road 3 and PBOC, much of the surface of the remaining sites is inundated.

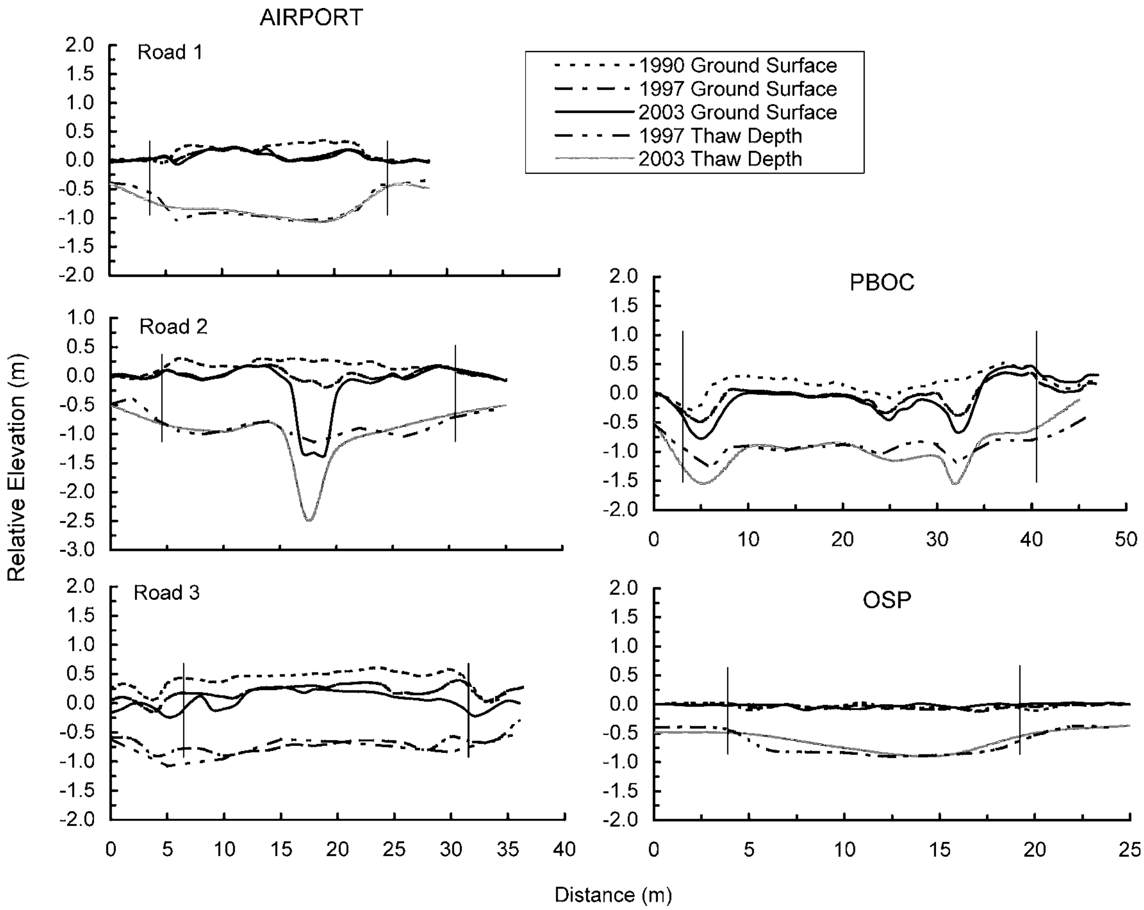

FIGURE 2. Ground surface and thaw depth profiles across gravel removal areas (mid-point), 1990, 1997, and 2003. Brackets indicate boundaries between adjacent, undisturbed tundra and gravel removal area.

In some areas, the water is more than 1 m deep. However, the subsidence, in combination with reduced gravel thickness, also has encouraged establishment of wetland hydrology, which is helping to promote wetland vegetation.

Second, the deep polygonal troughs that developed in some areas accelerated thermal erosion and increased the area occupied by deep ponds. The ponds are deep enough that plant colonization is limited to their margins, but the polygons are reconnecting with the polygonal network in the adjacent tundra. The result is visual integration with the surrounding tundra landscape (Fig. 3). The hydrologic connection with adjacent tundra plant communities also provides a means of input for nutrients, dissolved organic matter, and floating seeds.

Third, the persistence of a deep active layer indicates that the sites have yet to begin developing a thermal equilibrium comparable to that of undisturbed tundra soils; consequently, the sites may continue to subside and thermokarst indefinitely. If subsidence continues, the sites may become permanent deep ponds that keep out most plant species. However, with the exception of a few isolated locations, the 1997 and 2003 thaw-depth profiles are similar, and we suspect that any additional thermokarst will be limited. Also, the deeper active layer, which indicates that soil temperatures are higher at depth than in the adjacent tundra, provides for a deeper plant rooting zone and a potentially greater nutrient pool.

SOIL PROPERTIES

Physical and Chemical Characteristics

The soil physical and chemical characteristics of all the treatment areas in 2003 were largely unchanged from those measured in 1991 and 1997 (Table 1). Overall, soil properties were poor for supporting plant growth. The soil texture was still primarily gravel and sand, but the high percentages may reflect the loss of silts and clays during sampling; most of the surface was inundated in 2003 so it was difficult to retrieve samples without losing fine particles as the sample passed through the water column. Organic matter content, available nitrate, ammonium, and phosphorus were low in all years. An increase in soil pH from 7.7 in 1991 to 7.9–8.1 in 2003 probably reflects the origin of the gravel substrate (Put 23 and Put 25 mine sites), where carbonates associated with soils near the Putuligayuk River tend to drive pH upward (Walker, 1985). Electrical conductivity was within the range for non-saline soils (Brady and Weil, 2002). For exchangeable cations, all values except calcium were low in both 1991 and 2003, and calcium was lower in 2003 than in 1991. Cation exchange capacity also was very low. The relatively unchanged condition of soils in all treatments illustrates the slow development of soils in an arctic environment. It will likely take many more decades before soil properties begin to change measurably at any of the sites, given the slow rate of decomposition and organic matter accumulation in the Arctic (Oechel and Billings, 1992).

For the soil sample collected from the upper 2 to 3 cm in the fertilized treatment of Road 1 in 2003, the soil texture was predominantly sand, with comparable percentages of gravel, silt, and clay (Table 1). Organic matter content and available nutrients were low, but were slightly higher than in the subsurface samples described above. Concentrations of cations in the near-surface soil were several orders of magnitude higher than in the samples described above. These results suggest that the surface soil layer is developing characteristics more conducive to plant community development than the underlying

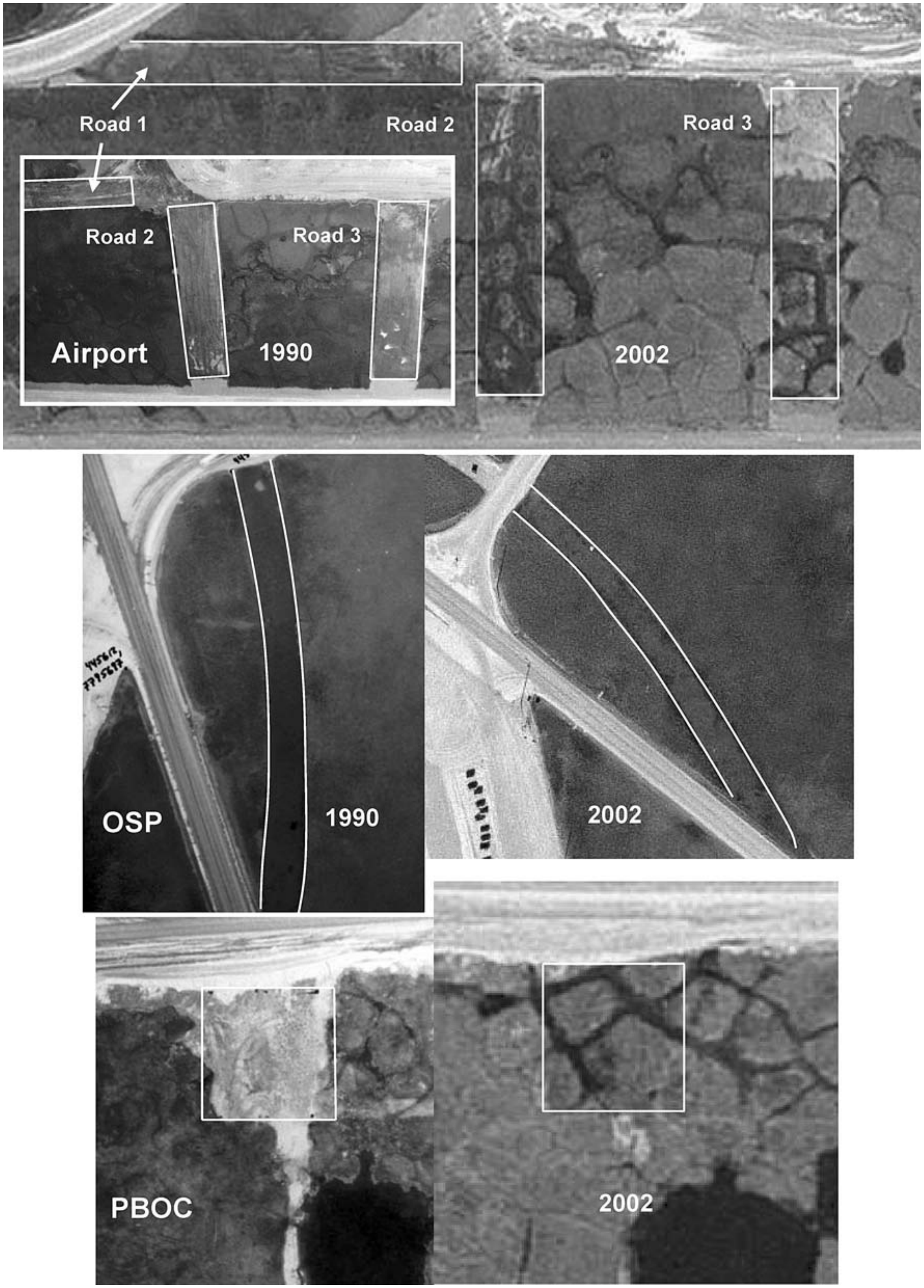

FIGURE 3. View of sites after gravel removal in 1990 and 2002.

soils, where conditions are still similar to those immediately following partial gravel removal.

Microbial Characteristics

Mean values for soil bacterial and fungal biomass were higher among all the treatments (and no treatment plots) in 2003 compared to 1997, but the increase also was observed in the adjacent undisturbed tundra (Fig. 4). The most notable change from 1997 to 2003 was that mean bacterial biomass in the plant cultivation treatments increased to levels comparable to those in the adjacent undisturbed tundra. Mean fungal biomass, however, was substantially lower in the plant cultivation treatments (and no treatment) than in the adjacent undisturbed tundra sampled.

TABLE 1

Mean (± SE) physical and chemical properties of thin gravel fill in four revegetation treatments (and "No treatment" control), Prudhoe Bay Oilfield, Alaska, 1991 and 2003.

	1991	2003					
	All treatments (n = 5)	No treatment (n = 4)	Fertilized (n = 4)	Tundra-plug transplants (n = 5)	Indigenous-sedge seed (n = 4)	Native-grass cultivars (n = 3)	Soil surface[e]
Physical[a]							
Particle size (%)							
Gravel	63.7 (5.0)	69.7 (7.3)	71.5 (3.6)	67.6 (3.3)	73.4 (3.9)	64.9 (5.2)	14.5
Sand	30.3 (4.3)	27.0 (5.9)	25.7 (3.0)	29.9 (3.3)	24.0 (3.8)	31.7 (4.3)	61.6
Silt	3.3 (0.3)	2.2 (1.0)	1.5 (0.5)	1.7 (0.4)	1.4 (0.3)	1.6 (0.5)	11.6
Clay	2.7 (0.4)	1.1 (0.8)	1.3 (0.4)	0.8 (0.1)	1.2 (0.4)	1.8 (0.6)	12.3
Chemical							
Organic matter (LOI)[b]	0.5 (0.1)	0.3 (0.1)	0.3 (0.1)	0.2 (<0.1)	0.2 (<0.1)	0.3 (0.1)	5.4
pH	7.7 (<0.1)	8.1 (<0.1)	7.9 (<0.1)	8.0 (<0.1)	8.0 (0.1)	8.0 (<0.1)	7.6
EC (dS/m)[c]	1.2 (0.2)	0.5 (0.1)	0.6 (<0.1)	0.4 (<0.1)	0.4 (0.1)	0.4 (0.1)	0.7
CEC (meq/100 g)[d]	2.9 (0.3)	0.5 (0.2)	0.4 (0.1)	0.4 (0.1)	0.4 (0.1)	0.4 (<0.1)	8.2
Exchangeable (mg/kg)							
NH_4-N	0.4 (0.1)	0.2 (<0.1)	0.2 (<0.1)	0.2 (0.0)	0.1 (<0.1)	0.3 (0.1)	1.7
NO_3-N	1.5 (0.1)	0.5 (0.2)	0.4 (0.2)	0.3 (0.1)	0.1 (<0.1)	0.2 (<0.1)	2.6
P	2.9 (1.9)	0.3 (<0.1)	0.7 (0.3)	0.7 (0.1)	1.0 (0.3)	0.8 (0.1)	6.0
K	1.4 (0.2)	4.2 (0.4)	4.4 (0.9)	3.3 (0.4)	3.9 (0.3)	5.4 (1.0)	140.9
Ca	2393.4 (380.1)	1668.6 (230.6)	1620.7 (209.4)	1745.0 (152.1)	1562.4 (272.7)	1953.5 (253.6)	9848.7
Mg	49.2 (7.5)	19.8 (2.4)	15.3 (2.8)	14.1 (1.2)	15.3 (1.8)	19.5 (4.7)	116.8
Na	4.4 (2.1)	9.5 (1.5)	6.3 (0.8)	6.4 (0.9)	5.5 (1.0)	8.9 (3.7)	58.3

[a] All samples expressed on whole sample basis, which includes the >2 mm gravel fraction.
[b] LOI = loss on ignition.
[c] 1 dS/m = 1 mmhos/cm.
[d] CEC = cation exchange capacity, expressed in millequivalents (meq.)/100 g soil.
[e] Sample was collected from developing moss peat layer (0–2 cm below the surface).

Since we have data for only two years and have no data on the seasonality of microbial populations, we are uncertain whether the increases in microbial biomass observed in 2003 reflect a positive trend, but these preliminary results are nonetheless encouraging. Microbial communities play an important role in nutrient cycling (Tate, 1985), and their presence at this early stage of plant community development is an indication of soil biological activity. The low fungal biomass in the plant cultivation treatments (and no treatment) probably reflects the extremely low organic content in these disturbed soils. Fungi are primarily responsible for the breakdown of organic compounds (Paul and Clark, 1996), and thus, we expect their numbers would be high in the more fibric, peaty soils associated with wet sedge tundra.

VEGETATION RESPONSE

Mean total live cover was highly variable among plots and treatments, but all had considerably higher mean total live vascular and non-vascular cover in 2003 than 1991, while cover in the no treatment plots increased only marginally over the same period (Fig. 5). The native-grass cultivar seed treatment had less than half the total live vascular cover (13.1 ± SE 3.6%) of the other treatments in 2003. Cover of non-vascular species among the treatments was comparable. The most dominant indigenous species among all the treatments included *Carex aquatilis*, *Eriophorum scheuchzeri*, *E. angustifolium*, *Utricularia vulgaris*, and *Ranunculus gmelini*.

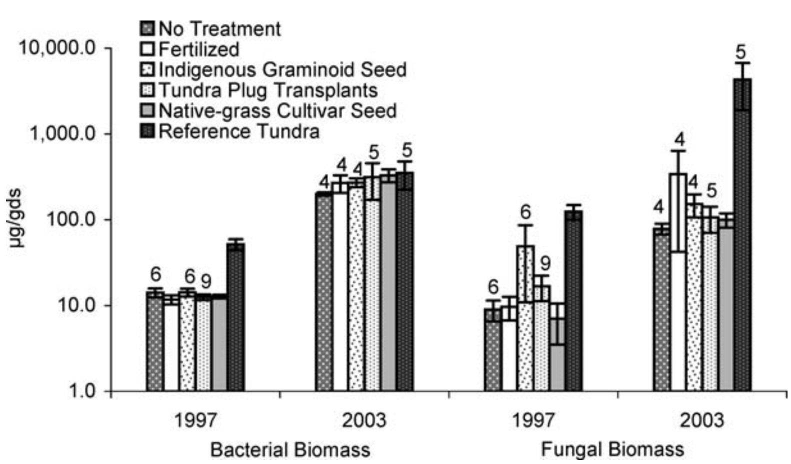

FIGURE 4. Comparisons of total microbial (bacterial and fungal) biomass (mean, ±1 SE, n = 3 unless otherwise noted) among plant cultivation treatments, 1997 and 2003. Biomass ($\mu g\ gds^{-1}$) is expressed under a log scale.

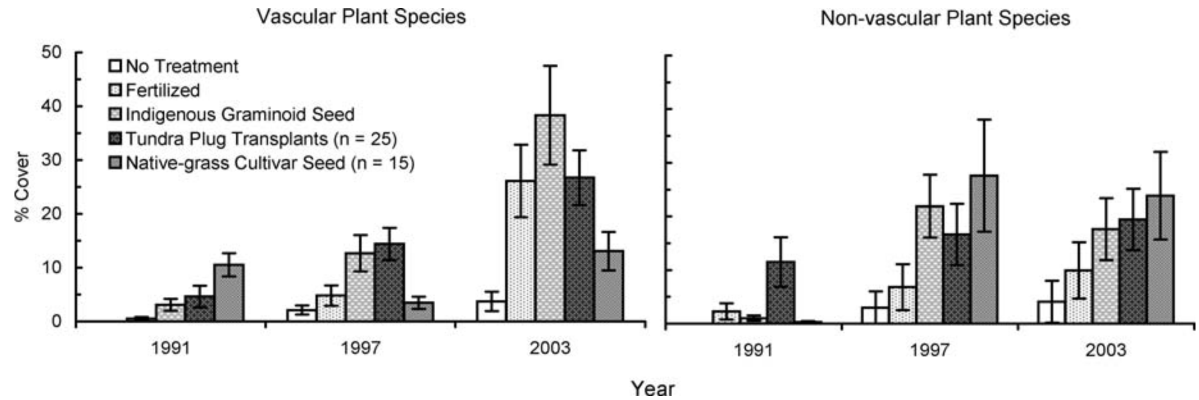

FIGURE 5. Total vascular and non-vascular cover (mean ±1 SE, n = 20 except where noted) among the four plant cultivation treatments and control (no treatment), 1991, 1997, and 2003.

Although non-vascular species made up the majority of the total live cover for all the treatments in 1991 (except the native-grass cultivar seed treatment), cover of indigenous graminoids was dominant in most treatments by 2003 (Fig. 6). Notable exceptions were the no treatment and the native-grass cultivar treatment, where non-vascular cover made up 53 to 65% of the total cover in 2003. The mean proportion of cover made up by native-grass cultivars in the native-grass cultivar seed treatment dropped dramatically between 1991 and 1997, and comprised only 8% of the total cover by 2003. The mean proportion of forb cover was higher in 2003 than previous years in the native-grass cultivar plots, but still only accounted for up to 10% of the total cover. The small amount of cover of native-grass cultivars present in the other treatments is attributed to incidental deposition during seed broadcasting in 1990.

In all treatments, taxonomic richness of indigenous species increased between 1991 and 2003 (Table 2), but the highest number of species (29) occurred in the indigenous graminoid seed treatment, closely followed by the tundra plug transplant treatment (24). Most of the species are commonly found in wetland tundra habitats, but some (e.g., *Alopecurus alpinus*, *Epilobium latifolium*, *Stellaria crassifolia*) are associated with more disturbed and/or gravelly environments (Jorgenson, 1997).

The mean area of the vegetation that spread from the original transplanted tundra plugs among the five sites increased from the initial 0.02 m^2 planting size in 1991 to 0.19–1.00 m^2 in 1997 (Fig. 7). Our inability to identify many of the plug boundaries in 2003 reflects the high degree of lateral expansion that has occurred since the initial planting (Fig. 8). Although we did not evaluate the viability of seed produced from plants within the tundra plugs, the abundant flowering observed suggests the plugs may have acted as a seed source, in addition to producing tillers.

Although mean plant cover was slightly higher in the indigenous graminoid seed treatment than in other treatments, mean cover was comparable for all treatments and was higher than areas where no treatment was applied. The comparable response of all treatments suggests that the main limitation to vegetation establishment was nutrients. The lack of a well-developed plant cover in the no treatment plots after 13 years also supports this assertion. An important benefit of seeding with indigenous graminoids and transplanting tundra plugs, however, was the resulting increase in taxonomic richness. The high numbers of species were due to (1) establishment of targeted species within the indigenous seed mix and tundra plugs, and (2) seed of additional species harvested during the indigenous seed collection or that were present in the soil collected with the tundra plugs.

The relatively poor long-term growth of vascular plants in the native-grass cultivar treatment was unexpected, although a recent study conducted at an abandoned exploratory well site in the Prudhoe Bay Oilfield produced a similar result (Kidd et al., 2004). At both sites, the level of grass cover was low enough (<20%) to minimize competition with natural colonizers, a factor that has reduced natural colonization at sites with denser grass cover (Younkin and Martens, 1987; Densmore, 1992). Perhaps the initial vigorous growth of grass depleted soil nutrients more rapidly than in the other treatments, although this was not apparent in soil analyses. We also considered the possibility that this treatment experienced through random chance a disproportionately higher degree of thermokarst and flooding than the other treatments, with resulting poor site conditions for plant establishment and growth. However, percent cover of water in the

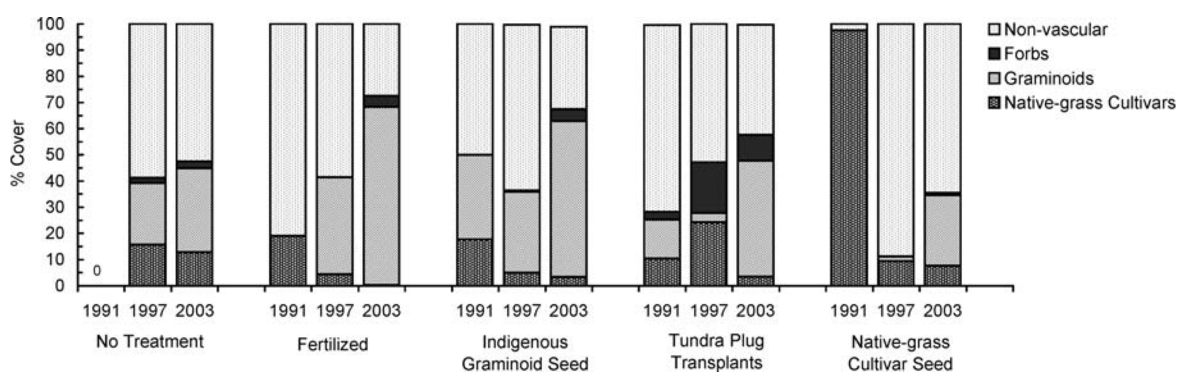

FIGURE 6. Percentages of each life form that make up the total live cover within each plant cultivation treatment, 1991–2003. Shrubs were excluded because they make up <1% of the total live cover.

TABLE 2

List of indigenous vascular species within plant cultivation treatments (and "No treatment" control) at the gravel removal sites in the Prudhoe Bay Oilfield, Alaska, 1991, 1997, and 2003.

	No treatment[a]		Fertilization			Indigenous graminoid seed			Tundra plug transplants			Native-grass cultivar seed		
Species	1997	2003	1991	1997	2003	1991	1997	2003	1991	1997	2003	1991	1997	2003
Forbs														
Artemisia arctica							x		x	x				
Braya sp.			x			x								
Caltha palustris		x		x	x					x				
Cerastium beeringianum								x						
Draba sp.							x	x		x	x			
Epilobium latifolium	x	x					x	x			x			x
Equisetum arvense											x			
Hippuris vulgaris					x		x	x						x
Melandrium apetalum								x						
Parnassia palustris								x			x			x
Pedicularis verticillata								x			x			
Polygonum viviparum											x			
Potentilla hookeriana								x		x	x			
Ranunculus gmelini				x			x	x		x	x			x
R. hyperboreus							x	x						
Sagina intermedia											x			
Saxifraga cernua							x	x						
S. hieracifolia														x
S. hirculus							x	x		x	x			
Stellaria crassifolia					x		x			x	x			
Utricularia vulgaris	x				x			x			x			x
Graminoids														
Alopecurus alpinus		x		x	x	x	x	x	x	x	x			x
Arctophila fulva		x			x			x						x
Carex aquatilis	x	x	x	x	x		x	x	x	x	x	x	x	x
Deschampsia caespitosa		x		x	x		x	x	x	x	x			x
Dupontia fisheri								x			x			
Eriophorum angustifolium	x			x	x		x	x	x	x	x		x	x
E. scheuchzeri	x	x		x	x		x	x		x	x		x	x
Festuca baffinensis	x						x							
F. vivipara							x			x				
Hierochloë pauciflora		x			x			x		x	x			
Juncus arcticus		x		x	x		x	x		x	x		x	x
Poa alpigena				x	x	x	x	x			x			
P. arctica								x						
Puccinellia langeana	x							x		x				
Trisetum spicatum					x	x	x	x		x	x			
Shrubs														
Salix arctica		x			x		x	x	x		x			x
S. ovalifolia		x			x		x	x			x			x
S. richardsonii lanata								x						
S. rotundifolia				x						x				
S. pulchra							x		x					
Total	7	11	2	10	16	4	22	29	7	18	24	1	4	15

[a] No vascular plants were present in 1991.

native-grass cultivar treatment was comparable to that measured in the other treatments. Given that the vascular cover in this treatment was dominated by indigenous sedges and grasses in 2003, we suspect that over time these species will increase in cover to levels comparable to the other treatments. Our current results suggest, however, that seeding with native-grass cultivars does not facilitate natural recovery more effectively than adding fertilizer or applying other plant cultivation treatments on sites cover with a residual layer of thin gravel (overlying tundra). In fact, our results suggest that the seeding effort may delay establishment of indigenous species, a finding that also has been observed at upland tundra sites seeded with grasses south of Prudhoe Bay along the Trans-Alaska Pipeline route (Densmore, 1992; McKendrick, 2002).

We believe the high variability in plant cover within and among treatments is at least in part a function of site heterogeneity. For example, because the OSP site was flooded soon after gravel was removed (Fig. 3), it was not possible to apply the two treatments involving broadcasting of seed. At this site, the ground surface has remained relatively stable, but the gravel removal created a depression that promoted rapid impoundment of water in the area. Although the transplanted tundra plugs have survived, there has been some mortality and they are less well developed than those at the Airport and PBOC

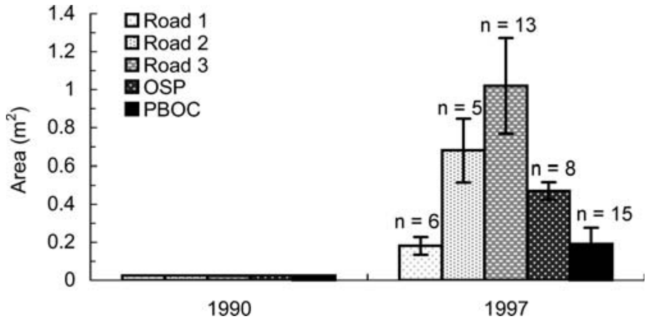

FIGURE 7. Mean area (m^2) of vegetation that spread from each tundra plug transplanted at the Airport, PBOC, and OSP sites, Prudhoe Bay Oilfield, Alaska, 1990 and 1997 (bars are ±1 SE). Plugs had coalesced to such an extent in 2003 that it was not possible to accurately measure their areas.

sites, where only portions of the sites are flooded. At the Airport and PBOC sites, partial gravel removal resulted in the disruption of the soil thermal regime, and deep, flooded troughs formed that are too deep to support most plant species. Consequently, the distribution of plant cover is patchy. The level of inundation and ground surface elevation, however, appear to be stabilizing. Thus, we expect that plant cover will continue to increase in areas that are only saturated or have shallow water depth. The margins of some of the deeper ponds may eventually be colonized by *Arctophila fulva*, a wetland grass that can establish in deeper water than can sedges such as *Carex aquatilis* or *Eriophorum* spp. *A. fulva* was present in trace amounts at both the Airport and OSP sites in 2003.

Conclusions

The results of this study have important implications for future land rehabilitation in the Prudhoe Bay Oilfield and similar settings. First, although thermokarst and thaw settlement occur in response to gravel removal, most of the changes in surface morphology and hydrology occur in the first seven years. In addition, thermokarst and subsequent shallow flooding do not necessarily halt the increase in cover by vascular plants. Second, while soil characteristics below the first few centimeters have not notably changed in more than 10 years, apparent changes in the first few centimeters of soil, as well as increased bacterial biomass at greater depths, suggest that slow changes are occurring. Nevertheless, fertilizer appears necessary to promote plant community development within time frames typically desired for land rehabilitation projects—that is, within 5 to 10 years. Third, the introduction of indigenous plant species, either through seeding or transplanting, does not dramatically increase plant cover compared to adding fertilizer alone, but may result in a higher taxonomic richness that may give emerging plant communities a greater pool of adaptive strategies and therefore greater flexibility to respond to changing site conditions. Finally, rapidly establishing plant cover using native-grass cultivars does not improve site conditions for natural recovery and, in fact, appears to slow the rate of establishment of indigenous species, at least in the time frame meaningful to most land rehabilitation projects.

The degree to which partial or complete gravel removal will be used to rehabilitate oilfield disturbances will be influenced by factors such as cost, the demand for gravel to be used on other projects, permitting requirements, and land use considerations. Nevertheless, it is likely that many abandoned facilities and well sites will be targeted for gravel removal. The results of this study will guide rehabilitation efforts at these sites to more effectively facilitate the establishment of plant communities dominated by indigenous species and to better promote overall vegetation recovery.

Acknowledgments

This study was funded by BP Exploration (Alaska), Inc., and ARCO Alaska, Inc. (now ConocoPhillips Alaska, Inc.). Tim Cater, Summer Andersen, and George Zusi-Cobb provided valuable field assistance and Sue Bishop gave constructive comments on the draft of this manuscript. We also thank Mike Joyce (formerly of ARCO Alaska, Inc.) for his support in the implementation of this study. Two anonymous reviewers also provided helpful comments for improving the quality of the manuscript.

References Cited

Aeromap, 2002: *Calculation of area impacted by oil field development North Slope Alaska*. Report prepared for BP clarifying work done for the National Academy of Sciences, 4 February 2002. Anchorage, Alaska: BP Exploration (Alaska) Inc.

Barbour, M. G., Burk, J. H., and Pitts, W. D., 1980: *Terrestrial Plant Ecology*. Menlo Park: The Benjamin/Cummings Publishing Company, Inc., 604 pp.

FIGURE 8. Comparison of transplanted tundra plugs 1990 (left) and again in 2003 (right), PBOC pad.

Brady, N. C., and Weil, R. R., 2002: *The Nature and Properties of Soils, Thirteenth Edition*. Upper Saddle River: Prentice Hall, 960 pp.

Chapin, S. C., III, and Chapin, M. C., 1980: Revegetation of an arctic disturbed site by native tundra species. *Journal of Applied Ecology,* 17: 449–456.

Densmore, R. V., 1992: Succession on an Alaskan tundra disturbance with and without assisted revegetation with grass. *Arctic and Alpine Research,* 24: 238–243.

Hopkins, D. M., 1949: Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. *Journal of Geology,* 57: 119–131.

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

Jorgenson, M. T., 1997: Patterns and rates of, and factors affecting natural recovery on land disturbed by oil development in arctic Alaska. *In* Crawford, R. M. M. (ed.), *Disturbance and Recovery in Arctic Lands: an Ecological Perspective*. NATO ASI Series 2 Environment, vol. 25. Dordrecht: Kluwer Academic Publishers, 421–442.

Jorgenson, M. T., and Joyce, M. R., 1994: Six strategies for rehabilitating land disturbed by oil development in the arctic Alaska. *Arctic,* 47: 374–390.

Jorgenson, M. T., Cater, T. C., and Joyce, M. R., 1993: Use of snow capture for land rehabilitation in Arctic oilfields. *In* Proceedings of Sixth International Conference on Permafrost, Beijing, China, 316–321.

Jorgenson, M. T., Cater, T. C., Kidd, J. G., Jacobs, L. L., and Joyce, M. R., 1995: Techniques for rehabilitating lands disturbed by oil development in the Arctic. *In* Proceedings High Altitude Revegetation Workshop No. 11. Ft. Collins: Colorado State University, Information Series no. 80: 146–169.

Jorgenson, M. T., Kidd, J. G., Cater, T. C., Bishop, S., and Racine, C. H., 2003: Long-term evaluation of methods for rehabilitation of lands disturbed by industrial development in the Arctic. *In* Rasmussen, R. O., and Koroleva, N. E. (eds.), *Social and Environmental Impacts in the North*. Dordrecht: Kluwer Academic Publishers, 173–190.

Kidd, J. G., Streever, B., Joyce, M. R., and Fanter, L. H., 2004: Wetland restoration of an exploratory well on Alaska's North Slope: a learning experience. *Ecological Restoration,* 22(1): 30–38.

Klute, A., 1986: *Methods of Soil Analysis*. Part 1. Physical and mineralogical methods. Madison: American Society of Agronomy and Soil Science Society of America, Agronomy Series number 9: 1188 pp.

McKendrick, J. D., 1991: Arctic tundra rehabilitation—observations of progress and benefits to Alaska. *Agroborealis,* 23(1): 29–40.

McKendrick, J. D., 1997: Long-term tundra recovery in northern Alaska. *In* Crawford, R. M. M. (ed.), *Disturbance and Recovery in Arctic Lands, an Ecological Perspective*. Dordrecht: Kluwer Academic Publishers, 503–518.

McKendrick, J. D., 2000: Vegetative responses to disturbance. *In* Truett, J. C., and Johnson, S. R. (eds.), *The Natural History of an Arctic Oilfield*. New York: Academic Press, 35–56.

McKendrick, J. D., 2002: *Soils and Vegetation of the Trans-Alaska Pipeline Route; a 1999 Survey*. Fairbanks: University of Alaska Fairbanks Agricultural and Forestry Experiment Station, Bulletin 109.

McKendrick, J. D., Scorup, P. C., Fiscus, W. E., and Turner, G., 1992: Gravel vegetation experiments—Alaska North Slope. *Agroborealis,* 24(1): 25–32.

Mitchell, W. W., 1979: *Three varieties of native Alaskan grasses for revegetation purposes*. University of Alaska: Alaska Agricultural Experiment Station Circular 32.

Moore, N., and Wright, S. J., 1991: *Revegetation with* Arctophila fulva, *1985–1989*. Final report prepared for ARCO Alaska, Inc., Anchorage, by Plant Materials Center, Alaska Department of Natural Resources, Palmer (http://www.dnr.state.ak.us/ag/61Revegetation-withArctophilafulva.pdf).

National Research Council, 2003: *Cumulative Environmental Effects of Oil and Gas on the North Slope*. Washington: The National Academies Press, 304 pp.

Oechel, W. C., and Billings, W. D., 1992: Effects of global change on the carbon balance of arctic plants and ecosystems. *In* Chapin, F. S., III, Jefferies, R., Shaver, G., Reynolds, J., and Svoboda, J. (eds.), *Physiological Ecology of Arctic Plants: Implications for Climate Change*. New York: Academic Press, 139–168.

Page, A. L., Miller, R. H., and Keeney, D. R. (eds.), 1982: *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. Madison: American Society of Agronomy and Soil Science Society of America, Agronomy Series number 9: 1159 pp.

Paul, E. A., and Clark, F. E., 1996: *Soil Microbiology and Biochemistry*. Second edition. San Diego: Academic Press, Inc., 273 pp.

Schmidt, E. L., and Paul, E. A., 1982: Microscopic methods for soil microorganisms. *In* Page, A. L., Miller, R. H., and Keeney, D. R. (eds.), *Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties*. Madison: American Society of Agronomy and Soil Science Society of America, 803–813.

Streever, W. J., McKendrick, J., Fanter, L., Anderson, S. C., Kidd, J., and Porter, K. M., 2003: Evaluation of percent cover requirements for revegetation of disturbed sites on Alaska's North Slope. *Arctic,* 56(3): 234–248.

Tate, R. L., III, 1985: Micro-organisms ecosystem disturbance and soil formation processes. *In* Tate, R. L., III, and Klein, D. A. (eds.), *Soil Reclamation Processes*. New York: Marcel Dekker, 1–24.

Walker, D. A., 1985: *Vegetation and environmental gradients of the Prudhoe Bay region, Alaska*. Hanover, New Hampshire: U.S. Army Cold Regions Research Engineering Laboratory (CRREL) Report 85-14: 239 pp.

Walker, D. A., Cate, D., Brown, J., and Racine, C., 1987: *Disturbance and recovery of arctic Alaskan tundra terrain: a review of recent investigations*. Hanover, New Hampshire: U.S. Army Cold Regions Research Engineering Laboratory (CRREL) Report 87-11: 63 pp.

Younkin, W. E., and Martens, H. E., 1987: Long-term success of seeded species and their influence on native species invasion at abandoned rig site A-01 Caribou Hills, N.W.T., Canada. *Arctic and Alpine Research,* 19: 566–571.

Ms accepted January 2006