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The Use of the Iñupiaq Technique of Tundra Sodding to Rehabilitate Wetlands in Northern Alaska

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ABSTRACT. Tundra sodding, a new technique available to rehabilitate disturbed wetlands in the Arctic, is based on Iñupiaq traditional knowledge. C. Hopson, an Iñupiaq elder from Barrow and author of this paper, guided the development and field application of this new technique by providing traditional knowledge he learned as a youth from his elders. Tundra sodding has several advantages over other land rehabilitation techniques, the most important being that it can establish a mature plant community of indigenous species in a single growing season. In all sampling years, the plant communities at sodded sites were dominated by two rhizomatous graminoids, *Eriophorum angustifolium* and *Carex aquatilis*. These sedges also were dominant in all years in reference tundra. Also common to the plant communities in both reference tundra and sodded sites were 18 other vascular species (grasses, evergreen and deciduous shrubs, and forbs). Results from two to five growing seasons indicate that tundra sod can reduce the overall subsidence due to thawing of shallow permafrost. We harvested sod on three occasions from an area slated for gravel mining. In the summers of 2007 and 2008, we transplanted 334 m^2 of tundra sod to portions of three sites to test the feasibility of the method. In summer 2010, we used the experience gained from that work to rehabilitate an entire site (1114 m^2). This tundra sodding technique is labor intensive and costly compared to other rehabilitation techniques, but it offers advantages that justify its use when rapid rehabilitation of a disturbed site is needed.

Key words: Iñupiat; *ivruq*; sod; turf; wetlands; North Slope; Alaska; Prudhoe Bay oil field; land rehabilitation; revegetation; restoration

RÉSUMÉ. L'engazonnement de la toundra, nouvelle technique qui permet de remettre en état les zones humides perturbées de l'Arctique, s'appuie sur les connaissances traditionnelles Iñupiaq. C. Hopson, aîné Iñupiaq de Barrow et auteur de cet article, a guidé la mise au point et l'application sur le terrain de cette nouvelle technique en faisant part des connaissances traditionnelles qu'il a acquises de ses aînés alors qu'il était jeune. Comparativement à d'autres techniques de réhabilitation, l'engazonnement de la toundra comporte plusieurs avantages, le plus important étant l'établissement d'une communauté végétale mûre d'espèces indigènes au cours d'une seule saison de croissance. Pendant toutes les années d'échantillonnage, les communautés végétales des sites engazonnés étaient dominées par deux plantes graminoïdes rhizomateuses, *Eriophorum angustifolium* et *Carex aquatilis*. Les laîches étaient également dominantes au cours de toutes les années de la toundra de référence. Par ailleurs, 18 autres espèces vasculaires (poacées, plantes sempervirentes, arbustes caducs et plantes herbacées non graminoïdes) se retrouvaient couramment au sein des communautés végétales de la toundra de référence et des sites engazonnés. Les résultats de deux à cinq saisons de croissance indiquent que l'engazonnement de la toundra peut réduire l'affaissement général en raison du dégel du pergélisol peu profond. Nous avons récolté de la toundra à trois occasions dans un secteur destiné à être transformé en gravière. Au cours des étés 2007 et 2008, nous avons transplanté 334 m^2 de toundra dans certaines parties de trois sites afin de mettre cette méthode à l'épreuve. Puis à l'été 2010, nous nous sommes appuyés sur l'expérience tirée de ces travaux pour réhabiliter un site au grand complet (1 114 m^2). La technique de l'engazonnement de la toundra exige beaucoup de main-d'œuvre et coûte cher comparativement aux autres techniques de réhabilitation, mais elle présente des avantages qui permettent de justifier le recours à cette technique lorsque le rétablissement rapide d'un site perturbé s'impose.

Mots clés : Iñupiat; *ivruq*; engazonnement; gazon; zones humides; North Slope; Alaska; champ pétrolifère de la baie Prudhoe; réhabilitation des terres; revégétalisation; restauration

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INTRODUCTION

Oil production on the Arctic Coastal Plain of northern Alaska, commonly referred to as the North Slope, occasionally damages tundra wetlands, triggering rehabilitation requirements. Some cases require excavation and backfilling, which completely destroy wetland vegetation and soils. Less intrusive activities may damage vegetation. All but the most superficial of disturbances can upset soil thermal regimes, allowing shallow permafrost to thaw and ice-rich soils to collapse, forming thermokarst, as described by Lawson (1986) and Pullman et al. (2007).

A variety of site preparation and plant cultivation techniques, including various seeding and plugging methods that work well in temperate regions, are available to revegetate disturbed sites in the North Slope oil fields (Jorgenson and Joyce, 1994; Forbes, 1999; Forbes and McKendrick, 2002; Jorgenson et al., 2003; Streever et al., 2003; Kidd et al., 2004). However, none of these methods act quickly enough to prevent at least partial thermokarst. In addition, the short growing season, cold temperatures, low precipitation, high winds, low nutrient availability due to slow decomposition, restricted drainage, and poor soil aeration dramatically retard revegetation done by conventional methods (Billings, 1987; Chapin, 1987). Typically, revegetating disturbed sites on the North Slope requires at least 10–30 years (Ebersole, 1987; Forbes and Jefferies, 1999; Forbes and McKendrick, 2002; Jorgenson et al., 2003).

This paper describes the development of a new technique, tundra sodding, to rehabilitate tundra wetlands in the North Slope oil fields. This use of tundra sod, comprising blocks of intact soil with a fully developed plant canopy and root system, arose from Iñupiaq peoples' use of sod blocks, sometimes called *ivruq* in Iñupiaq, to construct traditional sod houses (Webster and Zibell, 1970; Arnold and Hart, 1992) and insulate the roofs of ice cellars. C. Hopson, an Iñupiaq elder and lifelong resident of Barrow, Alaska, as well as an author of this paper, guided the development of this technique using traditional knowledge learned as a youth from his elders. C. Hopson also supervised the field effort by teams of Iñupiaq workers recruited from Barrow and other communities on the North Slope, many of whom were already familiar with traditional uses of tundra sod.

Billings (1987) was one of the first to suggest that since many of the graminoid species in the Arctic reproduce largely by rhizomes that spread to form clonal colonies, sod could be used to rehabilitate tundra wetlands on the North Slope. This technique has also been used elsewhere to rehabilitate disturbed lands (Conlin and Ebersole, 2001; Backus, 2004; Densmore et al., 2006). Testing began in July 2007 and was continued in 2008. The insights and experience gained from that work was used in 2010 to achieve what we believe is a milestone for damaged tundra wetlands on the North Slope: the rehabilitation of an entire site (0.11 ha) within a single growing season. We hypothesize that tundra sodding can be used under a variety of conditions to (1) rapidly establish a diverse and productive community of indigenous plant species that is similar to those of undisturbed tundra wetlands, thereby improving site appearance and site suitability for some wildlife species, and (2) establish a thermal regime that prevents thermokarst, achieving two objectives for the rehabilitation of tundra wetlands.

METHODS

Study Area

Sod was harvested from tundra that was slated for gravel mining at the existing Put River 23 mine located on Alaska's North Slope (Fig. 1). The sod was used to rehabilitate wetlands at four sites (Sites A, B, C, and D) that were damaged during cleanup responses to oil spills (Fig. 1). Harvesting was allowed under a permit issued by the U.S. Army Corps of Engineers and a State of Alaska Material Sales Contract issued by the Alaska Department of Natural Resources.

The donor site included two types of tundra: wet sedge tundra, within the remnants of an ice-rich thaw basin, and moist sedge-shrub tundra on higher terrain surrounding the thaw basin. Rhizomatous perennial graminoids, including the grass *Dupontia fischeri* (Fisher's tundragrass) and the hydrophytic sedges *Carex aquatilis* (water sedge), *Eriophorum angustifolium* (tall cottongrass), and *E. scheuchzeri* (white cottongrass) accounted for nearly all of the live plant cover in the wet sedge tundra. *C. aquatilis* and *E. angustifolium* also occurred within the moist sedge-shrub tundra, as did *C. bigelowii* (Bigelow's sedge), the evergreen shrub *Dryas integrifolia* (entireleaf mountain-avens), and the deciduous shrubs *Salix arctica* (Arctic willow) and *S. ovalifolia* (oval-leaf willow). Soil in both donor areas was characterized by an organic soil horizon 15–56 cm thick overlying mineral soil. Water drained from the donor area for three years prior to harvesting as the result of previous activities at the mine site. At the time of harvest, surface water was absent and the soil was not saturated. These relatively dry conditions allowed heavy equipment to operate more efficiently than would be expected for most types of undisturbed tundra.

Site Descriptions

As part of the cleanups at Sites A and D, the plant canopy and 1.2–2 m of the underlying soil were removed because of contamination (Table 1). These excavations were backfilled to the elevation grade that was present before the cleanup began, and tundra sod was transplanted onto the backfilled surface (Fig. 2a). At Site C, excavation also removed the plant canopy, but excavation was limited to the top 5–10 cm of soil, and excavated material was not replaced with backfill (Fig. 2e). After two growing seasons and before a portion of Site C was treated with tundra sod, only a few sprouts of surviving vegetation were visible in the excavated area, indicating that most of the viable plant materials had been

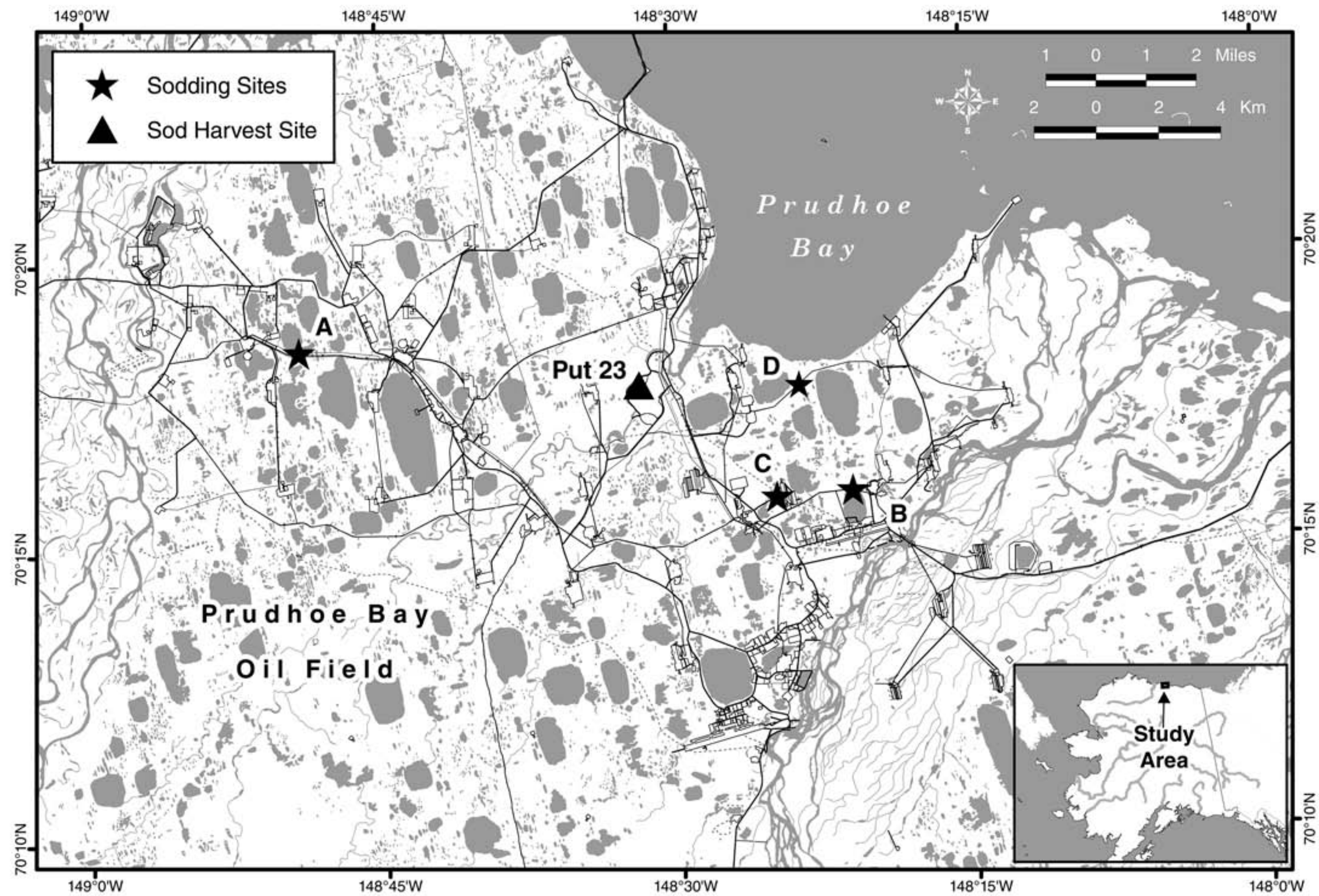

FIG. 1. Locations of the Put 23 mine site where sod was harvested and the four transplant sites within the Prudhoe Bay oil field, North Slope, Alaska.

killed or removed during the excavation. The removal of soil had also lowered the elevation of the tundra surface, causing an adjacent pond to flood part of the site. Shallow permafrost thawed, resulting in subsidence. Thus, vegetation recovery was impaired as water in previously flooded areas grew deeper and the flooded area grew in size.

Instead of excavating, the cleanup at Site B gently flooded the site with fresh water to recover contamination while minimizing impacts to vegetation and soil. However, as often happens following apparently superficial damage to tundra plant communities, some plants died and vegetation cover was reduced. Plant death was especially apparent in a network of pre-existing ice-wedge troughs (Fig. 2c). Not only were these troughs mostly barren two years after the cleanup, but they were also becoming visibly deeper and wider over time as shallow permafrost thawed. As a result of these changes in topography (i.e., thermokarst), surface water persisted in the troughs during the entire growing season, which increased the rate of heat transfer into the soil compared to the rest of the affected area, where surface water was not present for the entire summer.

The cleanup at Site D was different from that at the previous sites, in that tundra sodding was incorporated into the rehabilitation plan during the early stages of the cleanup. This planning was possible in part because the testing in 2007 and 2008 had led to the addition of tundra sodding as a rehabilitation tactic in the Tundra Treatment Guidelines (Cater, 2010).

Developing Sod Harvesting Techniques

In July 2007, the first time that sod was harvested for wetland rehabilitation (Site A), workers used knives with serrated blades 36 cm long to cut 0.09 m^2 blocks (20 cm thick) from the ground at the harvest site (Table 1). To increase efficiency the second time sod was harvested (Site B), workers used serrated knives to make vertical cuts in the tundra that corresponded to the width (1.3 m) of a small front-end loader's bucket. The bucket was then pushed horizontally under the tundra surface at a depth of 20 cm until the bucket was full (approximately 45 cm width), and workers made the final cut along the bucket's leading edge. This technique removed approximately 0.6 m^2 of sod with each load. To further increase efficiency during the third test harvest (Site C), we developed a technique that largely eliminated the need for serrated knives. A specially fabricated 1.1 m diameter steel disc with a sharpened edge was mounted on the bucket of an excavator and then rolled through the tundra,

TABLE 1. Characteristics of the four rehabilitation sites and the variables used to estimate efficiency of different techniques for harvesting and planting tundra sod.

	Units	Rehabilitation sites A	B	C	D
Cleanup date		March 2006	August 2006	April 2007	November 2009
Contaminant recovery tactic		Excavation	Flushing with water	Excavation	Excavation
Depth of excavation	m	≤ 2	0	0.05 – 0.10	≤ 1.2
Fertilizer treatment[1]	g/m^2	100	100	100	22
Sodding date		10 – 15 July 2007	19 – 22 September 2008	22 – 24 September 2008	15 July – 31 August 2010
Harvest technique		36 cm serrated knives	36 cm serrated knives + small loader	*nuna ulu* + zoom boom loader	*nuna ulu* + large loader + 36 cm serrated knives
Sod block size (l × w × d)	m	0.3 × 0.3 × 0.2	1.3 × 0.45 × 0.20	0.9 × 0.9 × 0.5	2.4 × 1. 2 × 0.20
Sod block volume	m^3	0.02	0.17	0.4	0.58
Fresh bulk density[2]	g/cm^3	0.91 (n = 2)	1.0	1.0	1.1 (n = 10)
Sod block weight	kg	16	260	≥ 400	576
Haul distance	km	20	15	10	12
Person hours (12 h day)	#	252	272	89	2029
Team size	#	6	8	4	9
Days needed to sod	#	4	4	2.5	30
Area treated with sod	m^2	96	160	78	1114
Sodding rate[3]	m^2/person/12 h day	4.6	7.0	10.6	6.7

[1] 21 g fertilizer tablets (20-10-5 NPK) were used except at Site D, where granules (20-20-10 NPK) were used.
[2] Fresh samples were weighed immediately after harvesting. Bulk density of 1.0 was used as an estimate for Sites B and C.
[3] Sodding rate = (Area treated ÷ Person hours) × 12 hours/work day.

easily cutting to a depth of about 0.5 m (Fig. 3a). A new Iñupiaq phrase, *nuna ulu*, meaning "land knife," was coined to describe this rolling steel disc. An excavator bucket removed 0.4 m^3 of sod with each load. The most efficient harvesting method was used at Site D in 2010: the *nuna ulu* and serrated knives were used as before, but with a large front-end loader with a larger bucket, which removed approximately 2.9 m^2 of sod as a single block (Table 1, Fig. 3b).

For Sites A and D, sod was harvested in mid-July, after snow had melted and soils had thawed to a depth of about 20 – 25 cm. For Sites B and C, sod was harvested in mid-September 2008, when soils had thawed to a depth of about 50 cm, which generally resulted in the removal of blocks as thick as 60 cm. We estimated fresh bulk density to be 0.91 – 1.1 g/cm^3 (Table 1). Regardless of the harvest time or technique, Iñupiaq workers familiar with harvesting requirements used serrated knives to process tundra into pieces that could be handled by a single person (< 22 kg). At Sites A, B, and D, each block was approximately 20 cm thick. Thicker pieces would have been preferred because plants would probably experience less transplant shock if the rooting systems were contained in a larger volume of soil. Also, thicker pieces should provide more insulation and decrease the potential for thermokarst. However, thicker pieces were too heavy for a single person to handle. Weight of individual blocks was an important safety consideration because workers needed to move sod underneath elevated pipelines that blocked Sites A, B, and D from the adjacent access road where the trucks hauling the sod were parked. Thus, workers typically trimmed soil from the bottom until each block was approximately 20 cm thick so that they could handle the blocks safely. Elevated pipelines were not blocking access to Site C, which allowed the use of an extendable boom forklift that could handle much larger blocks (approximately 60 cm thick, some weighing more than 450 kg). Before placing tundra sod, we applied fertilizer tablets or granules to ensure an abundant supply of nutrients (Table 1).

Sod Placement

At Sites A, B, and D, sod was carefully placed by hand to maximize contact between the sides of adjacent blocks (Fig. 2a). At Site B, where sod was placed in the portions of the ice-wedge troughs that had subsided (Fig. 2c), blocks were sometimes stacked on top of each other to ensure that plants in the top layer of sod were above the water surface. At Site C, the large sod blocks were placed as close to each other as possible (Fig. 2f). Portable skate wheel conveyors, typically seen in warehouses, were used to move sod under the pipelines and across a site, dramatically reducing the distance workers had to carry sod blocks. Plywood supported the conveyors and provided a stable surface for workers, which limited physical damage to the ground surface.

Vegetation Cover

Percent cover of vegetation at each site was measured using a standardized point-intercept method near the end of each growing season after planting (ITT, 1999). Because tundra vegetation has multiple canopy layers where multiple hits of vegetation can occur at the same point, the point-intercept method can yield cover estimates exceeding 100%. However, these cover measurements are generally well correlated with biomass (Jonasson, 1988). Sample points were distributed at 0.5 m intervals along transects,

FIG. 2. View of sites before sod was transplanted (left) and again in 2012 (right). (a, b) Site A; (c, d) Site B; (e, f) Site C.

with the location and length of transects determined subjectively from the size and shape of the area treated with tundra sod (Table 2). Percent cover was also measured in undisturbed tundra situated immediately adjacent to the treated areas at Sites B, C, and D (Table 2). These data were pooled across sites and years to define a reference state by which vegetation development in the treated areas can be assessed (Forbes et al., 2001).

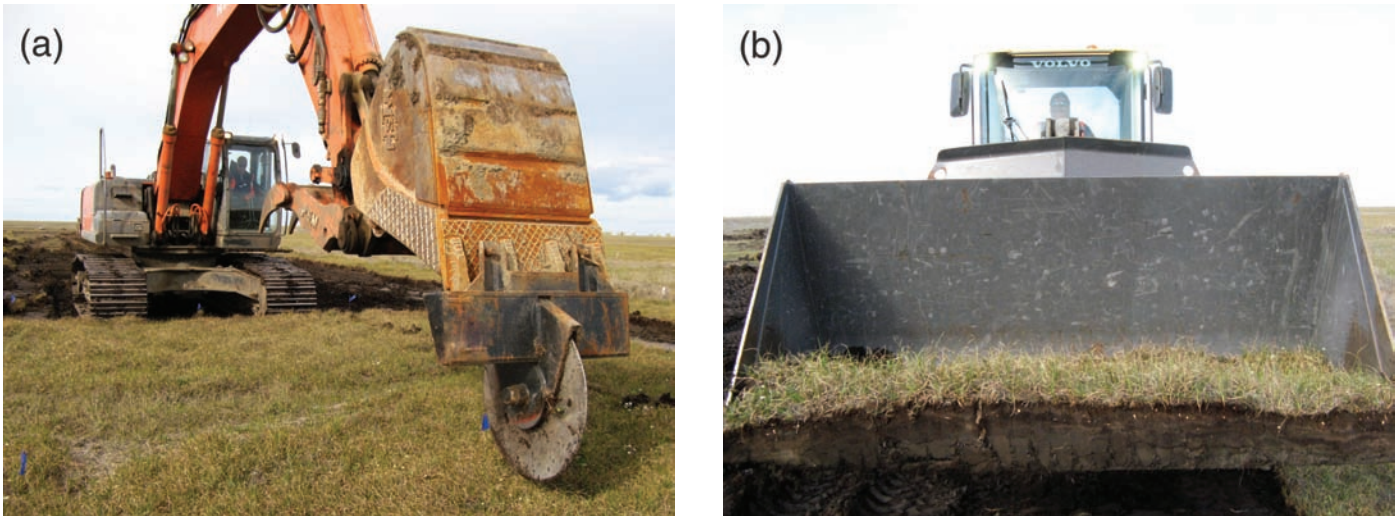

FIG. 3. (a) The mechanical sod cutter (*nuna ulu*) making vertical cuts at the harvest site, and (b) the loader used to remove large blocks of sod.

TABLE 2. Description of transects used to measure plant cover each summer at the four rehabilitation sites treated with tundra sod and in undisturbed (reference) tundra adjacent to Sites B, C, and D.

Site	Sampling area	Number of transects	Length of transects (m)	Sample points (#)	Distance between transects (m)
A	Treated	5	7–12	100	1
B	Treated	7	3–11.5	68	6
	Reference	9	9–12	505	6
C	Treated	2	3–9	10	6
	Reference	5	2.5–14	102	2
D	Treated	12	13–20	386	5
	Reference	12	15	360	5

For sampling at each point on a transect, we used a laser pointer mounted on a 1.2 m long metal rod, which was pushed into the ground so that the laser beam pointed downward, delineating the sample point. Vascular species were identified using nomenclature that followed Viereck and Little (2007) for shrubs and Hultén (1968) for other vascular species. Dead vegetation that was attached or fallen was included in a separate "litter" category. We recorded litter or bare ground only if no live vegetation was present at a point, but we always recorded surface water where it occurred.

We calculated the cover separately for each vascular plant species as the percentage of the total number of points sampled. Total live vascular cover was calculated from the sum of individual cover values for all vascular plants sampled. We also calculated percent cover of eight general categories: evergreen shrubs, deciduous shrubs, sedges, grasses, forbs, mosses, lichens, and bare ground, which included soil, litter, water, and animal scat.

Surface Stability

In addition to qualitative observations of changes in topography over time, we quantified the ability of tundra sodding to prevent subsidence at Site C, where excavation removed the plant canopy and the top 5–10 cm of soil. Immediately after excavation was complete (25 April 2007), ground surface elevation was measured using standard Global Positioning System Real-time Kinematic (GPS-RTK) techniques at 19 stations on a 4.6 m grid established across the site. We repeated the elevation survey on 14 October 2012, five growing seasons after excavation and four growing seasons after sod was planted.

RESULTS

Sodding Rate

The sodding rate ranged from 4.6 to 10.6 m^2/person/day (Table 1), progressively increasing for the first three sites as the harvesting technique was refined. Using the *nuna ulu* and heavy equipment to harvest large blocks of sod eliminated the labor needed to trim and hand-carry smaller blocks of sod, which was considered the primary reason that the highest sodding rate was achieved at Site C (Table 1). At Site D, where the most efficient harvesting technique was used, the sodding rate was moderate (6.7 m^2/person/day) because the sod needed to be trimmed for transport beneath

TABLE 3. Percent cover of vegetation and bare ground at four rehabilitation sites treated with tundra sod compared to mean cover (± SD) measured in reference tundra.

Cover type / Life form / Species	Site A	Site B	Site C	Site D	Reference tundra
Total live cover	148	119.2	140	82.7	105.1 ± 27.2
Total live vascular cover	143	103.0	140	77.0	51.1 ± 10.6
Evergreen shrubs		1.5		10.9	0.8 ± 0.6
Dryas integrifolia		1.5		10.9	0.8 ± 0.6
Deciduous shrubs	8	4.4		1.6	8.0 ± 2.6
Salix arctica	4	2.9			3.3 ± 2.2
Salix lanata		1.5			0.6 ± 0.7
Salix ovalifolia	1			0.3	2.6 ± 2.6
Salix pulchra	2			1.3	0.4 ± 1.1
Salix reticulata	1				1.1 ± 0.6
Sedges	113	97.1	140	58.7	34.5 ± 8.9
Carex aquatilis	9	14.7	130	0.3	12.1 ± 8.2
Carex bigelowii	4			3.9	3.0 ± 2.4
Carex membranacea				0.3	0.1 ± 0.2
Carex misandra				0.3	trace
Eriophorum angustifolium	97	82.4	10	53.6	18.8 ± 7.2
Eriophorum scheuchzeri	3				0.5 ± 1.1
Eriophorum vaginatum				0.3	< 0.1 ± 0.1
Grasses	13			2.1	5.1 ± 6.4
Alopecurus alpinus	8			0.5	0.8 ± 1.8
Arctagrostis latifolia	1			0.5	0.1 ± 0.3
Deschampsia caespitosa				0.3	
Dupontia fischeri	3			0.5	4.1 ± 4.7
Hierochloe pauciflora					0.1 ± 0.2
Poa alpigena	1				
Puccinellia angustata				0.3	
Forbs	9			3.7	2.7 ± 1.2
Braya sp.				0.3	0.1 ± 0.4
Cardamine hyperborea	3			0.8	< 0.1 ± 0.1
Cochlearia officinalis					0.1 ± 0.2
Equisetum arvense	3				
Equisetum variegatum				1.5	2.0 ± 0.9
Polygonum viviparum	3			0.8	0.2 ±0.4
Saxifraga cernua					< 0.1 ± 0.1
Saxifraga hirculus				0.3	0.1 ± 0.2
Stellaria sp.					0.1 ± 0.1
Total live nonvascular cover	5	16.2		5.7	54.0 ± 21.8
Mosses	5	16.2		5.7	54.0 ± 21.8
Lichens				trace	trace
Bare ground	23	27.9		40.2	24.8 ± 15.3
Soil		2.9		3.1	1.4 ± 1.3
Litter	23	23.5		37.0	22.8 ± 15.2
Water		1.5			0.5 ± 0.7
Goose scat					0.1 ± 0.1

elevated pipelines. This site required 2029 person-hours to complete, demonstrating that a moderate efficiency could be maintained over a one-month period.

Vegetation

Total live vascular cover on sodded sites in 2012 ranged from 77.0% to 143% (Table 3). These tundra sod plant communities comprised a combined total of 25 vascular species, 20 of which were also present in reference tundra. *E. angustifolium* and *C. aquatilis* dominated the sodded communities in all sampling years (see online Appendix 1). Also, these rhizomatous sedges were the dominant vascular species in reference tundra in all years. The other 18 vascular species common to both the reference tundra and sodded plant communities were other graminoids (e.g., *C. bigelowii* and *D. fischeri*), evergreen (*D. integrifolia*) and deciduous shrubs (*Salix*), and forbs (e.g., *P. viviparum*). In 2012, we observed an abundance of new shoots produced by *E. angustifolium*, which resulted in substantially higher cover of sedges at sodded sites compared to reference tundra (58.7% – 140% vs. 34.5%). In contrast to vascular plants, nonvascular plants typically had lower cover at sodded sites compared to reference tundra. Mosses comprised nearly all of the nonvascular cover on both sodded sites and reference tundra.

Vegetation in the transplanted sod appeared healthy and productive at each site in 2012 (Figs. 2b, 2d, 2f, and 4a). New growth of roots between blocks and into the underlying soil was clearly visible upon close inspection. However, we did observe patches of dead vegetation (Fig. 4b) at each site in 2012, apparently the result of grazing by tundra voles (*Microtus oeconomus*) or other microtines, as well as their burrowing between and through some of the sod blocks.

FIG. 4. (a) The sodded area at Site D surrounded by undisturbed tundra, and (b) a patch of dead vegetation attributed to microtine activity after tundra sodding at Site B.

Surface Stability

The absence of depressions where surface water can accumulate suggests that the elevation of the ground surface after tundra sodding has remained relatively stable (Figs. 2b, 2d, 2f, and 4a). Quantitative measurements at Site C showed that the ground surface elevations at three points where tundra sod was transplanted were 2–20 cm higher in 2012 than in 2007, before sod was planted. Thus, although tundra sodding did not prevent thermokarst, the thickness of the sod pieces (up to 60 cm thick) offset the subsidence that did occur, resulting in the treated areas' having an elevation similar to the original tundra surface. In contrast, the ground surface elevations at the 16 stations without tundra sod were 5–78 cm lower in 2012 than in 2007. The ground surface at most of these stations has become incorporated into the adjacent pond.

DISCUSSION

Rehabilitating disturbed sites with blocks of intact tundra sod has some important advantages over other techniques typically used in the North Slope oil fields. Not only can tundra sodding revegetate a site in a single growing season, it also results in a plant community that is dominated by indigenous plant species, which is not always the case with other revegetation techniques. Also, the soil in tundra sod should contain the organic matter and microorganisms needed for a healthy soil environment, thereby maintaining natural soil processes (e.g., nutrient cycling). At sites where substantial excavation has occurred, tundra sod can replace at least the upper portion of the excavated soil, decreasing the volume of backfill needed to return the site to an elevation grade that is similar to the surrounding tundra. Tundra sod also establishes a fully developed root system, which provides protection against erosion much faster than plants developing from seed.

Our results demonstrate for the first time that relatively large, severely impacted sites can be rehabilitated within a single growing season, even in the extreme environment found on Alaska's North Slope. These results also demonstrate that tundra sodding reduces the overall subsidence of the ground surface, a factor that is directly linked with successful revegetation. Without the insulation provided by the sod, deeper thawing of shallow permafrost would have occurred, which often allows surface water to accumulate to depths that inhibit plant recovery. Thus, tundra sodding appears capable of rehabilitating tundra wetlands under a variety of conditions, resulting in a diverse and productive community of indigenous plant species.

The abundant supply of nutrients provided by the fertilizer treatment probably promoted vascular plant cover exceeding that found in nearby undisturbed reference tundra, but this difference is expected to decline over time. Increased shoot production was especially visible for *E. angustifolium* and C. *aquatilis*, the rhizomatous sedges that were the dominant species in the tundra sod plant communities. This result is consistent with that of Forbes et al. (2001), who identified the rhizomatous graminoid as the growth form most resistant to disturbance in Arctic ecosystems. The importance of the decline in cover of *C. aquatilis* at sites A and B between 2011 and 2012 remains to be seen. Differences in plant cover and species composition among sites were attributed mostly to natural variation at the harvest site, rather than the result of different environmental conditions among the four rehabilitation sites. For example, the sod used at Site D was harvested from higher terrain where species typical of drier tundra (e.g., *D. integrifolia* and *P. viviparum*) were common, whereas the sod used at the other sites was harvested from the lower area of a former thaw basin where conditions were wetter and rhizomatous graminoids (e.g., *E. angustifolium* and *D. fischeri*) dominated the plant community. The significance of the plant mortality caused by burrowing microtines for the long-term success of tundra sodding is unknown, but will probably vary between years as microtine populations fluctuate.

CONCLUSIONS

Despite the obvious benefits offered by tundra sodding, this technique is not a panacea for rehabilitation of disturbed tundra wetlands on the North Slope. Harvesting sod completely removes tundra vegetation, so only sites slated for mining or other activities that will destroy vegetation should be considered as possible donor sites. Ultimately, limited availability of donor sites significantly limits the availability of sod.

In addition, labor costs associated with sodding are dramatically higher than labor costs or even overall costs associated with other approaches. Sodding may reduce requirements for the long-term monitoring and earthwork that are sometimes required to reverse subsidence, but in our experience, the total cost per unit area for sodding is at least ten times higher than those associated with other methods, even after inclusion of reduced monitoring costs. Costs of sodding are expected to decline as the technique is refined, especially where heavy equipment can be used to both harvest and place sod; however, they are not likely to decline to a level at which sodding will be cost-competitive with other approaches. With the realities of cost and limited sod availability in mind, tundra sodding should be reserved for use on sites requiring rapid rehabilitation. If these initial results continue in the long term, using this new technique can also achieve the more ambitious objective of restoring the original wetland functions at disturbed sites on the North Slope.

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APPENDIX 1

The following tables are available in a supplementary file to the online version of this article at:
http://arctic.journalhosting.ucalgary.ca/arctic/index.php/arctic/rt/suppFiles/4518/0

TABLE S1. Percent cover of vegetation and bare ground on areas treated with tundra sod at four rehabilitation sites in the Prudhoe Bay oil field. Species with trace cover (tr) were present but not hit during sampling.

TABLE S2. Percent cover of vegetation and bare ground in reference tundra at three of four rehabilitation sites in the Prudhoe Bay oil field. Species with trace cover (tr) were present but not hit during sampling.

REFERENCES

Arnold, C.D., and Hart, E.J. 1992. The Mackenzie Inuit winter house. Arctic 45(2):199–200.
http://dx.doi.org/10.14430/arctic1393

Backus, L. 2004. Engineering naturally: Lefthand Creek channel improvement project. In: Keammerer, W.R., and Todd, J., eds. Proceedings of High Altitude Revegetation Workshop 16. Information Series No. 99. Fort Collins: Colorado Water Resources Research Institute, Colorado State University. 185–193.
http://www.cwi.colostate.edu/publications/IS/99.pdf

Billings, W.D. 1987. Constraints to plant growth, reproduction, and establishment in Arctic environments. Arctic and Alpine Research 19(4):357–365.
http://dx.doi.org/10.2307/1551400

Cater, T.C. 2010. Tundra treatment guidelines: A manual for treating oil and hazardous substance spills to tundra, 3rd ed. Juneau: Alaska Department of Environmental Conservation.
http://dec.alaska.gov/spar/ppr/r_d/ttman

Chapin, F.S., III. 1987. Environmental controls over the growth of tundra plants. Ecological Bulletins 38:69–76.

Conlin, D.B., and Ebersole, J.J. 2001. Restoration of an alpine disturbance: Differential success of species in turf transplants, Colorado, U.S.A. Arctic, Antarctic, and Alpine Research 33(3):340–347.
http://dx.doi.org/10.2307/1552241

Densmore, R.V., Vander Meer, M.E., and Dunkle, N.G. 2006. Native plant revegetation manual for Denali National Park and Preserve. Information and Technology Report 2000-0006. Anchorage: U.S. Geological Survey.

Ebersole, J.J. 1987. Short-term vegetation recovery at an Alaskan Arctic coastal plain site. Arctic and Alpine Research 19(4):442–450.
http://dx.doi.org/10.2307/1551410

Forbes, B.C. 1999. Restoration of high latitude wetlands: An example from the Canadian High Arctic. In: Streever, W.J., ed. An international perspective on wetland rehabilitation. Dordrecht, Netherlands: Kluwer Academic Publishers. 205–214.
http://dx.doi.org/10.1007/978-94-011-4683-8_22

Forbes, B.C., and Jefferies, R.L. 1999. Revegetation of disturbed Arctic sites: Constraints and applications. Biological Conservation 88(1):15–24.
http://dx.doi.org/10.1016/S0006-3207(98)00095-0

Forbes, B.C., and McKendrick, J.D. 2002. Polar tundra. In: Perrow, M., and Davy, A.J., eds. Handbook of ecological restoration. Cambridge: Cambridge University Press. 355–375.

Forbes, B.C., Ebersole, J.J., and Strandberg, B. 2001. Anthropogenic disturbance and patch dynamics in circumpolar Arctic ecosystems. Conservation Biology 15(4):954–969.
http://dx.doi.org/10.1046/j.1523-1739.2001.015004954.x

Hultén, E. 1968. Flora of Alaska and neighboring territories: A manual of the vascular plants. Stanford, California: Stanford University Press.

ITT (Interagency Technical Team). 1999. Sampling vegetation attributes: Interagency Technical Reference 1734-4. Report No. BLM/RS/ST-96/002 + 1730. Denver, Colorado: Bureau of Land Management – National Applied Resources Science Center, U.S. Department of the Interior.
http://www.blm.gov/nstc/library/pdf/samplveg.pdf

Jonasson, S. 1988. Evaluation of the point intercept method for the estimation of plant biomass. Oikos 52(1):101–106.
http://dx.doi.org/10.2307/3565988

Jorgenson, M.T., and Joyce, M.R. 1994. Six strategies for rehabilitating land disturbed by oil development in Arctic Alaska. Arctic 47(4):374–390.
http://dx.doi.org/10.14430/arctic1311

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, Netherlands: 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 22:30–38.
http://dx.doi.org/10.3368/er.22.1.30

Lawson, D.E. 1986. Response of permafrost terrain to disturbance: A synthesis of observations from northern Alaska, U.S.A. Arctic and Alpine Research 18(1):1–17.
http://dx.doi.org/10.2307/1551209

Pullman, E.R., Jorgenson, M.T., and Shur, Y. 2007. Thaw settlement in soils of the Arctic coastal plain, Alaska. Arctic, Antarctic, and Alpine Research 39(3):468–476.
http://dx.doi.org/10.1657/1523-0430(05-045)[PULLMAN]2.0.CO;2

Streever, W.J., McKendrick, J., Fanter, L., Anderson, S.C., Kidd, J., and Portier, K.M. 2003. Evaluation of percent cover requirements for revegetation of disturbed sites on Alaska's North Slope. Arctic 56(3):234–248.
http://dx.doi.org/10.14430/arctic619

Viereck, L.A., and Little, E.L. 2007. Alaska trees and shrubs, 2nd ed. Fairbanks: University of Alaska Press.

Webster, D.H., and Zibell, W. 1970. Iñupiat Eskimo dictionary. Fairbanks: Summer Institute of Linguistics.