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Short-term Revegetation Performance on Gravel-dominated, Human-induced Disturbances, Churchill, Manitoba, Canada

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Abstract

The Churchill area has many examples of gravel-dominated, human-induced disturbances such as gravel pits and pads. These disturbances have occurred in a geographically small area with high biological diversity and detract from the aesthetics of this tourist destination. Eight treatments consisting of combinations of peat moss, seeding, fertilizer, snow fencing, and microrelief alteration were installed to improve the growth conditions on three gravel pits and two gravel pads ranging from predominantly tundra to predominantly boreal forest ecosystems. Plant-related assessments of the treatments (density, frequency, and cover) were made after the first and second growing seasons. Twenty-six species of plants were considered to be successful colonizers by at least one of the following criteria: >2% cover, >20% frequency, or >10 stems m^{-2}. *Androsace septentrionalis* L., *Carex* L. spp., and *Dryas integrifolia* Vahl were the only taxa to meet all three criteria in both years. Differences related to the sites (i.e., seed bank, seed source, and substrate conditions) were greater than treatment differences. At three of the sites, seeded treatments had significantly more seedlings than the non-seeded treatments. These three sites were species-poor prior to revegetation testing and were dominated by the seeded species. The other two sites were dominated by species from the seed bank or from seed rain. Total seedling density on seeded plots increased by 17% compared to the controls while cover did not increase appreciably in the short term. Six native species were tested and three (*Anemone multifida* Poir., *Hedysarum mackenzei* Richards., and *Linum lewisii* Pursh) considered suitable for future use, adding to those tested by Firlotte (1998) in the Churchill region. It was determined that seed bank and potential for seed rain had a major influence on the success of seeding as opposed to substrate improvements alone.

Introduction

The growing season in the Arctic and Subarctic is cool, dry, and short, which when combined with a growth-limiting substrate can make reclamation of gravel-dominated disturbances difficult (Stonehouse, 1989; Harper and Kershaw, 1996; Kershaw, 2003; Lavrinenko et al., 2003). Gravel extraction sites—borrow pits—can comprise up to 40% of the disturbances in an area where roads have been constructed (Johnson, 1987b). Around the Churchill Northern Studies Centre (CNSC) located near Churchill, Manitoba, Canada (Fig. 1), these gravel disturbances also include activities associated with the Churchill Research Range and military presence in the region (Coutts, 2000). These disturbances are close to main roads and are highly visible even in forested areas.

The Churchill area is a popular ecotourism destination for bear, whale, bird, and northern lights watchers (Town of Churchill, 1997), bringing in approximately $1 million Canadian annually to the local economy (Manitoba Tourism, 2002 unpublished). In addition to being biologically disruptive, unreclaimed disturbed sites are aesthetically unpleasant and detract from visitor experiences.

Natural revegetation in the Subarctic can be a slow process (Harper and Kershaw, 1996; Jorgenson et al., 2003) due to environmental conditions, and it is further slowed on unsuitable growth substrate created by human disturbance. Eventually graveled disturbances will become revegetated by natural processes (Borgegard, 1990; Forbes and Sumina, 1999); however, naturally revegetated pits often have persistent bare ground and impoverished floras compared to surrounding undisturbed plant communities (Cargill Bishop and Chapin, 1989; Borgegard, 1990; Firlotte, 1998; Kershaw, 2003), especially within coniferous forests (Borgegard, 1990).

Leaving the disturbed areas to recover naturally requires no monetary investment; however, it leaves the sites biologically barren for long periods and leaves them open to erosion and colonization by non-native, weedy species. Many revegetation experiments in the Arctic and Subarctic have used exotic, agronomic plant species. The use of native species is now viewed as a better alternative in the long-term since native species are better adapted to northern climates (Elliot et al., 1987; Cargill Bishop and Chapin, 1989; Densmore, 1992; McKendrick, 1998); however, the lack of commercially available seed is a serious limitation on their use (Densmore and Holmes, 1987; Elliot et al., 1987; Johnson, 1987b; McKendrick et al., 1992; Jorgenson et al., 2003). Selection criteria for native species in revegetation projects such as this one included (Skriabin, 1981; McKendrick et al., 1992):

(1) ability to tolerate well-drained soil,
(2) potential to improve the growth substrate,

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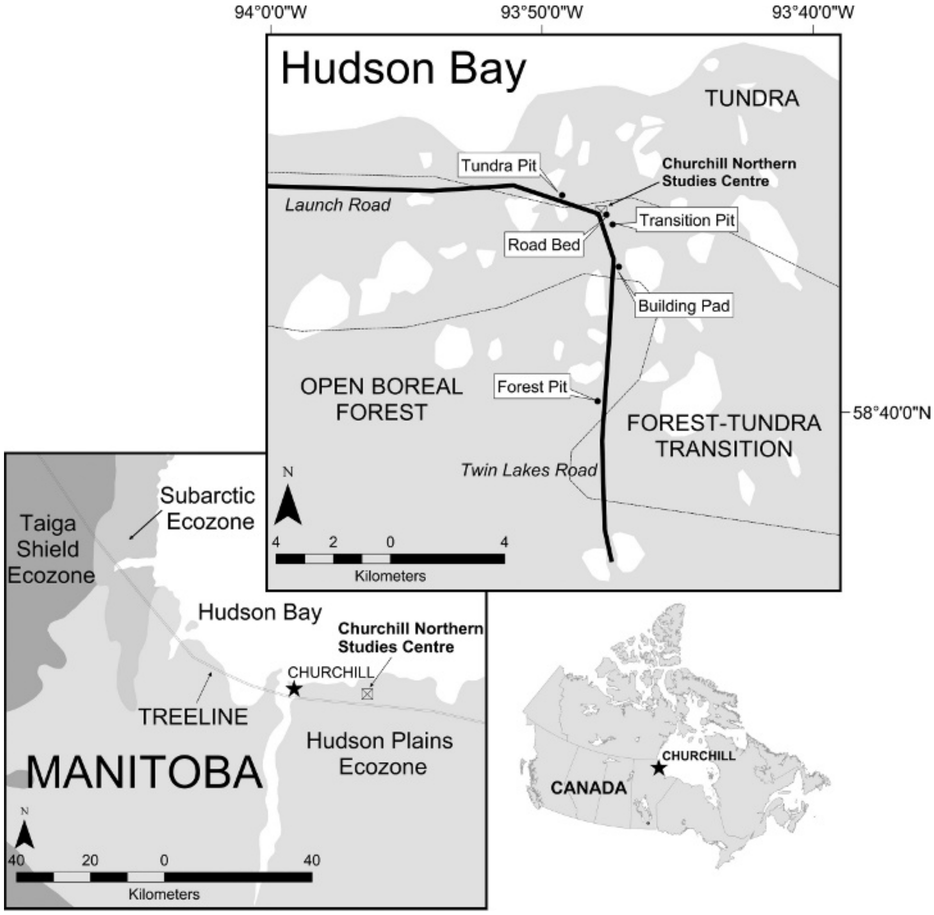

FIGURE 1. Location of Churchill, Manitoba, study area and revegetation site locations.

(3) species that are perennial,
(4) species that are aesthetically-pleasing,
(5) availability commercially in sufficient quantities, and
(6) species that are native to the Churchill region.

Species meeting these criteria were *Anemone multifida* Poir. (cut-leaf anemone), *Castilleja raupii* Pennell (Raup's Indian paintbrush), *Chamerion angustifolium* (L.) Holub (fireweed), *Hedysarum mackenzei* Richards. (northern sweetvetch), *Hierochloe odorata* (L.) Beauv. (sweetgrass), and *Linum lewisii* Pursh (Lewis' flax).

This study was similar to one conducted in Churchill in 1993–1994 in two gravel pits surrounded predominately by tundra. Firlotte (1998) used peat moss, fertilizer, and locally collected seeds to assess the revegetation potential of Churchill gravel pits. Observation of her sites almost a decade after the study was initiated showed promise for revegetation of local disturbed sites. This project built on methods used by Firlotte to increase the choice of techniques and diversity of species present. It also included expansion of the study area to include disturbed sites in the forest-tundra transition zone and boreal forest.

Abandoned disturbances need to be revegetated so they blend in with the surrounding landscape, recover their ecological function, and enhance the aesthetics of the Churchill region for ecotourism. The objective of this study was to evaluate the success (based on frequency, density, and cover) of six seeded species plus several naturally occurring species for the revegetation of gravel-dominated disturbances in response to eight different substrate treatments. In effect, the project was designed to alleviate environmental factors thought to be limiting recovery of disturbances and thereby facilitate natural revegetation.

Methods

SITE DESCRIPTION

Three borrow pits and two gravel pads were selected for the study because they were large enough to contain the treatments, had relatively uniform microtopography, and had <10% total plant cover. The sites differed in location, size, age, and surrounding vegetation (Table 1, Fig. 1).

TREATMENTS

To speed up the recovery process, treatments designed to ameliorate the harsh growing conditions and add seeds to the disturbances were installed. These included snow fencing (F) to collect snow, which can protect plants from wind abrasion in the winter. In the spring, snowmelt produces a burst of moisture, which is a key requirement for germination (Bell, 1975). Another treatment, microrelief alteration (M), provided a series of ridges and troughs to provide microscale shelter from wind and zones of increased moisture in the troughs. The seed mix treatment (S) included application of peat moss, fertilizer, and seeds of six species. This treatment was intended to increase the water-holding capacity of the substrate and provide nutrients and a seed source. The control (C) was a reference for natural recovery without human intervention. Other treatments included combinations of the above.

TABLE 1

Reclamation study sites.

Site	Date abandoned	Location	Description
Forest Pit	ca. 1960	58°40′22.5″N, 93°48′24.0″W	Surrounded by boreal forest Undulating topography
Tundra Pit	1961 (redisturbed 2000–2001)	58°44′20.4″N, 93°49′26.9″W	Surrounded by tundra Uniform topography Along main highway Same pit as Firlotte (1998)
Transition Pit	1984	58°43′49.8″N, 93°47′43.2″W	Surrounded by forest patches broken by open tundra Uniform topography Adjacent to road bed site Lower than adjacent undisturbed areas
Road Bed	1984	58°43′56.4″N, 93°47′50.6″W	Surrounded by forest patches broken by open tundra Uniform topography Compacted road bed Adjacent to transition pit site Raised 1.5 m
Building Pad	1997	58°42′56.0″N, 93°47′27.3″W	Within open treed area Uniform topography Compacted building foundation pad Raised 0.6 m

Six 5 m × 5 m treatment plots were set up at each site in early July 2002. These were randomly arranged throughout the site, although some adjustments were made to ensure unfenced plots were not downwind of fenced plots. All plots had the ''top'' edge oriented perpendicular to the northwest, the prevailing wind direction, to increase the effectiveness of the snow fencing treatment. Five meters of 0.6-m-high plastic mesh snow fencing was installed along the northwest edge of three of the plots at each site. The fencing was monitored regularly throughout the growing seasons and winters for failures. Within each plot, four 1 m^2 randomly located quadrats were marked and treated. Each plot contained half of the treatments (all with fencing, or all without fencing), so each treatment was replicated three times at each of the five sites (quadrats, $n = 120$).

Quadrats receiving the microrelief treatment were raked and shoveled to create three to five ridges perpendicular to the prevailing wind direction (ridge trough to crest ≈ 5 cm).

For the seed mix treatment, the top 2.5 cm of gravel was removed and a portion of it mixed with 300 seeds $species^{-1}$ (seeding density = 1800 seeds m^{-2}) and 30 g of SmartCote 12-12-12 NPK (12% nitrogen, 12% available phosphoric acid [P_2O_5], and 12% soluble potash [K_2O]) time-release fertilizer (300 kg ha^{-1}). Approximately 2.5 cm of peat moss was spread over the plot and covered with the remaining previously removed gravel. The seed-gravel-fertilizer mixture was sprinkled over the plot and lightly packed down by walking over the plot to maximize seed contact with the substrate in order to increase the chances of seedling germination (Skriabin, 1981; Vough et al., 1995). The six seeded species (*Anemone multifida, Castilleja raupii, Chamerion angustifolium, Hedysarum mackenzei, Hierochloe odorata*, and *Linum lewisii*) were selected because they were suited to the conditions of gravel-dominated substrates, were perennial, were aesthetically-pleasing, were available commercially in sufficient quantities (Polunin, 1959; Johnson, 1987a; Hardy BBT Limited, 1989; Johnson et al., 1995; Knowles, 1995; Burt, 2000; ALCLA Native Plants, 2002; Devonian Botanical Garden, 2002), and were native to the Churchill region (Scott, 1996). Seeds were not collected from the Churchill area because of timing, nor were they available from any Manitoba supplier. Seeds of *A. multifida* and *L. lewisii* were purchased from Blazing Star Wildflower Seed Company (Melfort, Saskatchewan), and the remaining seeds were obtained from ALCLA Native Plant Restoration (Calgary, Alberta).

On the quadrats that received the combination of the seed mix and microrelief treatments (FSM and SM), the ridges were shaped and packed by hand. The control quadrats (C) within the unfenced plots received no treatment, and the control (FC) in the fenced plots was the reference for the ''fencing only'' treatment.

SEEDLING DENSITY, FREQUENCY, AND GROUND COVER

In late August 2002 and 2003 the species and approximate location of each individual plant were recorded by placing a 1 m^2 sampling frame divided into 100 squares over each of the 120 reclamation quadrats to map the seedling locations on a grid (quadrat map). The plant mapping or charting method was time consuming but useful for monitoring of permanent quadrats (Bonham, 1989). Density was calculated as the number of stems m^{-2}, and frequency as the proportion of quadrats containing each species. Percent ground cover (plants, litter, and rocks) was estimated visually by the same observer for both years for each quadrat in 1% increments (1–10% and 90–100%) or 5% increments (10–90%). If there was less than 1% of a species present, it was assigned a cover percentage of 0.01% (Kershaw and Kershaw, 1987).

The 1 m^2 sampling frame was also used to assess ground cover on 12 (six in each of 2002 and 2003) randomly located quadrats within the disturbance but outside the reclamation treatments (natural recovery quadrats). In addition, there were six (all in season one) sampled from the surrounding undisturbed plant community (undisturbed quadrats). The assessment was the same as for the reclamation plots but without the location data.

SUCCESS CRITERIA

Revegetation success can be assessed using a variety of measures: establishment of seedlings of native plants, increased species richness, reproduction in colonizing species, accumulation of litter, development of a moss layer, and/or 85% ground cover (Gillis, 1991; McKendrick, 1997; Munshower, 2000; Streever et al., 2003). However, because this was a short-term study limited by

TABLE 2

"Successful" reclamation species. Averaged value for all treatments given for species that met minimum success criteria in that category on at least one quadrat in either growing season. Averaged value may be less than the criteria for success. Multiple values per field indicate values for each growing season.

Species	Density (>10 stems m^{-2})	Frequency (>20%)	Cover (>2%)	No. quadrats species successful (out of 120)
Androsace septentrionalis L.	39.38/75.15	0.39/0.51	0.16/0.97	31/46
Anemone multifida Poir.	10.93	0.45		0/23
Arabis arenicola (Richards. ex Hook.) Gelert	6.85	0.22/0.29		6/2
Astragalus alpinus L.	3.91			0/2
Brassicaceae spp.	8.67/13.00	0.43	0.18	5/16
Carex L. spp.	31.45/61.55	0.26/0.26	0.46/0.71	20/20
Draba L. sp.	5.22	0.41/0.28		7/1
Draba L. spp.	7.89	0.46		0/13
Dryas integrifolia Vahl	5.61/7.14	0.47/0.68	0.58/0.66	24/19
Erysimum cheiranthoides L.	12.00			0/4
Euphrasia subarctica Raup	9.17			2/0
Festuca L. spp.	5.71	0.28		0/0
Hedysarum mackenzei Richards.	47.56/26.79	0.51/0.52		59/53
Linum lewisii Pursh	69.79/19.95	0.51/0.50		60/38
Minuartia L. spp.	21.04/58.31	0.58/0.82		29/69
Picea glauca (Moench) Voss		0.22/0.25		—
Poaceae spp.	13.87/13.72	0.43/0.56	0.41	18/20
Potentilla bimundorum Soják	24.92/29.00	0.24	1.67	6/11
Potentilla L. spp.	7.75	0.20		3/0
Sagina nodosa (L.) Fenzl	33.90/47.54	0.34/0.42		19/33
Salix L. spp.	4.67/7.29	0.28/0.35	0.31	12/13
Saxifraga tricuspidata Rottb.	8.00			0/2
Silene involucrata (Cham. & Schlecht.) Bocquet	9.96/28.56	0.42/0.49		16/30
Stellaria L. spp.	9.11			4/6
unidentified dicot 3	7.81			4/0
unidentified dicot 6	4.08	0.21		0/2

extreme growing conditions, other criteria such as increased species richness, colonization by native species, or increased plant cover (McKendrick, 1997; Kershaw, 2003) were more appropriate. Consequently, >2% ground cover, >20% frequency in the samples (Kershaw and Kershaw, 1987), or >10 stems m^{-2} were adopted as indicators of successful colonization. A species had to meet at least one of these criteria.

Plant nomenclature followed that of the Integrated Taxonomic Information System (2006).

TREATMENT ASSESSMENT—LAB METHODS

Statistical analysis was conducted using General Linear Multivariate Model analysis-of-variance (MANOVA) with Scheffe's post-hoc multiple comparison test to examine differences in treatment means for density and cover. MANOVA was selected over univariate analysis-of-variance (ANOVA) to reduce the Type I errors resulting from the correlation between density and cover. ANOVA was used to examine the difference between overall reclamation quadrat seedling densities at each site. In addition, cover values for the reclamation treatments were pooled into "seeded" and "non-seeded" cover (excluding the controls) and compared against the cover values collected from the natural recovery and undisturbed quadrats. Density and cover data were natural log transformed to meet the analysis-of-variance assumption of equal variances. There were small deviations from normality, however; analysis-of-variance is much more robust to deviations from normality than unequal variances (Clewer and Scarisbrick, 2001). McNemar's analysis of contingency tables were used to analyze the frequency data. Unless otherwise stated, the *P*-value for significance was <0.05.

Results

Eighty-four taxa were recorded from the study quadrats. Total average percent ground cover was 2.0% in the first growing season and 1.8% in the second. Total seedling density per quadrat between the seeded quadrats and the controls was nearly identical (54 seedlings quadrat^{-1}) in the first growing season. In the second growing season density was 17% greater on the seeded quadrats than the controls.

SUCCESSFUL SPECIES—SEEDED AND NATURALLY OCCURRING

Of the 84 taxa recorded, only 26 were classified as "successful" by one or more of the success criteria (cover, density, or frequency). Three of these were species that were sown (*A. multifida, H. mackenzei*, and *L. lewisii*). *Androsace septentrionalis* L., *Carex* spp., and *Dryas integrifolia* Vahl were the only species, whether sown or naturally occurring, to meet all three criteria of success (Table 2).

The largest proportion of successful species satisfied the density criteria (25 of 26 species) (Table 2). Twelve species were density-successful in both years. There were significantly more *Draba* sp., *H. mackenzei*, and *L. lewisii* in season one and *D. integrifolia, Minuartia* spp., *A. septentrionalis*, and *A. multifida* in season two (Fig. 2). Density of the six seeded species increased

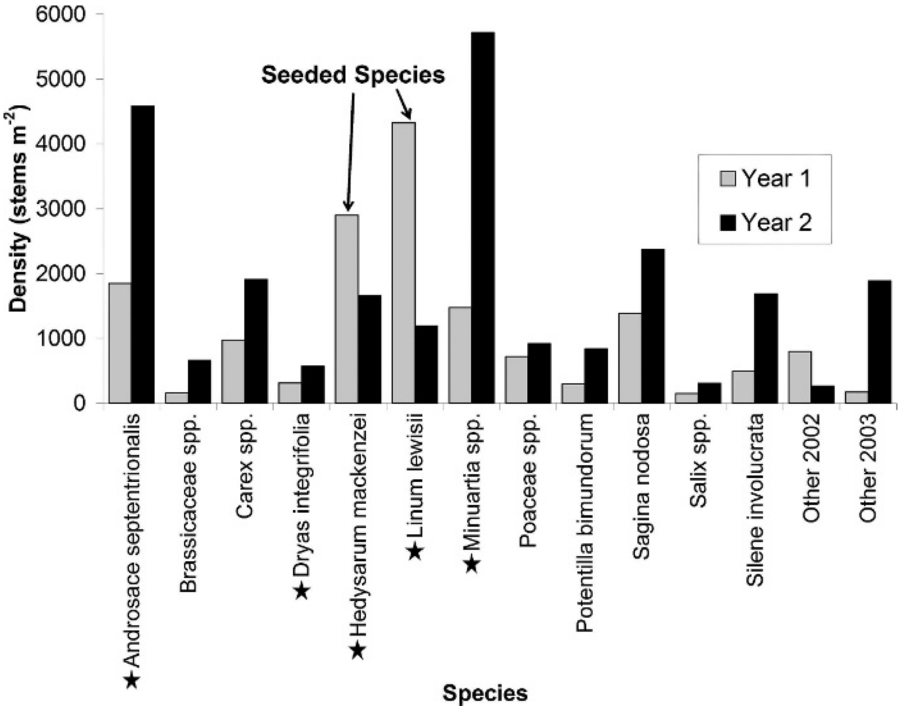

FIGURE 2. Total density of successful (density-determined) species for season one and season two. Star denotes significant ($P < 0.05$) differences between seasons.

between 83% and <100% for *C. angustifolium, C. raupii, H. odorata*, and *A. multifida* and decreased for *H. mackenzei* and *L. lewisii* by 43% and 72%, respectively.

Based on frequency, 20 of the 26 species were classified as successful. Thirteen species were present in over 20% of the quadrats in both years. Eight of the successful taxa significantly increased in frequency by the end of the second growing season [*A. multifida, Arabis arenicola* (Richards. ex Hook.) Gelert, *Astragalus alpinus* L. (density successful), Brassicaceae spp., *Draba* spp., *Festuca* sp., *Minuartia* spp., and Poaceae species], while an unidentified taxon (probably in Brassicaceae) significantly declined. Although three of the seeded species (*C. angustifolium, C. raupii*, and *H. odorata*) did not meet any of the success criteria, they had significantly increased frequency by the second season.

Percent ground cover >2% was the most restrictive measure of success (7 of 26 species). Only three taxa were cover-successful in both years: *D. integrifolia, Carex* spp., and *A. septentrionalis*. *Dryas integrifolia* had significantly greater percent cover than all other species.

TREATMENT AND SITE DIFFERENCES

Treatments that included the seed mix (seeding) had greater density than those without at Tundra Pit, Forest Pit, and Road Bed. There was no significant difference between the seeded and non-seeded treatments at Building Pad and Transition Pit. Cover on the surrounding undisturbed plant community was significantly ($P < 0.001$) greater than on the natural recovery and reclamation test treatments. There was no difference between the natural recovery quadrats and the seeded reclamation quadrats by the second season. However, both the natural recovery and seeded reclamation quadrats had greater cover ($P < 0.001$) than that of the non-seeded microrelief quadrats.

Overall, the cover and density relationship was Building Pad and Transition Pit > Tundra Pit, Forest Pit, and Road Bed; however, treatment effects were only significant at Tundra Pit, Forest Pit, and Road Bed. At these sites the seeded treatments increased density, and cover and the microrelief treatments without seeding (FM and M) decreased with respect to the control. There was no effect on the vegetation as a result of the snow fencing treatment.

Discussion

SPECIES SUCCESS—NATURALLY OCCURRING

Frequency was used as an indicator of diversity and each species' geographical success at colonizing disturbed sites. Ten of the successful species increased in frequency over the two growing seasons, and many of the individuals were large, robust, and vigorous. The remainder of the successful species maintained their average frequency between the first and second growing seasons. The one exception that had decreased frequency was the unidentified taxon which was misidentified the first year and should have been included in the Brassicaceae species group. Many of the frequency-successful species had smaller, non-leafy life forms. Although they did not contribute much to cover, they responded well to the improved growing conditions from the treatments and were more often the species which had sexually mature individuals.

Change in percent cover of plant species is often used to evaluate revegetation success. However, cover values changed little over the two years of the study, and only *D. integrifolia, A. septentrionalis*, and *Carex* spp. increased. *Dryas integrifolia* was the only mat-forming, aesthetically pleasing species of these; however, all three species had growth forms that could aid the production or collection of organic matter and thus would improve the substrate characteristics for plants. *Androsace septentrionalis* (biennial) covered little ground per individual, but had high frequencies and so could contribute organic matter to the substrate once completing its life cycle. The *Carex* spp. were clumped and had high enough frequencies that they were contributing to the accumulation of above-ground litter; however, this species of *Carex* was rhizomatous, which left bare ground between tillers. In contrast, *D. integrifolia* with a mat or cushion life form can eventually cover extensive areas of a disturbance but had low density in this study. A few individuals of *D. integrifolia* can eventually cover large areas on disturbances but this would take more than the two growing seasons of this study. Emerging seedlings are small and cover little ground. As such, cover is not a good indicator of success in the early stages of gravel-dominated substrate reclamation.

SPECIES SUCCESS—SEEDED SPECIES

The two seeded species, *L. lewisii* and *H. mackenzei*, that were successful in the first growing season decreased in density and cover by the end of the second growing season while their frequency remained the same. *Linum lewisii* and *H. mackenzei* were likely more successful than the other seeded species (*A. multifida, C. raupii, C. angustifolium*, and *H. odorata*) because of their larger seed size, which ensured that seeds got onto the quadrats, that they were not as easily lost to wind or water erosion, and that they were not as immediately reliant on substrate characteristics (i.e., more resistant to desiccation and low nutrient availability) (Densmore, 1992; Dalling and Hubbell, 2002). The decline in cover and density of these two species might be a result of the time of sowing. Northern perennials are best seeded in the spring when there is enough moisture for germination and for providing the plant with a long enough growing season for maturation and hardening for winter (Klebesadel, 1977; Johnson, 1981; Skriabin, 1981). Planting for this project was completed in early July, which reduced the potential growing season by as much as 30 days. The major first-to-second growing season mortality in the two seeded species could also potentially be due to the southern provenance of the seed which could be reflected in their responses to the Subarctic signals of winter—the different temperature and photoperiod changes (Klebesadel, 1977) from that of northern Alberta (source of *H. mackenzei* seeds) and central Saskatchewan (source of *L. lewisii* seeds). Some individuals of both species were larger with dead basal leaves in the second growing season, a sign of having over-wintered (Hernandez, 1974), so not all the individuals recorded in the second growing season were new seedlings. However, these second year seedlings were primarily found in the fenced quadrats or wind-protected areas, so the insulative and protective qualities of the snowpack could have aided the survival of these individuals. Several individuals of *L. lewisii* were flowering in late August of the second growing season, again in quadrats that had a snowpack during the winter.

Anemone multifida and *H. odorata* were the only sown species that did not emerge in the first growing season. It is likely that some seedlings of *H. odorata* were present but that they were grouped into the Poaceae species category because of their small size and lack of distinguishing features. *Anemone multifida* was not pretreated despite potentially requiring freezing or spring meltwater immersion to germinate. This was done to determine if this step could be omitted by a local aggregate pit operator to ease the cost and time requirements for reclaiming disturbed sites. However, no seedlings of *A. multifida* were recorded during the first year, and they are distinctive, so it is less likely that they were overlooked or misidentified. In the second year, however, there were high densities of *A. multifida*, which confirmed the requirement for seed pretreatment in order to improve germination.

Chamerion angustifolium and *C. raupii* had increased seedling density in the second growing season; however, it cannot be determined whether this was a treatment effect since these species were naturally present within the disturbance. The exception was at Tundra Pit, where the individuals were likely from sown seeds as these species were found neither within the disturbance nor within the surrounding undisturbed community.

EFFECTIVENESS OF TREATMENTS AND SITE VARIATION

The differences between the seeded and non-seeded treatments were most obvious in the plant density on the three species-poor sites: Tundra Pit, Forest Pit, and Road Bed (Fig. 3). The seeded quadrats had on average four times higher densities than the control quadrats after two years, despite the substrate at these three sites being less suited to growth than that of Transition Pit and Building Pad (Rausch, 2005 unpublished). This was attributed to the substrate improvements from the seeded treatments (additions of peat moss and fertilizer) as well as the addition of a seed source through the six seeded species. At Tundra Pit, Forest Pit, and Road Bed most of the seedlings in the first growing season were those of *L. lewisii* and *H. mackenzei* from sown seeds. The sown species that did not meet the success criteria (*C. raupii, C. angustifolium*, and *H. odorata*) were also more prominent at Forest Pit and Tundra Pit as there were few seedlings originating from sources outside the sites or from the buried seed bank and thus less competition for the seeded species from naturally occurring species. The species composition at Forest Pit and Tundra Pit was different from that at Road Bed despite the densities being similar. Forest Pit and Tundra Pit had species such as *A. alpinus, Oxytropis campestris* (L.) DC., *Saxifraga tricuspidata* Rottb., and *Stellaria* spp. that were absent or rare at the other three sites.

The other two sites, Transition Pit and Building Pad, had the highest densities both on the treated reclamation quadrats as well

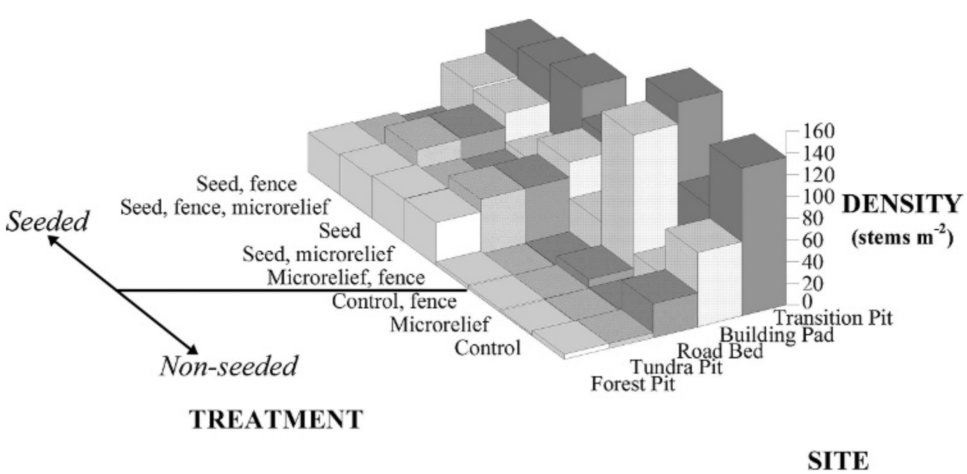

FIGURE 3. Seedling density by treatment type and site for growing season one. Building Pad and Transition Pit had more seedlings present naturally, regardless of treatment. Treatments which included the seed mix were more effective at increasing density at the three naturally species-poor sites: Tundra Pit, Forest Pit, and Road Bed.

TABLE 3

List of species suitable for revegetation in Churchill, Manitoba. Suitability rating: HIGH = good cover or density or frequency, good emergence, showy, reasonable growth; MODERATE = similar to HIGH, but with either poor emergence, slow growth, poor ground cover, not showy, or difficult to collect/expensive to buy; POOR = similar to MODERATE, but with more than two of the undesirable traits.

Species	Seeded or naturally occurring	Suitability	Study
Androsace septentrionalis L.	Natural	POOR	This paper
Anemone multifida Poir.	Seeded	HIGH	This paper
Arabis arenicola (Richards. ex Hook.) Gelert	Natural	POOR	This paper
Astragalus alpinus L.	Natural	MODERATE	This paper
Brassicaceae spp. (including *Draba* spp. L.)	Natural	MODERATE	Firlotte (1998), this paper
Carex L. spp.	Natural	POOR	This paper
Castilleja raupii Pennell	Seeded	MODERATE	This paper
Chamerion angustifolium (L.) Holub	Seeded	MODERATE	This paper
Dryas integrifolia Vahl	Seeded/natural	HIGH	Firlotte (1998), this paper
Leymus arenarius (L.) Hochst. (formerly *Elymus arenarius* L.)	Seeded (rhizomes)	HIGH	Firlotte (1998)
Euphrasia subarctica Raup	Natural	POOR	This paper
Hedysarum mackenzei Richards.	Seeded	HIGH	Firlotte (1998), this paper
Hierochloe odorata (L.) Beauv.	Seeded	LOW	This paper
Linum lewisii Pursh	Seeded	HIGH	This paper
Minuartia L. spp.	Natural	LOW	Firlotte (1998), this paper
Picea glauca (Moench) Voss	Natural	POOR	This paper
Poaceae spp. (including *Festuca* sp. L.)	Natural	POOR	This paper
Potentilla L. spp.	Natural	HIGH	This paper
Sagina nodosa (L.) Fenzl	Natural	POOR	This paper
Salix L. spp.	Natural	POOR	Firlotte (1998), this paper
Saxifraga tricuspidata Rottb.	Seeded/natural	MODERATE	Firlotte (1998), this paper
Silene involucrata ssp. *Involucrate* (Cham. & Schlecht.) Bocquet	Natural	MODERATE	This paper
Stellaria L. spp.	Natural	LOW	Firlotte (1998), this paper
Lesquerella arctica (Wormsk. ex Hornem.) S. Wats.	Natural	MODERATE	Firlotte (1998)

as on the control and natural recovery quadrats, making the differences due to treatment less noticeable (Fig. 3). These species-rich sites had volunteer species which must have been producing viable seed capable of exploiting the increased nutrients and moisture provided by the treatments. Seeds could also have been in the soil seed bank, although propagule abundance in graveled areas in Churchill is small compared to other types of sites (Staniforth et al., 1998; Lavrinenko et al., 2003). As most of the seeds in gravel areas in the region are in the top 5 cm (Staniforth et al., 1998) and Building Pad was a recently created gravel pad, the seeds could have been brought onto the site from the gravel source site (i.e., a newly created gravel pit) and/or dispersed in from the adjacent area. Transition Pit was an older site that was wetter since it was in a depression.

The microrelief-only quadrats (FM, M) had significantly fewer seedlings than any of the other treatments (Fig. 3), especially in the first year. This is likely due to the disturbance-during-installation effect where the pretreatment plants were disturbed or destroyed and did not have time to recover by the end of the first growing season. Although this was the case at all five sites, it was the most pronounced at the species-rich sites, possibly because the existing seed bank was buried during the treatment installation.

There was no difference in the measurable plant data between the fenced and non-fenced treatments despite expectations based on previous studies (Jorgenson et al., 1993; McKendrick, 1996, 1999). However, McKendrick et al. (1993) only found a fencing effect after the first few years. There was a difference in the snowpack (7.7 cm unfenced vs. 33 cm fenced) (Rausch, 2004 unpublished), which could be the reason for the second-year seedlings and flowering individuals in the fenced treatment.

Plant cover at Building Pad and Transition Pit was greater than at the other sites. Building Pad was a newer disturbance with greater potential for viable seed still present in the fill, while Transition Pit was a wetter, more depressed area than the other sites. The individual plants on Building Pad and Transition Pit were physically larger, and thus covered more ground than those at the other sites with the exception of *L. lewisii* at Tundra Pit, which were flowering.

As expected, the surrounding undisturbed plant community had far greater cover than the natural recovery or reclamation quadrats. The undisturbed plant community had hundreds of years (Dredge, 1992) to develop and modify the substrate to improve growing conditions. As a result, the species composition was quite different from that of the recovery and reclamation quadrats and had fewer pioneer species. By season two the seeded reclamation quadrats developed plant cover equal to that of the natural recovery quadrats (the rest of the surrounding gravel pit or pad). It is expected by years 7–10 that the seeded treatments will have far greater cover as the native forbs mature (Klebesadel, 1971; McKendrick, 1999).

APPLICATION OF FINDINGS

Dryas integrifolia was clearly the most successful species among the undisturbed, recovery, and reclamation treatments. This would have been facilitated by several of the species' inherent abilities: (1) it can efficiently capture nitrogen through nitrogen-fixing bacteria in root nodules (Kohn and Stasovski, 1990; Kohls et al., 1994); (2) it has light, easily dispersed, abundant seeds; (3) it is tolerant of a variety of substrate conditions (Viereck and Little, 1972; Johnson, 1987a); and (4) it has a spreading, mat-forming habit that facilitates its colonization. Future reclamation studies in the area should test the seeding of *D. integrifolia* as a means to accelerate revegetation.

The six tested species all proved they have potential for reclamation of gravel-dominated disturbances in Arctic and

Subarctic environments. However, the small seed size and high seed cost of *C. angustifolium, C. raupii*, and *H. odorata*, and the relatively low density, cover, and frequency of seedlings produced after two growing seasons reduce their desirability. Nevertheless, plants of *C. angustifolium, C. raupii*, and *H. odorata* are aesthetically pleasing when mature because of their conspicuity, green foliage, and profusion of flowers or large seed heads. *Anemone multifida, L. lewisii*, and *H. mackenzei* are very suitable for gravel reclamation although, to increase success, the seeding rate (300 seeds m^{-2} $species^{-1}$) should be doubled to compensate for potential winterkill and loss due to drought.

Seeding sites such as Tundra Pit, Forest Pit, and Road Bed where there is little plant cover and few species/propagules in the seed bank is an appropriate reclamation strategy (Jorgenson et al., 2003). In other circumstances, revegetation can be enhanced by modifying the existing site to encourage growth and reproduction of already established individuals (e.g., Building Pad or Transition Pit, where seeding had little effect on plant density, but the addition of peat moss and fertilizer produced a positive response).

Summary

This study and that of Firlotte (1998) have resulted in a list of 24 taxa suitable for revegetation of gravel-dominated disturbances in Arctic/Subarctic regions (Table 3). Fifteen of these species have been added as a result of this research. These species include those that are naturally occurring, harvestable, and/or commercially available. This study expanded the applicability of these techniques to include forest-tundra and boreal forest ecosystems. Thus, the number of taxa suitable for revegetation and the geographical region that they can be used in have been considerably expanded.

In order to optimize ecological recovery, disturbance sites should be assessed for the presence of a seed bank or adequate seed rain from adjacent areas. Sites which meet these criteria do not require seeding and respond well to the addition of growth substrate amendments such as peat moss and fertilizer. Other sites require the addition of seeds to produce significant plant density and cover that will facilitate revegetation and reduce the natural rate of recovery.

The effects of snow fencing and microtopography alteration are not yet apparent in this study, due to its short-term nature. However, these factors could have longer-term implications when seedlings become tall and risk abrasion by wind and snow crystals in the unfenced plots.

Hedysarum mackenzei and *Linum lewisii* were the best performers of the six seeded species. The significant winterkill of these two species can be compensated by increasing the initial seeding rates. Naturally occurring *Dryas integrifolia* was the most successful species overall with the highest percent cover, as well as high frequency and moderate density, across all quadrats.

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