University of Alberta

Reclamation of gravel-dominated disturbances, Churchill, Manitoba, Canada

by

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Abstract

Churchill, Manitoba has many examples of gravel-dominated, human-induced disturbances which have occurred in a geographically-small area with high biological diversity. Eight treatments; combinations of peat moss, seeding, fertilizer, microrelief alteration and snow fencing were applied to determine the main limitation(s) to growth – moisture, nutrients or wind exposure – at five gravel disturbances. The addition of peat moss decreased soil bulk density by half and doubled soil water content. Combined with the applied seed mixture and naturally-occurring propagules on the sites, the peat moss treatment resulted in a 50% increase in plant cover and a 33% increase in plant density. All of the applied fertilizer was undetectable by the second growing season. The snow fencing and microrelief treatments had no effect in the short-term. Moisture availability was the most limiting factor to plant growth. Proposed techniques and species suitable for future reclamation projects in the region are included.

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For my parents Brent and Deleigh,
who were adventurous enough to move our family to the NWT,
and for my supervisor Pete,
who was adventurous enough to take me on as a student;
all of whom share my love of the North.

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CHAPTER 1 - Introduction: Background, Context and Literature Review of Gravel-dominated Disturbances and the Churchill Region

BACKGROUND

Aggregate resources have been exploited in the Arctic and Subarctic for decades. Consisting mostly of sand and gravel, it is a non-renewable resource we are unlikely to run out of, although it can become scarce in some locations (Werth, 1980). Its use as a ground covering for stability and drainage and as permafrost insulation (Johnson, 1987b; McKendrick, 1991a) has required a constant supply of coarse mineral aggregate across the North, primarily near communities or in association with industrial infrastructure. Construction of roads, aircraft landing strips, building and drill-rig pads, and field camp sites are the main use for aggregate (Werth, 1980). Sand and gravel pits are one of the most familiar disturbances in the developed world (Munshower, 1994). In Alaska 74% of land degraded by hydrocarbon development is gravel-related disturbances (Jorgenson and Joyce, 1994). In areas where roads have been built, gravel pits alone can comprise up to 40% of the disturbed area (Johnson, 1987b). Roads are an important aspect of life in Canada due to the geographical distribution of the population. This is especially evident in northern regions where population centres can be hundreds of kilometres away from one another and all-weather roads are the primary means of ground access. Roads also facilitate commercial and recreational activities (Alke, 1995) as well as access to subsistence hunting and fishing areas. Due to military activities in the Churchill region many gravel pits and pads were created to support construction of infrastructure and the movement of personnel (Groom, 2001). The Churchill Research Range with rocket launch and tracking was also a major consumer of aggregate.

Gravel pits, or borrow pits, are disturbances where aggregate has been removed from the surface. The pits can be deep or shallow and many have steeply sloped banks (>20°). They are usually large (Johnson, 1987b) although compared to all types of disturbances they are meso-scale disturbances, normally <100ha (Walker, 1997; Smreciu *et al.*, 2003).

Gravel pads in the area consist primarily of roads and building pads created as part of the Churchill Research Range. These pads are comparable to those created by oil and gas exploration and extraction where aggregate is added to the ground surface to create a compacted pad for working or building on. These pads are usually 1.5-2.2m thick (Brown, 1975; McKendrick, 1991a). The two gravel pads in this study were 0.6m and 1.5m thick, classifying them as medium and thick pads (Streever *et al.*, 2003), respectively. Gravel pads protect the ground surface from traffic, prevent permafrost melting and thermokarst subsidence and provide stability and good drainage to protect equipment and buildings on the pad (Large, 1978; Johnson, 1987b; McKendrick, 1991b).

Manitoba's largest mining sector is the aggregate industry valued at \$45 million $year^{-1}$ (Manitoba Industry Economic Development and Mines, 2004). Fifty-four percent of the gravel extracted in Manitoba is used for road construction (Large, 1978) and that which is used has <5-25% material finer than No. 200 sieve (75 um) depending on what use the material is required for. Road surfacing permits a higher fines content than building pads and airstrips (MacLaren Plansearch, 1982).

The aggregate available in Churchill is of high quality because it was deposited glacially and by wave action, meaning it is well-sorted by size and contains little or no clay or organic matter (Large, 1978; Werth, 1980; Dredge, 1992b). Despite its potential for sale, it is a valuable resource only used locally because of the high cost of transporting it in and out of the region (Bamburak, 2000). Part of the problem with the gravel sites in Churchill is that since the gravel is easily extracted, instead of using already disturbed sites when gravel is needed, previously undisturbed deposits closer to the area where the gravel is required are disturbed. This has created a patchwork of disturbed gravel sites on the landscape and includes the ancillary road and trail networks leading to landscape 'nibbling' as Walker *et al.* (1987) termed it. Many of these disturbances are decades old and when they were created there were no regulations or guidelines in place for mitigation or reclamation.

Churchill Area

Churchill, Manitoba, 58° 45'N, 97° 04'W (Figure 1-1), and the area surrounding the Churchill Northern Studies Centre (CNSC) has numerous examples of gravel-dominated disturbances. Surface mining activity has been occurring at Churchill since 1733 (mainly building stone extraction in the early Fort Prince of Wales days) (Bamburak, 2000), however many of the gravel pits and pads were created in association with military activities (1942-1980) (Groom, 2001) and the Churchill Research Range, a rocket launch facility and research station that was active from the early 1950s until the mid-1980s with a brief revival of activity in the late 1990s (Coutts, 2000). Although the Research Range is no longer used for launching rockets, the buildings are still present. Some are closed to the public but still owned by the Canadian Government and others are now part of the CNSC which provides logistical support for researchers (private and university-affiliated) undertaking a variety of projects. The CNSC is also the end point (in the West) of one of the major roads in the Churchill area, Launch Road, and the start of another (to the South), Twin Lakes Road which provides access to, for example, birders, hunters, wood gatherers, recreational hikers and cabin owners.

Gravel-dominated disturbances in the Churchill region occur in a small area of high biological diversity (Ritchie, 1962) including tundra (Southern Arctic Ecozone), forest-tundra

(Taiga Shield Ecozone) and boreal forest (Boreal Shield Ecozone) ecosystems. The boreal forest-tundra transition zone is dominated by non-continuous tree cover of sparse, stunted-growth coniferous trees. Islands of trees are present within primarily tundra areas, along with dwarf shrubs. Most of the vegetation is comprised of three community types: 1) *Carex* spp. (sedge) meadow and shrub and scrub forest, 2) same as 1 with the addition of open *Picea* spp. (spruce) forest with moss and shrub, and 3) *Larix laricina* P. Mill. (tamarack) forest with open stands of *Picea* underlain by moss and shrubs (Ritchie, 1962). Churchill is located in the Hudson Bay Lowland Ecoregion (of the Hudson Plains Ecozone) (Riley, 2003; Environment Canada, 2004) where the vegetation patterns are determined primarily by topography (and thus drainage), followed by climate, disturbance and history of the area. In other parts of Canada, topography and climate are usually considered equally important (Ritchie, 1962). The Hudson Bay Lowland is one of Canada's most varied and diverse community types (Ritchie, 1962; Riley, 2003). Of the plant taxa present in the Hudson Bay Lowland, about 54% are considered Arctic/Subarctic species and 46% boreal or temperature and overall 41.2% of the species are confined solely to this ecoregion (Ritchie, 1962; Riley, 2003). The ecotone provides an important link for wildlife between the boreal forest and tundra biomes (Conservation of Arctic Flora and Fauna, 2001).

Churchill lies within the continuous permafrost zone (Dredge, 1992a; Dredge, 1992b). The active layer on exposed mineral sites is about 1m (Dredge, 1992a; Dredge, 1992b) to 3m thick (Kershaw, unpubl. data). There is a dominance of carbonates in the substrate from the Paleozoic Severn River Formation parent material comprised mainly of dolomitic limestone (calcium-magnesium carbonates) which overlays the Ordovician Churchill River Group (dolomite and limestone) and Precambrian Churchill Quartzite Formation (quartzite and subgreywacke) (Dredge, 1992a; Dredge, 1992b; Bamburak, 2000). Scattered within the patchy treed/tundra landscape are thin (5-20m thick) sandy and gravely beach ridges left by isostatic rebound after the melting of the Laurentide Ice Sheet (Dredge, 1992a; Dredge, 1992b). The ridges are usually covered by dry lichen heath tundra (Johnson, 1987a) while peat began to accumulate in the low areas about 6000 years ago (Dredge, 1992a; Dredge, 1992b).

Churchill has long been a popular tourist destination, primarily as a relatively easy to access location for viewing polar bears ((*Ursus maritimus*) (Phipps, 1774)), but also for aurora borealis (northern lights), whales and birds, including some rarer or harder to logistically view species such as the Ross' Gull (*Rhodostethia rosea* (MacGillivray, 1824)) and Hudsonian Godwit (*Limosa haemastica* (Linnaeus, 1758)) (Town of Churchill, 1997; Sibley, 2000). Altogether, the tourism industry brings in approximately $1 billion to the local economy (Manitoba Tourism, pers. comm., 2003), making the preservation of the eco-tourists' experience a valuable goal (Densmore and Holmes, 1987). Most of the disturbances in Churchill are close to main roads (<10m) and highly visible even in treed areas. McKendrick (1997b) listed four reasons to revegetate tundra in Alaska, to: prevent soil erosion, create and/or restore habitat for wildlife, comply with permits or regulations, and improve aesthetics. Of these, the last is the most applicable to Churchill because of tourism. Unreclaimed disturbed sites are aesthetically unpleasant and detract from the visitors' experiences, therefore, from a socio-economic perspective, assisted reclamation is desirable. In addition, there is a fifth reason; to restore ecological function, however this reason does not often inspire or justify economic expenditure.

Environmental Constraints of the Ecotone

Natural revegetation in the Subarctic can be a slow process (Harper and Kershaw, 1996) due to environmental conditions such as low temperatures and high winds. Many species of plants are adapted to produce fewer seeds (Johnson, 1987b). Although seed set in good years depends on temperature (McKendrick *et al.*, 1992), few are viable and germination is usually low. Cold temperatures (mean monthly growing season temperature is less than 10°C) and high winds further complicate recovery (Webber and Ives, 1978; Arnalds *et al.*, 1987; Stonehouse, 1989) by resulting in slow invasion rates (Johnson, 1981) and poor nutrient cycling due to slow decomposition (Haag, 1974).

Churchill's mean annual air temperature is -7.3°C. About half of the 400mm annual precipitation falls as snow (Johnson, 1987a; Dredge, 1992a; Dredge, 1992b). There are 500-750 Growing Degree Days (GDD ≥5°C), (Energy Mines and Resources Canada, 1995) and over 250 days out of the year have frost (Johnson, 1987a). The annual average wind speed is 23 km h^{-1} from the northwest with the strongest winds occurring in November when the majority of the snow falls and the ice forms on Hudson Bay (Johnson, 1987a; Dredge, 1992a; Dredge, 1992b).

In winter, plants present in wind-swept, snow-free areas have high evapotranspiration rates (Stonehouse, 1989; Walker *et al.*, 2001) and can have branches, needles and portions of the stem abraded by wind action (Scott *et al.*, 1993). Uncovered plants on a sunny winter day can lose water via cuticular transpiration (stoma are closed), have no way of replenishing the lost moisture and go into severe drought stress because all the available water is frozen (Walker *et al.*, 2001). Snow cover can help protect vascular plants against frost damage, wind and wind-blown particle damage, desiccation and it limits the deep freezing of the soil by insulating the surface and the soil (Walker *et al.*, 2001). A study in a fellfield (an environment similar to a gravel disturbance) found that while the temperature around the surface of exposed plants was –15°C, those covered in snow were only -1°C, never dropping below -3.5°C (Walker *et al.*, 2001). As an insulator from wind and extreme temperatures snow is six times more effective than soil of the same depth because of its high porosity

(Pomeroy and Brun, 2001). Snow beds also trap mineral and organic particles (such as soil and plant debris) which fall to the ground when melt occurs. Some of these particles are lost with spring meltwater but a portion remains on site especially if there is plant cover to help trap the particles (Walker *et al.*, 2001). This can improve soil quality and build soil structure (Sharp *et al.*, 1995).

Environmental Constraints of the Disturbance

Temperature is not as limiting to polar propagule development and establishment as high evaporation (from sun and wind exposure) and particle abrasion (ice and soil) action (Lewis-Smith, 2000). Moisture availability and retention in the spring and growing season can be very limited in gravel-dominated substrates and sites are subjected to rapid drying (Down, 1974; Addison, 1975; Ontario Ministry of Natural Resources, 1978; Densmore *et al.*, 1987; Lavrinenko *et al.*, 2003). Water deficiency reduces carbon assimilation and plant growth (Addison, 1975).

The main source of summer moisture in areas where a large percentage of the annual precipitation falls as snow, is from the soil and the moisture stored within (Van Miegroet *et al.*, 2000). Melt from snow can be a good source of moisture, however due to the coarse-grained texture of the substrate and rapid, short melt period; most of it quickly drains and is lost to plants (Walker *et al.*, 2001). The water content of gravel airstrips, roads, pits and pads ranges between 3.5-45% (Addison, 1975; McKendrick *et al.*, 1993; Forbes and Sumina, 1999). Lack of moisture and vegetative cover contribute to the fluctuation of substrate temperature (Johnson, 1987b; Harper, 1994).

Seedling growth and germination studies have found seedling roots are only moderately tolerant to drying (-12 to -14 bars) and cold. Disturbances which lead to soil drying and surface hardening are especially restrictive to seedling growth (Bell, 1975a). Germination is also closely linked to moisture where environments with large sized particles have low germination because of lack of moisture (Down, 1974) and some species require immersion in snow meltwater to germinate, perhaps because the immersion increases water uptake at lower temperatures, and seedling mortality is mainly attributed to soil drying (Bell, 1975b). Seeds that fall into crevices where there is a concentration of moisture and nutrients, as well as protection from predation and wind desiccation, have higher germination success (Bell, 1975b) and seedling survival (Mitchell, 1987).

Another limitation to growth on gravelled disturbances is nutrient availability or rather deficiency (Jorgenson *et al.*, 2003). Nutrients can only be taken up by plants in solution so uptake by plants is limited by availability of the nutrients to the roots rather than phenological characteristics (Schimel *et al.*, 1996). As gravel disturbances are so dry, they further prohibit uptake and transport of nutrients to plants (Forbes, 1993). In addition, because of the low cation exchange capacity (CEC), when nutrients are added to the substrate, they can be easily leached (Johnson, 1987b; Auerbach *et al.*, 1997). The ability of a plant to succeed in this environment is related to its capacity to produce (N-fixation) and/or find and absorb nutrients (Kershaw, 2003a). Nutrients speed up growth and reduce time to maturity (Skriabin, 1981). The higher pH which is often associated with aggregate disturbances also limits nutrient uptake. These high pH disturbances can negatively impact surrounding plant communities which are normally acidic in many northern environments. This is particularly the case with gravel roads where traffic deposits and transports a lot of basic-rich dust onto acidophilus plant species (Everett, 1980; Auerbach *et al.*, 1997).

There are few northern plant species adapted to grow on gravel-dominated soils (Johnson, 1987b; Forbes, 1993; Jorgenson *et al.*, 2003). Colonization of gravel sites is more difficult in boreal forest areas as compared to tundra as the undisturbed boreal forest is species poor and the range of species able to recolonize is much smaller (Borgegard, 1990).

In addition, gravel- and sand-dominated substrates have a limited seed bank (Gartner *et al.*, 1983; Staniforth *et al.*, 1998; Lavrinenko *et al.*, 2003) and 90% of what is present is restricted to the top 5cm of the gravel (Staniforth *et al.*, 1998).

Gravel disturbances have very little organic matter (McKendrick, 1987; Harper and Kershaw, 1996), often less than 1% organic carbon (Walker and Everett, 1987). After many years it can start to accumulate (Kershaw, 2003a) if there are sufficient locations in which it can be trapped (e.g. crevices, around the base of seedlings and plants). However, the particle size is normally more than 90% >2mm in the top 5cm (Walker and Everett, 1987) and the fine fraction (<2mm) is mainly sand and not silt or clay (McKendrick *et al.*, 1993) restricting the potential for trapping and retaining organic or fine particles and moisture. Due to the large particle size, bulk density is normally around 1.6gcm^{-3} but can be as high as 2.3gcm^{-3} if the substrate is very stony and/or compacted (McKendrick *et al.*, 1993).

Gravelled areas are normally windswept because of their smooth surface. Gravel pads are even more likely to be snow-free due to their raised profile. This smoothness, or lack of roughness, does not cut wind speed or allow snow to accumulate (Pomeroy and Gray, 1995).

Combining the importance of tourism to the region as well as the uniqueness of the ecosystem, abandoned disturbances need to be revegetated so they blend in with the surrounding landscape, recover their ecological functions and enhance the eco-tourism value of the Churchill region.

DEFINITIONS AND TERMS

Some of the terms used in reclamation are interchangeable or synonymous. However, some have subtle differences that imply specific meaning about the method or technique. It is important to know how the author uses these terms for clarity by the reader. Definitions were taken from the author's interpretation and from the following sources (Ritchie, 1962; Powter, 1995; Pruitt, 1969; Johnson, 1981; McKeague, 1981; MacLaren Plansearch, 1982; Kershaw, 1984; Walker *et al.*, 1987; Kershaw, 1988; Forbes, 1993; Huston, 1994; Jorgenson and Joyce, 1994; Munshower, 1994; Dunster and Dunster, 1996; Soil Classification Working Group, 1998; Ritter, 2003).

Reclamation

Reclamation is manipulation of the topography, vegetation or soil to get the disturbance to function as an ecosystem and meet the end land use requirements of the site or other productive uses. It can be similar to or completely different from the original site and could require perpetual management of the site. It can also involve erosion control and introduction of wildlife or fish species to the reclaimed disturbance. Over time, the reclaimed site could evolve to a stable ecological state comparable to the adjacent natural systems. Overall, this project is reclamation testing since it involves manipulations of the soil and vegetation. However, since the main focus is on the plants, and their growth response, the term revegetation is commonly used throughout.

Rehabilitation

Rehabilitation is a synonym for reclamation.

Restoration

Restoration is a restrictive term which requires returning the site to the original ecological state (composition, structure and function) prior to disturbance. These conditions include plant and wildlife species and their relative abundances, soil type and nutrient status as well as parameters such as soil microorganisms. It is the most difficult and time-consuming of the reclamation strategies and may not be achievable on a human time scale as it requires detailed knowledge and understanding of all the original species, functions, interactions and relationships within the system. In addition, the disturbance could have produced such severe change that the restoration of the site to pre-disturbance conditions can be impossible even on an extremely long timescale.

Revegetation

Revegetation is the phase of reclamation that involves the establishment of post-disturbance vegetation. It makes no specific reference to species selection or composition. Revegetation can involve planting seeds (native or non-native), cuttings, transplanting live plants or fertilizing the surrounding plant community to encourage seed production for natural wind/animal transport to the site. In the case of natural revegetation, it includes encroachment or colonization of the site by seeds or vegetative propagules from within and surrounding the disturbance.

Assisted versus Natural (reclamation or revegetation)

The use of the term assisted distinguishes human intervention or manipulation from natural processes to reclaim or revegetate the site. Assisted is used when any human involvement encourages the natural processes (for example, adding fertilizer to the surrounding plant community) to full-scale reclamation involving substrate manipulation and seeding/planting of native or non-native species. Natural is reserved for use when speaking about the processes entirely unaided by humans since the creation of the disturbance.

Subarctic

The Subarctic is a region that spans across Canada from Labrador to northern Québec, around Hudson Bay and to the Northwest from northern Manitoba to the Yukon and into Alaska. It contains continuous and discontinuous permafrost which is limited by the -1°C mean annual isotherm and maintained by plant and snow cover (minimum 40cm snow). Plants and animals in the Subarctic are adapted to cold weather, wind, snow and winter for most months of the year. Climatic variability (within and between years) is greater in the Subarctic than in other biomes. During the brief summer, long days of continuous or near continuous light provide a long enough growing season or summer for species adapted to the high quantity, low quality light. The latitudinal range for the Subarctic is 50°N to 70°N.

Boreal

The boreal forest is within the Subarctic climate and is dominated by coniferous trees with patches of deciduous trees. Soil is usually poorer quality than that of the temperature forest and rocky from the presence of the Canadian Shield. Most of the discontinuous permafrost is found in the boreal region. Wet areas such as bogs and fens are common and plants and animals are adapted to deep snow. The boreal forest biome covers nearly 5 million km^2 of the Canadian landscape.

Tundra

Tundra is characterized by few or no trees and species adapted to heat conservation and taking advantage of snow cover as protection during the winter by being low to the ground. Adaptations by plants and insects such as orientation to the sun and growth of heat conserving hairs are found. Wildlife species such as small mammals devise ways to survive by remaining under the snow for most or all of the winter to benefit from the warmer temperatures at the snow-ground interface. Permafrost is continuous and the environment is very dry with little precipitation. That which does fall, falls mainly as snow. Patterned ground is present from freeze-thaw action. It is the southern tundra that is referred to in this thesis. The southern portion of the tundra biome covers approximately 1 million km^2 of Canada.

Gravel (disturbance or -dominated substrate or site)

The term gravel is used loosely throughout this thesis. It does not strictly include only particles in the 2-75mm range, but refers mainly to material larger than sand (>2mm). Thus the term can include pebbles (2-64mm), cobbles (64-256mm) and boulders (>256mm). Gravel disturbances or gravel-dominated substrates or sites can include those that naturally occur (as in beach ridges or eskers), however except where this is clearly stated, the term is used to refer to man-made or human-induced disturbances such as roads, building pads and borrow pits. Aggregate is also a synonym for gravel including coarse or fine (but still >2mm) particles.

Disturbance

Land on which material (soil, earth, gravel) has been removed or deposited. In terms of this thesis, disturbance refers to an area where human activity has altered ecosystem function with a significant loss of biomass. Disturbances can be natural; however, in this thesis the term is used to refer to human-induced disturbances.

Undisturbed plant community

The term undisturbed plant community defines the area normally surrounding or adjacent to the disturbance which has not be affected in any noticeable way by human activities. The original soil type and structure as well as the original plants are present. If restoration was selected as the end goal of the project then the undisturbed plant community would be used as the baseline or template to work towards and the mark for determining success.

REVEGETATION – NATURAL AND ASSISTED

Succession

There is often the assumption that the Arctic (and Subarctic) is a fragile ecosystem, however, this is not the case. The North is quite resilient; the difficulty is that its recovery time is much slower than that of southern ecosystems (McKendrick, 1997b). The true danger to northern ecosystems is not disturbance itself, instead it could be the subjection of areas to high frequency of disturbance, affecting large areas at one time or where the landscape is fragmented into small undisturbed blocks and in all cases there is insufficient time for recovery.

Disturbance destroys the equilibrium of the climax or stable community (Clements, 1936). Each seral stage is dominated by a different suite of plants which is replaced by another suite in the progress towards the climax sere (Clements, 1936). However, because the environment of a gravel disturbance is quite different from that of the undisturbed community, the climax of the gravel disturbance may look similar to an earlier seral stage in the undisturbed community. Without disturbance, the climax sere is usually climate controlled (Clements, 1936).

Left alone many severe gravel disturbances will have little recovery on a human time scale. The substrate is so altered that vascular plants cannot grow on the site until the conditions are improved (Walker *et al.*, 1987) (Figure 1-2). Because of the lack of suitable growth substrate and seeds or propagules, these sites must follow a primary succession sequence (Cargill and Chapin, 1987). Most gravel disturbances, with human assistance can be reclaimed to "negative functional recovery" (Figure 1-2). That is, the system is stable and functioning but productivity is less than the surrounding undisturbed community (Walker and Everett, 1987; Strandberg, 1997). Dry sites are more resistant to change, but less resilient than wet sites (Strandberg, 1997). However, there are some upland communities, such as those dominated by *Dryas* spp. where resilience and resistance are low (Strandberg, 1997). Resilience refers to the system's ability to return to the pre-disturbance conditions, while resistance is the ability to withstand change (Forbes, 1993). If the system's resistance threshold is surpassed then the community's composition changes and productivity decreases (Walker and Everett, 1987). However, if the resilience threshold is exceeded then the system cannot naturally return to the pre-disturbance state (Walker and Everett, 1987), except on a long timescale. This is the case in most gravel-dominated disturbances.

Competition is not normally an important factor in the establishment of plants on gravel disturbances except where individuals come into direct contact as available space becomes occupied (Forbes, 1993). The establishment and survival of species is the most important factor rather than competition and species replacement (Forbes, 1993) which is more common in normal successional processes. The pioneer stage of natural gravel revegetation is dominated by species such as *Chamerion latifolium* (L.) Holub (sic *Epilobium latifolium* L.), *Astragalus alpinus* L. and *Oxytropis* spp. At its climax the community would likely resemble that of willow or *Dryas* heath (Bliss and Cantlon, 1957) but the system might never reach this climax.

Because the original soil and thus growth substrate has been so changed, the climax or stable community that the succession of the site will tend towards will be different from that of the pre-disturbance or surrounding undisturbed community (Kershaw, 1984; Huston, 1994). Determination of the climax community is also difficult as the community is always changing (Kershaw, 1984) and what point we assess the community will determine our evaluation of succession. Given enough time it is assumed the community will evolve towards that of the pre-disturbance community. However, the time required for this is so unreasonably long in terms of the human life span, that this might never become a reality.

Natural Revegetation

Natural revegetation of disturbed sites produced by gravel extraction can result in low species diversity (Cargill-Bishop and Chapin, 1989; Borgegard, 1990) compared with undisturbed Subarctic plant communities which can be diverse. Leaving disturbed areas to recover naturally costs little, however, it leaves the sites biologically barren for long periods and also leaves them open to colonization by non-native, weedy species (Staniforth and Scott, 1991). Staniforth and Scott (Staniforth and Scott, 1991) discovered naturally recovering abandoned disturbances near Churchill did not have any of the 106 weedy species present in the region. Sites that were unstable or which were recently disturbed were susceptible to introduced species such as *Sinapis arvensis* L. (sic *Brassica kaber* (DC.) L.C. Wheeler), *Capsella burse-pastoris* (L.) Medik., *Chenopdium album* L., *Descurainia sophia* (L.) Webb ex Prantl, *Erysimum cheiranthoides* L., *Poa pratensis* L., *Polygonum arenastrum* Jord. ex Boreau, *Polygonum convolvulus* L., *Potentilla norvegica* L. and *Thlaspi arvense* L. Weedy taxa have increased over the past 30 years in the Churchill area due to a shift in grain shipping from wheat to weed-rich barley (Staniforth and Scott, 1991). Refuse tips (piles of waste material from grain processing) were determined to be the best sites for weed seed production (and worst as a threat to the natural plant communities) as the decomposition of the organic material provided a sheltered, nutrient-rich, warm environment which thawed sooner in the spring to produce a longer growing season. Two of the most invasive species were *T. arvense* and *Crepis tectorum* L. as these species were reproducing and thus were able to expand their populations. Neither of these species was found in native plant communities even when present in the general area, therefore the best way of preventing weed invasion is to promote or establish the growth of native plant communities on these disturbances.

If abandoned long enough some disturbances will be naturally revegetated (Borgegard, 1990; Forbes and Sumina, 1999). Forbes (1993) found that patchy sites with poor species composition were those that had been disturbed the most intensely regardless of how much time had elapsed since the disturbance. Borgegard (1990) examined borrow pits up to 100 years old in Sweden and found species such as *Sorbus aucuparia* L., *Picea abies* (L.) Karst., *Juncus effusus* var. *conglomeratus* (L.) Engelm. (sic *Juncus conglomeratus* L.), *Potentilla erecta* (L.) Raeusch. and moss spp. (such as *Pleurozium schreberi* (Brid.) Mitt.) in the older pits. However, these naturally revegetated pits were very different from, and always less species rich, than the surrounding undisturbed plant community, especially within coniferous forest. Species richness was lower within boreal pits because the species invading are usually pioneer species, of which there are fewer. As generalists, these pioneer species are able to out-compete other native species (of which there are more). In some cases species richness can be higher on the naturally revegetated disturbances, but this is in situations where the undisturbed communities were impoverished to begin with (Kershaw, 1984).

The ability of species to invade a disturbance is dependent on the availability of seed, seed dispersal patterns, seed viability and germination, seedling establishment and growth to maturity and reproduction (Younkin, 1974). Of these, testing in the Tuktoyaktuk, NT (Younkin, 1974) region listed germination as the key determinant for species establishment on disturbances. Temperature was the main control on species preferring warm temperatures (≈20°C) (Younkin, 1974; Clebsch and Billings, 1976), but germination can occur at temperatures as low as 5°C to 0°C (Younkin, 1974; Shaver and Billings, 1977) as long as the colder temperatures were not continuous (Younkin, 1974). Direct sunlight is also a requirement for germination of most species (Walker, 1996). The warmer temperatures and direct sunlight are usually conditions present in bare gravel-dominated disturbances (Densmore, 1979; Gartner, 1983).

Assisted Revegetation

Assisted revegetation is useful because it shortens the timeline to success and eases the recovery of a disturbance helping it blend with the surrounding landscape (McKendrick *et al.*, 1992). However, it must be qualified that this 'shortened timeline' (i.e. less than 10 years) is by no means guaranteed, especially with gravel-dominated disturbances. Even with assistance it can take several decades to blend a graveled site in with the surrounding undisturbed plant community (Bradshaw, 1984).

McKendrick *et al.* (1992) observed that wildlife preferred using revegetated gravel disturbances over the surrounding undisturbed tundra, possibly because of the availability of young and more palatable plants. These sites are also preferred by migratory birds. Others (Densmore *et al.*, 1987) have found moose (*Alces alces* (Linnaeus, 1758)) to be attracted to willows often used in gravel revegetation. So plant species selection can be designed to attract specific wildlife species if that is one of the reclamation goals and use of the site by wildlife will not hinder the revegetation process. Species selection could also be directed to the creation of a diverse plant community. This can be done by selecting a number of different species with a range of life cycles (annual, biennial, perennial), longevity, growth forms and reproductive strategies (Smreciu *et al.*, 2003). It should also include species that are adapted to the habitat of the disturbance, are available, have no regulatory restrictions (such as non-native species in national Parks) and that will be a useful addition to the desired end land use (e.g. palatable or unpalatable to wildlife) (Munshower, 1994).

Substrate manipulation can reduce the overall cost of revegetating sites by creating a substrate more hospitable to invading native species and reduces the amount of seed that needs to be applied in a seed mix application. Substrate manipulation can result in more rapid revegetation than if the site were left to recover naturally (Johnson, 1987b). The physical system (substrate) must be improved/stabilized before the biological system (plants) can be expected to succeed (i.e. decreased bulk density and particle size, increased water holding capacity and nutrients) (Walker and Everett, 1987). One method of substrate manipulation is to improve the nutrients and provide a suitable growth medium by adding an organic amendment (Gartner *et al.*, 1983; Bateman and Chanasyk, 2001). In soil, organic matter usually refers to humus or decayed plant and animal residue. However, in reclamation it is used to describe humus plus any source of carbon that is added to the soil (Munshower, 1994). This could be the original overburden (soil removed from the surface, typically the A horizon, during construction of the disturbance), commercially produced topsoil, wood chips, peat moss, straw mulch, sewage sludge or fly ash. The latter two are not well suited to gravel situations because of the rapid internal drainage and exposure to wind.

The addition of wood chips is a cost-friendly amendment since wood chips are readily available in most areas and where they are not, are light to ship in comparison to topsoil. In the eastern United States, wood chips increased the total nitrogen (N) content of a mine spoil substrate by 10% and mineralizable N by 50% more than the control (Schoenholtz *et al.*, 1992). The climate at Churchill is far different from that of the eastern United States; however, the same principles can be applied, just with an expectation of lower N values because of slower decomposition. One downside of wood chips is although they provide a good source of N in the long-term; their benefits are not immediately apparent because of slow decomposition. They could be used in conjunction with another, short term amendment, but alone or in combination, it is unlikely wood chips would provide any benefits to the soil that seedlings could take advantage of.

Straw mulch is another way to add a slower decomposing source of N to a site. However, this method requires infrastructure to keep the mulch from blowing away. Chambers *et al.* (1990) placed mulch between two layers of plastic netting and staked it to the ground using 'U' pins, however even with the additional infrastructure only 20-30% of the straw added was still present after two years. So in windy environments this is not a very effective method. In some projects, this plastic netting is left in place permanently or it can be removed by hand. Unfortunately, removal is labour intensive and can cause damage to the plants, especially those that are shallow-rooted. Another downside to straw in the Subarctic is the potential for transportation of weedy species within the straw to the disturbance.

Topsoil, defined as the naturally-occurring mineral or organic material at the surface that supports the majority of plant growth (Soil Classification Working Group, 1998), has also been called coversoil in reclamation projects (Munshower, 1994). The addition of topsoil or coversoil is another organic amendment. It increases the water-holding capacity, decreases the bulk density, and traps, collects and stores organic matter, fine material, litter, seeds and nutrients on a site (Ontario Ministry of Natural Resources, 1978; Johnson, 1981; Gartner *et al.*, 1983; McKendrick *et al.*, 1993; Sharp *et al.*, 1995; McKendrick, 1999). Less than 5cm of topsoil can support (Ontario Ministry of Natural Resources, 1978) and significantly improve plant growth (McKendrick, 1997b) and accelerate establishment (McKendrick, 1997a). On Alaska's North Slope, adding topsoil resulted in 30% greater canopy cover than untreated plots and topsoil alone was the second best treatment (behind seeding) for increasing cover of native forbs (McKendrick *et al.*, ; McKendrick, 1999). Topsoil also increased the CEC of the substrate which resulted in higher concentrations of N and calcium in the tissue of the plants on the topsoiled plots. However, the best feature of topsoil (and many other organic amendments) is that it can significantly increase the moisture-holding capacity of the substrate (Jorgenson and Joyce, 1994) which can result in improved growth (Jorgenson *et al.*, 1993). Because there is little clay in most gravel-dominated topsoils the water in the substrate is held at low tension making it readily available to plants (McKendrick *et al.*, 1993).

Peat moss (peat) is a useful soil amendment because its decomposition provides a slow release of N (Logan, 1978). The best feature of using peat moss on excessively-drained substrate such as gravel is that it increases the moisture-holding capacity of the substrate by changing the total porosity (Logan, 1978). This enhances the water storage on these sites which benefits plants (Moskal *et al.*, 2001). This relationship has been observed in Churchill (Rouse and Kershaw, 1971). Peat should be incorporated into the gravel to reduce its loss due to wind and water erosion, and to reduce the drying out of the substrate (Logan, 1978). Other benefits of peat moss are that it traps small particles and prevents erosion of fine material, lowers surface pH (which is an excellent side-effect in calcareous high pH substrate such as that of Churchill), moderates substrate surface temperature fluctuations, increases the CEC, improves root distribution, and reduces bulk density (Logan, 1978; McKendrick *et al.*, 1993; Querejeta *et al.*, 2000; Moskal *et al.*, 2001). Drier soils freeze and thaw more rapidly than wetter soils (Sharratt *et al.*, 1999) which can be harmful to seedlings and seedling roots, so moderation of this effect by the peat moss is beneficial. The additional moisture provided by the peat, even if only in small amounts is valuable because the species present on the gravel disturbances are adapted to low moisture conditions so they are efficient at taking advantage of small amounts of water, even near the permanent wilting point (Querejeta *et al.*, 2000).

These soil amendments, especially topsoil and peat moss increase the water-holding capacity of the substrate. Most Arctic/Subarctic species have seeds that are adapted to drought and can germinate once suitable moisture conditions develop (Younkin, 1974). Any moisture added to the site through snow melt water or rain will be better retained by organic matter/amendments and provide suitable germination habitat.

Chemical fertilization is another way to increase the nutrient status of the substrate. Decomposition is slow due to the lower temperatures in the North so nutrients are not recycled as quickly as they are in southern environments (Johnson, 1987b). Due to slower decomposition and the ability of Arctic plants to conserve nutrients once they are obtained, fertilizer can have a long-lasting effect. A N:P:K:Mg:Ca:S:B:Cl fertilizer mixture increased plant survival by 20% and germination frequency by 90% in certain native plant species in Svalbard (Klokk and Rønning, 1987). High Arctic studies (Babb, 1974) found *Dryas integrifolia* Vahl and *Saxifraga oppositifolia* L. responded best to a NPK fertilizer mix applied at 336 kg ha^{-1} and *Cerastium alpinum* L. displayed a 15-fold increase in biomass following fertilization despite being rare in the undisturbed community. Other fertilizer studies (Babb, 1972) found *Draba* L. spp. responded well to NPK fertilizer and rapidly invaded disturbances due to more efficient seed production. However, whatever fertilizer was not immediately assimilated by the plants was lost to immobilization or leaching (Babb, 1974). Thus, fertilizer application rates must take into account the well-drained nature of the substrate.

Another method of substrate manipulation is to physically alter the topography on a macro-, meso- or micro-scale. The creation of ridges and troughs, or depressed hollows across the gravel disturbance provides micro-sites for the establishment of seedlings. Additional moisture and even nutrients are collected in the troughs, providing suitable moisture for germination, and protection from wind for emergence (Errington, 1975; Lesko *et al.*, 1975; Mitchell, 1987; Smreciu *et al.*, 2003). Depressions as shallow as 2.5cm can collect seeds and fine mineral and organic material which can promote germination and seedling establishment (Lesko *et al.*, 1975) as well as plant density (Etter, 1971).

Roughened surfaces create microsites which increase germination rates because of the additional moisture collected in the troughs or depressions (Johnson, 1981). Species richness and abundance is also greater in the microsites (Forbes, 1993; Lewis-Smith, 2000). The surface roughness also helps to cut windspeed and increase snow accumulation (Pomeroy and Gray, 1995). In an Alaskan study, snowcover reduced plant winterkill by 57% (Klebesadel, 1974). If the microtopography alteration is done to set up terraces on slopes it helps increase infiltration and discourages runoff (Querejeta *et al.*, 2000). Densmore (1987) found that meso-scale (20-30cm) ripped furrows in borrow pits were more important for seedling growth (especially *Chamerion* and woody species) than fertilization.

Topographic alteration can also be done through adding structures to the surface to create larger-scale wind protection. Berms made out of substrate can help by providing sheltered, moister areas for plants to grow and snow fences, ideally with a porosity of 40-60%, can be effectively used to accumulate snow on normally windswept surfaces such as gravel (Pomeroy and Gray, 1995). Jorgenson *et al.* (1993) used 0.5m and 1m high berms to trap snow on gravel disturbances. They found the smaller berms were not efficient at capturing snow, but even in dry years the bermed quadrates were the only areas with any snow cover (<5cm). The higher berms collected much more snow and in the trough areas it remained for about two weeks longer in the spring than non-bermed areas.

McKendrick *et al.* (1992) and McKendrick (pers. comm., 2001) found that berms did not work very well in their revegetation experiments on Alaskan drilling pads. They replaced the ineffective berms with 1.2m plastic-mesh snow fencing. The fences collected snow, allowing it to pile up and provide additional moisture to the site (McKendrick *et al.*, 1992) as well as protection against the abrasive action of wind and snow particles on vegetation (Scott *et al.*, 1993) by burying it. The fences were left up year round as they collected soil and plant particles helping to reduce erosion, and they provided a wind break for vegetation

(McKendrick *et al.*, 1992). The 1.2m fence height was determined to be too high in that it collected too much snow and left the sites covered late into the growing season. The height was shortened to 0.6m which accumulated the same height of snow and was determined to be the optimum height. Plots without fencing were snow-bare in the middle of winter and averaged only 12.7cm of snow cover. An additional benefit of the snow fences was that they deterred ground squirrel predation of seeds and emerging vegetation (McKendrick *et al.*, 1992) which can be a major problem (Jorgenson *et al.*, 2003). This avoidance was assumed to be because the squirrels were not able to easily see approaching predators. Fencing can also be used to prevent caribou grazing if it encloses the site (McKendrick *et al.*, 1992). Jorgenson *et al.* (1993) acknowledged that the berms do not collect as much snow as fencing; however they believed that berms are more effective in the long term because they are permanent and require no maintenance.

In the case of berms or fencing, the snowpack collected provides greater soil recharge in the spring (Sharratt *et al.*, 1999) and depending on the freeze-thaw conditions can pool on the substrate surface for up to a week at melt (Jorgenson *et al.*, 1993). Much of this additional moisture is lost to throughflow or evaporation, but when applied in combination with an organic amendment, the peat or topsoil can retain some of this moisture by increasing the storage capacity of the gravel (Jorgenson *et al.*, 1993). This is especially important when there is little rain and high radiation (Jorgenson *et al.*, 1993).

Another benefit of the snowpack created by berms or snow fencing is the formation of pukak (depth hoar), and thus a milder temperature at the ground surface. Pukak can be the most important snow feature governing vegetation composition by protecting the seedlings and allowing preferential selection of chionophilic (snow-loving) species such as *Salix lanata* L. (Schafer and Messier, 1995). However, this increased snowpack can also select against chionophobic species such as *Oxytropis* spp. and *Saxifraga oppositifolia* (Schafer and Messier, 1995).

Encouragement of native legumes can be beneficial to other plant species. Some species are N-dependent and although they will grow on graveled sites without sufficient N, their growth and production is enhanced by its presence. Legumes are a slower, but longer-term alternative to fertilizer for adding nutrients to the substrate through N-fixation. Cargill-Bishop and Chapin's (1989) vegetation survey of abandoned gravel pads in Alaska found native legumes such as *Oxytropis borealis* DC., *O. campestris* (L.) DC., *Hedysarum mackenzei* Richards. (sic *Hedysarum mackenzii*), *H. alpinum* L. and *Astragalus alpinus* to be common. *O. borealis* normally grows on gravel bars in riparian areas and is not found in the surrounding tundra but it was the second most frequent native species on the gravel pads. They also found that more species were present on pads closer to riparian areas than those farther away, possibly due to many forbs having larger, heavier (and thus more difficult to transport) seeds. Presence of these species at sites not adjacent to riparian areas can be facilitated through seed collection.

Harvesting seeds from species that naturally grow on riparian gravel bars and other gravely sites improves chances of establishment because these species are adapted to lack of shelter and coarse-grained substrates (McKendrick *et al.*, 1992). As well, those disturbances located closer to areas with gravel bars and riparian areas will have more successful natural revegetation (Johnson, 1987b; Cargill-Bishop and Chapin, 1989; Jorgenson *et al.*, 2003).

McKendrick (pers. comm., 2001) conducted a ten year experiment on a drilling pad in Alaska in which the following forbs were the most successful of all plant species (>90% germination): *Artemisia campestris* var. *borealis* (Pallas) M.E. Peck (sic *Artemisia boreale* Pallas), *Hedysarum* spp., *Oxytropis* spp. and *Castilleja* spp. The additional benefit of these forbs was that they have visually-appealing flowers (McKendrick *et al.*, 1997). *Salix* spp.

such as *S. alaxensis* (Anderss.) Coville, *S. glauca* L., *S. planifolia* Pursh, *S. lanata*, *S. myrtillifolia* Anderss. and *S. reticulata* L. did well in colonizing gravely substrate in the Northwest Territories (Harper, 1994). This is because they have high turnover, grow rapidly and produce abundant, light seed which is important for early colonizing species.

One method of encouraging colonization of a disturbance is through application of fertilizer to the surrounding undisturbed plant community. Chapin and Chapin (1980) found *Eriophorum vaginatum* L. from the undisturbed community was better at revegetating a cleared area (not gravel-dominated) than commercial grass seed varieties including *Poa* spp. and *Festuca* spp. This method enables use of native species and is a more cost-effective method for revegetating large areas without having to harvest or buy seed.

Fertilization of the surrounding plant community also helped the native sedges. After 10 years, all traces of the commercial plants were gone and the sites were more productive than the surrounding undisturbed tundra covered mainly by *E. vaginatum* and *Carex bigelowii* Torr. ex Schwein. Fertilizer application to the actual disturbed site was not necessary, but fertilization of the surrounding plant community increased (25 times) seed production of *E. vaginatum* which has a small, light seed. However, the cleared area in this experiment was not a graveled area, and *E. vaginatum* is usually found colonizing frost boils in Alaska (Chapin and Chapin, 1980) and seismic lines and vehicle trails in Tuktoyaktuk Peninsula (Hernandez, 1973) because it grows best on moist sites.

Despite the difference between these environments and gravel-dominated disturbances, the same principle of fertilizing the natural plant community could be applied. The pioneer species might not be frequent or obvious in the surrounding plant community, but they can be present and will respond quickly to the additional nutrients provided by fertilizer by producing more seed.

Although many revegetation experiments in the Arctic and Subarctic have used non-native (agronomic) plant species, native species are now generally viewed as a better alternative, especially in the long-term. Non-native species establish quickly and are valuable on highly erodible sites, however they are not suited to the growing conditions in the Arctic/Subarctic and can quickly die off, leaving a mat of litter which can inhibit colonization by native plants (Younkin and Martens, 1987).

Cargill-Bishop and Chapin (1989) assessed an 18 year old gravel pad that had been "successfully restored" (p.1080) using non-native species eight years prior to their study. They discovered only 0-7% of the plant cover was living with the remaining cover made up of dead plant material (Cargill-Bishop and Chapin, 1989).

Densmore (1992) determined that sites revegetated with a non-native grass species (*Festuca rubra* L.) severely inhibited the growth of *Salix alaxensis*, a shrub which normally dominates sandy sites in the area. Non-native species are rarely able to set seed without fertilizer additions, nevertheless they can be persistent in the boreal forest where they can out-compete native species (Dabbs *et al.*, 1974; Webber and Ives, 1978). This competitive advantage could be because the non-native species form dense, shallow roots which create a warmer, drier, more hostile environment for incoming native seeds. As well, the non-native species take up much of the already scarce N in the system (Densmore, 1992). *Festuca rubra* has been documented to produce root leachates which can be lethal to native species seedlings (Densmore, 1992). McKendrick (1998) found that seeded non-native species were preventing succession by native species even after 25 years. Often the inclusion of non-native species involves only a few species creating a near monoculture on the disturbance (McKendrick, 1991a).

Native species are better adapted to northern climate conditions, such as reduced light, growing season length, and temperature; and increased snow cover and wind

(Klebesadel, 1973, 1974). They help maintain ecosystem diversity within and among species at the community and landscape level (Smreciu *et al.*, 2003). Native species are more preferred by wildlife. The main drawback of using native species in revegetation projects is seed availability. Northern native plant species are rarely available commercially, so their use in a project involves 'settling' for those few species available and paying high prices; or collecting seed and/or plants from the wild (Johnson, 1987b; Jorgenson *et al.*, 2003).

Seed collection can be very successful if it is a good year (warm growing season with adequate moisture) and if collection is timed for each species, since some have a very short window between seed ripeness and dehiscence. Large quantities of seed must be gathered, and often taken to a laboratory, threshed and cleaned for use in a revegetation project (McKendrick *et al.*, 1992). Seeds might also have to be cold stratified as with fall-dispersing willow species, to maximize germination (Densmore and Zasada, 1983). Seeds can be stored for a few years (Densmore and Zasada, 1983) (exact storage length tolerability is species dependent) so if too many are collected, they can be used in future revegetation projects or sold (McKendrick pers. comm., 2001). Seeds of woody species can also be collected and seedlings grown prior to planting. Collection and use of local seeds for this project was not possible because it would have delayed implementation of the study quadrats by a year.

Prégent *et al.* (1987) tested survival of *Alnus viridis* ssp. *crispa* (Ait.) Turrill (sic *Alnus crispa* (Ait.) Pursh) and *Pinus banksiana* Lamb. seedlings in borrow pits in the James Bay region. *A. viridis* ssp. *crispa* was the more successful species because it controlled erosion, was good at creating humic material because of high litter production, and fixed N if there was adequate phosphorus (P) nutrition. This P could be supplied through inoculation of the *A. viridis* ssp. *crispa* seedlings with mycorrhizal fungi or with the addition of slow-release fertilizer. *P. banksiana*, found naturally on dry, infertile northern soils, required a minimum amount of organic carbon which was not supplied by the borrow pit substrate. Consequently it is recommended only for sites where there is enough organic carbon, or in association with *Alnus* spp. which can act as a source.

Some of the difficulty in establishing a plant community is successful germination. An experiment in Denali National Park, Alaska collected native seed from plants within the park. They then germinated the seeds in a lab and then planted seedlings on the disturbed gravel fill to help "overcome the limitations on establishment from seed" (Densmore and Holmes, 1987 p.546). The seedlings were watered and fertilized and at some sites, topsoil was added prior to planting. In all treatments, survival of the individual plants was high (73-100% survival after one growing season). Species used included shrubs (*Dasiphora floribunda* (Pursh) Kartesz, comb. nov. ined. (sic *Potentilla fruticosa* auct. non L.) and *Salix alaxensis*), forbs (*Arnica frigida* C.A. Mey. ex Iljin, *Artemisia tilesii* Ledeb. and *Aster sibiricus* Linnaeus), leguminous forbs (*Astragalus eucosmus* B.L. Robins., *Hedysarum alpinum*, *Oxytropis campestris* and *O. deflexa* (Pallas) DC.), and a grass (*Festuca altaica* Trin.). Plants grown from cuttings of *D. floribunda* were used as this species is found growing on dry, unstable slopes in the Park (Densmore and Holmes, 1987). A concern with accepting these findings as successful is that the seedlings were planted with the soil plug in which the seed had been germinated. The plug was made up of a peat/silt/sand mix and it was not determined whether the seedlings were still living within the plug or whether the roots had grown into the gravel fill. Although establishing seedlings is more labour intensive than seeding, it resulted in higher survival rate percentages than seeding and provided a sparse yet immediate cover on the site which is good for aesthetics. Using seedlings also helps remove losses from rodent seed predation (Densmore and Holmes, 1987).

Transplants are another revegetation strategy that is an option if there are suitable plants in the area which can be transplanted (Johnson, 1987b). A concern with transplantation is that the shock to the plant of the new substrate can result in high mortality which is not cost-effective for a technique that is very labour intensive. Collecting plugs of native plants is another method as it allows the plants to adapt more slowly to the new environment because there are some available nutrients in the intact clump of soil. Any dormant seeds in the soil plug could colonize the new site while starting out in a suitable growth medium (Klokk and Rønning, 1987).

Willow cuttings are another way of establishing plants on a graveled site (Johnson, 1987b). Cuttings can be inserted into the soil to root (Skriabin, 1981). Species selection is important as illustrated by Prégent *et al.* (1987) where they found that *Salix planifolia* and *S. bebbiana* Sarg. cuttings were not suitable for revegetating borrow pits because of low soil N levels.

The use of native species in northern revegetation is preferred since they can grow rapidly, reproduce at a high capacity, germinate in a variety of conditions, and resist cold and frost (Skriabin, 1981). The contribution of each species to aesthetics (Densmore and Holmes, 1987; McKendrick *et al.*, 1992) can be important if enhancing appearance is one of the goals of the project. Often northern perennials are best seeded in the spring as there is enough available moisture for them to germinate and it provides the plant with the longest growing season possible. If the plant can produce tillers, it will over winter in the tillering stage (Johnson, 1981; Skriabin, 1981). This will improve the likelihood of it surviving the winter and developing normally during the second growing season. Watering is also important to establishing native species in dry years. Other recommendations to aid in revegetation success include seeding onto a damp surface and lightly raking the seeds to maximize contact with the substrate (Skriabin, 1981).

Seeding rates of 0.6-2.7kg ha^{-1} (McKendrick, 1997b) and 1000-3200 seeds m^{-2} (Walker and Everett, 1987) have been recommended for use in Alaska on gravel pads to establish cover of native species and still provide space for other plants to colonize the site (Walker *et al.*, 1987; McKendrick, 1997b).

Seedling/Revegetation Failure

Revegetation success is not guaranteed, especially in the short-term. There are several steps at the beginning of the revegetation process where failure can occur. The first is the seed source (Bradshaw, 1983). Seeds must be available on site either through the seed bank or seed rain, or added through human manipulation. Then once the seeds are on site, they must be adapted to the conditions (dry, exposed, low nutrients) of the disturbance (Bradshaw, 1983). After these conditions have been met, revegetation can fail due to lack of germination. This can result from seeds with an impermeable seed coat that were not scarified or otherwise treated, insufficient oxygen either from the seed being sown too deep or being too wet and insufficient moisture which is affected by temperature. Fluctuations in temperature and moisture levels can lower seed viability and eventually result in death (Vough *et al.*, 1995). Failure can occur in the emergence stage. Drying, freezing, poor soil-seed contact (either too lose or too compacted) or depth (too deep or too shallow), a crusted soil surface (usually in fine-textured soils) and toxicity from direct contact with fertilizer or improper use of herbicides can all prevent seedlings from emerging (Vough *et al.*, 1995). Once the seedlings have emerged, they can fail in the growth stage, either exhibiting stunted growth or dying due to unsuitable pH, low soil fertility, poor or excessive drainage, competition (although this is usually not a major source of mortality until the seedling are established plants (Gartner *et al.*, 1983)), herbivory, pathogens, winter kill (death due to lack of winter hardiness) and especially drought.

Drought is the most common reason for seedling failure. It is expected that only one third of sown seed will result in seedlings and of that only one half of the seedlings will survive the first year (Munshower, 1994; Vough *et al.*, 1995). Native forb seedlings have a slightly better survival rate where 20-40% survive the first growing season and will reach maturity (Smreciu *et al.*, 2003). However, the mortality rate is expected to be even greater in the colder, growth limiting conditions of the Subarctic and gravel-dominated substrates.

Winterkill is another major reason for seedling failure which can occur when the plant is not physiologically prepared for winter. These changes are triggered by shortening of the photoperiod and increasingly colder temperatures and involve cessation of growth and commencement of phenological changes such as lowering tissue water content (Klebesadel, 1977). The actual death of the plant is a result of cold stress, desiccation (dependant on the velocity and duration of wind), disease (such as mould or rot), suffocation (due to an icy layer in the snowpack), physical injury (abrasive ice particles), soil heaving and/or warm winter periods which trigger the plant into breaking dormancy leaving it unprepared for the resumption of winter (Klebesadel, 1974, 1977). Gartner *et al.* (1983) determined summer mortality to be the main cause of seedling loss in first year seedlings but that winter mortality was the main mortality factor for second and third year seedlings, with many instances of winter herbivory (because the seedlings were easier to spot on the gravel disturbances than plants on undisturbed areas).

EXTENT AND HISTORY OF GRAVEL DISTURBANCES IN THE CHURCHILL AREA

Use of Geographical Information Systems

A database of all the disturbances in the area, including their ages (creation and abandonment), current status (abandoned or active), size, causal agent, disturbance type (pit, pad, road, etc.) and current state of recovery was created using Geographical Information Systems (GIS) to aid determination of the extent of disturbed gravel areas in the Churchill region. An attribute for sites already being studied was also included with a contact name to encourage research overlap and provide a public record of the sites as areas where research is in progress which may aid in their conservation.

Previous studies (e.g. Firlotte (1998)) resulted in an inventory of potential areas for aggregate extraction and another map of areas that had been exploited. Although this information in the form of an undigitized map is useful; a digital form would be more user-friendly especially when accompanied by information beyond that found in the legend. By transferring this information into a GIS database (ArcGIS 8.2, ESRI, California, 2002), adding in gravel pads and abandoned roads, as well as attributes about each disturbance it is now a resource for researchers and land users/managers in the area. It can now be used by organizations considering reclamation of some of these disturbances or for future development permit applications. It can be queried to provide quantitative data, for example on the total area disturbed and the amount of ecosystem fragmentation.

The chronology of site disturbances was attempted by mapping them based on aerial photographs taken since the mid-1920s borrowed from Dr. Richard Bello (York University). The aerial photographs were scanned, geo-rectified against a geo-referenced and ground-truthed 5m resolution IRS imagery (provided by Cam Elliott, Manitoba Conservation). Borrow pits and other gravel disturbances are easily detected off of the aerial photographs due to their light colour. However, the years for which the aerial photographs were available precluded any accurate dating of these disturbances. Most of the disturbances were created in the 1960s and 1970s for which no photographs were available free of charge. If these missing images are acquired in the future, they can be added to the database and disturbance creation dating can be completed.

Groom (2001) determined there to be six active pits in the Churchill region, and that these were designated for use in concrete and asphalt for the Town and airport runway repairs. However, of the 54 sites visited by Firlotte (1998), she found almost half of them were still being disturbed in some manner (e.g. ATVs, hunting, extraction). The map which accompanied the Groom (2001) study was scanned and digitized for inclusion in the GIS. It provided the main source for querying the extent of disturbances in the Churchill region.

Of the available sand and gravel in the study area (Figure 1-3), 5.4% of it was disturbed by gravel pits and pads (~227ha). This was slightly higher than Firlotte's estimate of 4.5% (~175ha) due to the expansion of existing pits in 2001 and creation of new pits near the CNSC. All of the existing disturbed gravel areas and 94% of the potential future aggregate sources are within 2km of existing roads, a concern about the ease of future disturbance and re-disturbance. The average gravel disturbance size was 2.30ha, but was larger for developed areas (7.43ha) which included the CNSC, settled areas outside of the townsite and the airport. The total area disturbed by human activities was 186ha which was less than that calculated by Firlotte (237ha) because of the decreased size of the study (mapped) area where the townsite was not included (Table 1-1).

Disturbance Prevention and the Manitoba Permitting Process

The disturbed sites that were the subject of this research were pre-existing. However, the study should be relevant to management of future disturbances in addition to those already affecting the landscape. Disturbance mitigation can include restricting the disturbance to the smallest areal extent possible, selecting gravel extraction sites that are not located within sensitive plant communities or where they will affect the water table and selecting sites where the surrounding plant community contains species that will be able to recolonize the disturbance. Retention of the overburden including the vegetation is the most important way to facilitate further revegetation since many of the nutrients in Arctic and Subarctic systems are stored in the topsoil and vegetation, propagules can be stored in the soil, and many plant species are capable of vegetative propagation from tissues included in the stock pile. Thus spreading the overburden back over a disturbed site can return nutrients (those remaining after storage losses) back to the site and facilitate species colonization from stored propagules (Johnson, 1987b). In the past overburden was burned (Firlotte and Staniforth, 1995) rather than stockpiled. On aggregate deposits in the Churchill region the overburden can be discontinuous to only a few centimetres thick. Preservation of this topsoil is likely not feasible (Densmore, 1987). Harvesting topsoil from adjacent undisturbed areas may be a suitable option if it is known that this will not create a larger-scale disturbance. Since wetter areas naturally recover much faster than dry or xeric areas (McKendrick, 1987; Jorgenson *et al.*, 2003), removal of topsoil from the surrounding areas if there is sufficient depth, can be a viable option.

Regulation of gravel pits is another important measure in prevention of further gravel-related disturbances. The permitting process should ensure that new pits; roads and pads are not constructed when there are other suitable existing alternative such as reactivating abandoned corridors or extraction sites. Other methods of accessing sites rather than using gravel roads, such as winter snow roads can help reduce the long-term effects of gravel disturbances. With winter or snow roads, compacted snow is used to construct the roadbed creating less of an impact on the soil organic layers. Winter roads have no effect on active layer thickness or surface elevation (i.e., no thermokarst) and do not cause compaction if they are properly constructed (Hardy Associates Ltd., 1980).

Manitoba has a Pit and Quarry Rehabilitation Program that was created in 1992 and paid for through a \$0.10 tonne^{-1} environmental levy collected from all aggregate programs (Manitoba Industry Economic Development and Mines, 2004). Landowners can apply to have reclamation work done and paid for through the Program (Manitoba Industry Economic Development and Mines, 2004). Over 12 years the Rehabilitation Program has brought in \$14 million and spent over $10 million reclaiming 4800ha of land to agricultural use. Some areas have been changed into wildlife management areas and provincial forests and parks, but the focus has been on the southern portion of Manitoba (Manitoba Industry Economic Development and Mines, 2004). There is also a Quarry Minerals Regulation (1992) which says that no royalties need to be paid if the gravel is extracted for a public agency and used for public purposes (Manitoba Industry Economic Development and Mines, 2004). However, since there are no quarry leases in the Churchill area, no royalties or levies are charged (Manitoba Industry Economic Development and Mines, 2004), so there are no private operators to apply for rehabilitation funds.

Often whether or not a disturbance is reclaimed depends on the value of and demand for that land, what the end land use will be and the political setting (Werth, 1980). On government-owned or crown land, barren and harder to reclaim disturbances are often not seen as worth using tax payers money to reclaim (Schreckenberg *et al.*, 1990).

In Manitoba the Sustainable Development Act lists rehabilitation and reclamation as Principles of Sustainable Development in Schedule A (Sustainable Development Act, 1997). It states that "Manitobans should (a) endeavor to repair damage to or degradation of the environment; and (b) consider the need for rehabilitation and reclamation in future decisions and actions." (Schedule A, 6, Sustainable Development Act, 1997). However, despite this section in the Act, reclamation does not seem to be a part of any of the Manitoba Government's division or branch missions or mandates, except for the Pollution Prevention Branch (Manitoba Conservation, 2004a) which focuses solely on reclamation (remediation) of solid waste and landfill sites. Proposed land uses causing terrain disturbances are vetted through the Environmental Approvals Branch (Manitoba Conservation, 2004b), however "old" disturbances appear to be outside government control/concern. A positive comment for Manitoba is that the Manitoba environmental technology industry is more advanced in soil reclamation and remediation in comparison with other provinces (Western Economic Diversification Canada, 2004). However, application of this technology appears restricted to southern portions of the province while the North is neglected.

PROJECT OBJECTIVES, HYPOTHESES AND GOALS

Prescribed revegetation treatments are usually site-specific and what is successful on one type of disturbance in a specific ecoregion might not be directly transferable to another. It largely depends on the degree of similarity in environmental conditions. However, because the study area occurs within an ecotone (transition) where tundra meets boreal forest (Ritchie, 1962; Stonehouse, 1989; Ecological Stratification Working Group, 1995; Conservation of Arctic Flora and Fauna, 2001), testing of revegetation methods could provide results directly applicable to the revegetation of disturbances in a much larger region (boreal and lower tundra biomes) and areas with similar environmental conditions such as in the Northwest Territories, Yukon, Nunavut, and Nunavik (northern Québec). This application to other regions is possible because the ecosystems found in the Churchill region occur from the Labrador-Ungava Peninsula west to the Mackenzie Delta. Direct application would be more difficult in the Yukon and Alaska because of the influence of the mountains on vegetation patterns (Ritchie, 1962).

Northern gravel disturbance revegetation has been studied mainly in Alaska (Gartner *et al.*, 1983; Densmore, 1987; Densmore and Holmes, 1987; Densmore *et al.*, 1987; Elliot *et al.*, 1987; McKendrick, 1987; Mitchell, 1987; Walker *et al.*, 1987; Walker and Everett, 1987; Cargill-Bishop and Chapin, 1989; McKendrick, 1991a; Densmore, 1992; McKendrick *et al.*, 1992; McKendrick *et al.*, 1993; Jorgenson and Joyce, 1994; McKendrick, 1996; Walker, 1996; Jorgenson, 1997; McKendrick, 1997a, 1997b; Walker, 1997; McKendrick, 1999), especially the effect of native species and snow fences in assisted revegetation. Revegetation research on gravel pits has also been conducted in the Churchill region (Firlotte, 1998) using fertilizer, peat moss and seeding on tundra sites. This study combined techniques from the Alaskan studies with those already tested in the Churchill region, and expanded the Churchill reclamation sites to include those in treed areas.

Project Objectives

The objective of this project was to determine which factor(s), (1) moisture availability, (2) nutrient availability or, (3) wind (and its abrasive action) was most limiting to:

a) seedling emergence and,

b) first winter (first to second season) seedling survival,

on gravel disturbances (pits and pads) in the forest-tundra ecotone.

An additional objective was to:

1) determine the suitability (based on emergence and survival) of each of the six seeded species tested (Table 1-2) for short-term revegetation of gravel-dominated disturbances in the Churchill area.

As stated above, the main objective of this project was to determine the limitation(s) to seedling growth and early survival (and thus revegetation success) on gravel disturbances. However, there were several secondary or value-added goals to be considered when evaluating project success. These included aesthetics (reduction of 'unsightliness'), ease of application of techniques for local operators, including considerations of labour and equipment needs. That is, what treatment or treatments could make a noticeable difference (biologically and aesthetically) for a relatively small monetary investment? Two key reclamation processes can be used to determine success; colonization (presence and establishment of species) and development of ecosystem function (including biomass accumulations and nutrient circulation) (Bradshaw, 1984). Two benchmarks in plant community development are: 1) initial establishment which is measured after the first growing season and is affected by climate post-seeding conditions, the ability of the seed to germination and seedling vigour; and 2) plant maturity which is usually measured after three years from seeding (Smreciu *et al.*, 2003). It is also affected by climate, but also by disturbance of the plants, competition and rate of spread (Smreciu *et al.*, 2003).

Quantifiable success of a revegetation program can be measured in many different ways depending on what the original objectives of the project were. The following is a list of possible methods of success assessment proposed by McKendrick (1997b), Streever *et al.* (2003), Gillis (1991), Munshower (2000) and Alberta Environment (2004):

- seedlings of native species establish,
- high species diversity,
- vigorous reproduction,
- high litter production,
- developing high moss cover, and/or
- significant plant cover (e.g., 85% ground cover, or a percentage appropriate for the site, based on project requirements or goals).

In Alaska (Streever *et al.*, 2003), some projects were required to obtain 30% cover in three years, however the definitions of what 'cover' included were vague and led to problems. Another consideration is that often cover and community composition are only loosely linked (Streever *et al.*, 2003). If diversity is an end goal, then cover may not be an adequate method of assessing success.

Moss cover is a good indicator of longer term revegetation success as moss species accumulate organic matter and provide a source of nutrients for other plant species

(McKendrick, 1997b). Streever *et al.* (2003) suggested that mosses and lichens should be included in cover estimates on reclamation projects. McKendrick (1987; 1991a) and Streever *et al.* (2003) argue that cover should not be used as an assessment on gravel-dominated disturbances. They suggest using the rangeland method of evaluating success and the successional trend of the community on a site-specific basis, and the establishment of self-perpetuating cover and/or use by wildlife. Assessing performance should be delayed since at least three years are needed for most native forbs to reproduce in the North (Klebesadel, 1971), and often up to seven growing seasons on gravel-dominated disturbances (McKendrick, 1999). Measuring cover of these forbs on a short timeline would not be appropriate. However, extending the time for completion of reclamation projects can be viewed as undesirable. Success, based on specified criteria should be exhibited within ten years (Urbanska, 1997). This also allows for fluctuations in success, whether measured by cover or by other means, as the site can vary in success over different growing seasons (Streever *et al.*, 2003).

Restoration of gravel-dominated disturbances is probably impossible. Some maintain that disturbances will never resemble or have the same species composition as the surrounding undisturbed plant community (McKendrick, 1987; Walker and Everett, 1987; Borgegard, 1990; Forbes, 1993; Jorgenson and Joyce, 1994; Streever *et al.*, 2003), except perhaps on an infinitely long timescale (Forbes, 1993). However, it is possible to *reclaim* these sites to blend in with the landscape and recover sustainable, ecological function within a few decades or less (Walker and Everett, 1987; Jorgenson and Joyce, 1994).

THESIS FORMAT

The layout and citation style are not consistent throughout the thesis as three of the chapters were prepared according to the guidelines for the journal they were submitted to. However, the page numbering is consistent throughout. Figures, tables and references cited can be found immediately following each chapter, with all appendices at the end of the thesis. Plant nomenclature follows that of the Integrated Taxonomic Information System available online through a partnership between United States, Canadian and Mexican agencies, organizations and taxonomic specialists (Integrated Taxonomic Information System, 2006).

TABLES

Table 1-1: Extents of gravel / aggregate disturbances in the Churchill area.

Category	Area (ha) This paper	Area (ha) Firlotte (1998)	Ave. Individual Disturbance Size (ha)
CLASSES			
Gravel disturbances (up to 1993)	181.16	175 (combined: gravel disturbances up to 1993, 1994-present, and quarry)	2.59
Gravel disturbances (1994-present)	43.84		1.66
Quarry	1.84	No Data	0.61
Developed Areas	186.21	237	7.43
Sand and Gravel Potential (undisturbed)	3973.30	3753	-
Rock and Aggregate Complexes	181.23	147	-
Exposed Bedrock	602.29	777	-
RELATION TO ROADS (within 2km)			
Disturbances (gravel, quarry and developed)	413.04	No Data	3.10
Gravel/Aggregate Available	4275.39	No Data	-
TOTALS			
Sand and Gravel Pits/Pads	225.00	175	2.30
Total Gravel/Aggregate Disturbances	413.04	412	3.10
Total Gravel/Aggregate Undisturbed	4154.53	3753	-

Table 1-2: List of species selected for seeding on reclamation test plots.

Species	Common Name	Family
Anemone multifida Poir.	Cut-leaf Anemone	Ranunculaceae
Castilleja raupii Pennell	Raup's Indian Paintbrush	Scrophulariaceae
Chamerion angustifolium (L.) Holub	Fireweed	Onagraceae
Hedysarum mackenzei Richards.	Northern Sweetvetch	Fabaceae
Hierochloe odorata (L.) Beauv.	Sweetgrass / Vanillagrass	Poaceae
Linum lewisii Pursh	Lewis' flax / Lewis blue flax	Linaceae

FIGURES

Figure 1-1: Location of study area, Churchill, Manitoba, Canada.

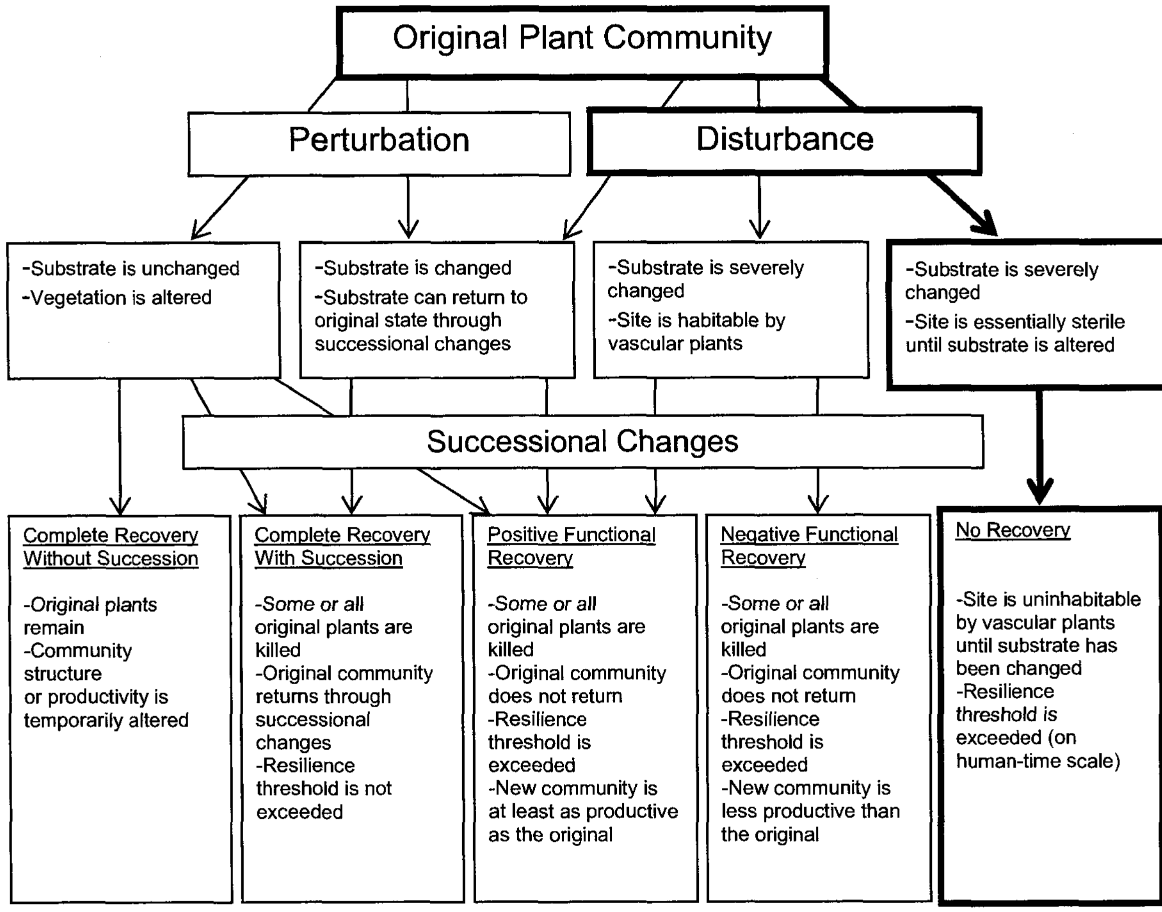

Figure 1-2: Disturbance natural succession pathways (modified from Walker *et al.* (1987) with Huston (1994). The pathway for natural (unassisted) gravel recovery is bolded.

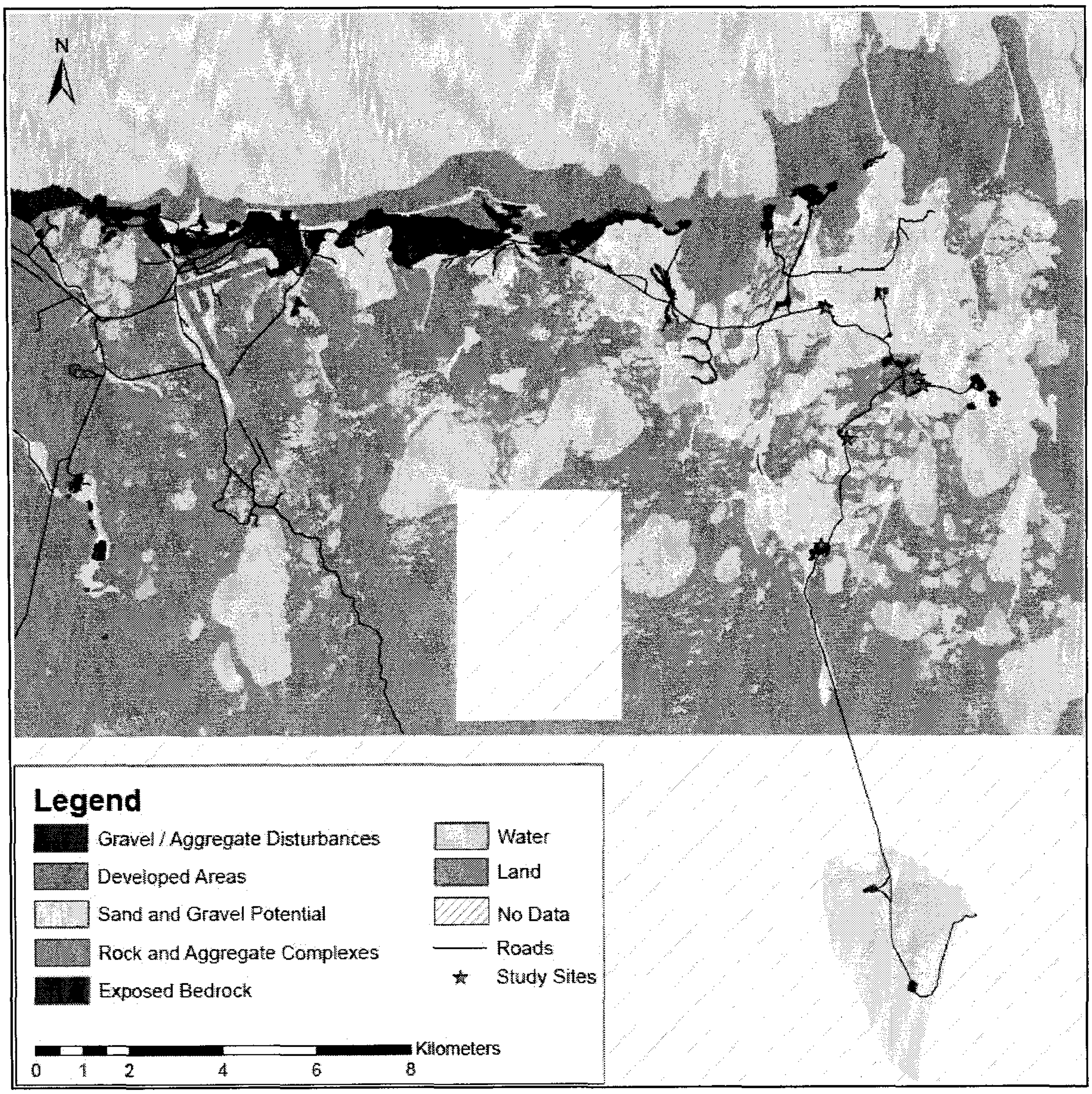

Figure 1-3: Map of gravel / aggregate disturbances and potential sources in the Churchill area. Modified from Groom (2001) with an IRS remotely-sensed image provided by Cam Elliot (Manitoba Conservation)

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CHAPTER 2 - Short-term revegetation performance on gravel-dominated human-induced disturbances, Churchill, MB, Canada[1]

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, 2003a; 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. 2-1), these gravel disturbances also include activities associated with the Churchill Research Range, a rocket launch facility that was active from the early 1950s to the mid 1980s with a short resurgence of activity in the late 1990s (Coutts, 2000). In the Churchill region all of these disturbances are close to main roads and are highly visible even in forested areas. The gravel is easy to find because of the prevalence of beach ridges (Groom, 2001), and easy to extract as the vegetation cover is not difficult to remove. This has lead to a patchwork of exposed gravel sites on the landscape.

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

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Natural revegetation in the Subarctic can be a slow process (Harper and Kershaw, 1996; Jorgenson *et al.*, 2003) due to environmental conditions such as low temperatures and high winds, and is further slowed on unsuitable growth substrate or soil created by human disturbance. These conditions, including drought and ice-abrasion, can result in major seedling failure (Vough *et al.*, 1995), further slowing revegetation. Colonization of disturbed sites in the Arctic and Subarctic is problematic because there are few seeds and because few species are tolerant of gravelly substrates (Johnson, 1987b). Eventually certain disturbances, such as borrow pits, 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, 2003a) especially within coniferous forests (Borgegard, 1990). It has been hypothesized that species richness is lower within the pits because the species in the surrounding undisturbed plant community are not well-suited to colonizing xeric substrates (Firlotte, 1998; Jorgenson *et al.*, 2003). In some cases, greater species diversity occurs in disturbances than in surrounding communities. For example, within vehicle tracks propagules are often retained in the soil (Harper and Kershaw, 1996).

The establishment of a more diverse plant community can be beneficial in returning the disturbed site to a more natural state in the long-term. The ability for biological diversity to recover depends on the type of disturbance. Recovery of community diversity is significantly lower where the disturbance involves the removal of the seed bank and vegetative propagules (as in gravel extraction or deposition operations) as compared to disturbances such as fire (Vavrek *et al.*, 1999) where residual propagules can dominate the process of revegetation.

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. Abandoned disturbed sites near Churchill that have successfully established native plant communities are not weedy despite the 106 weedy species present in the area, while sites without native plant communities have increased numbers of exotics (Staniforth and Scott, 1991).

Many revegetation experiments in the Arctic and Subarctic have used agronomic plant species; however the use of native species is now viewed as a better alternative in the long-term (Elliot *et al.*, 1987; Cargill-Bishop and Chapin, 1989; Densmore, 1992; McKendrick, 1998). The advantage of having non-native species establish quickly can be offset when they die due to a lack of adaptation to the northern environment. The dead biomass can form a dense thatch that prevents colonization by native species and seed production can be dependent on fertilizer application (Webber and Ives, 1978; Cargill-Bishop and Chapin, 1989; Densmore, 1992).

Native species are better adapted to Arctic/Subarctic climates, and they are preferred by wildlife. However, the lack of commercially-available seed is a serious limitation on their use (Younkin, 1974; Bailey, 1981; 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 (Bailey, 1981; Skriabin, 1981; McKendrick *et al.*, 1992; Scott, 1996):

- potential for rapid biomass accumulation,
- high reproductive capacity,
- broad germination requirements,
- resistance to cold and frost during the growing season,

- ability to tolerate well- to excessively-drained soil,
- nitrogen fixation potential,
- quick establishment,
- potential to improve the growth substrate to possibly facilitate the establishment of species from the adjacent area,
- perennial,
- aesthetically-pleasing,
- available commercially in sufficient quantities, and,
- most relevant to this study, be 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 1993-4 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. Some of the treatment plots had large, vigorous, sexually-mature plants with over 80% ground cover (field observation). 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 (*Anemone multifida, Castilleja raupii, Chamerion angustifolium, Hierochloe odorata, Hedysarum mackenzei* and *Linum lewisii*) 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 <10% cover requirement was made to leave pits with larger naturally-revegetated areas intact. The sites differ in location, size, age, and surrounding vegetation (Table 2-1, Fig. 2-1).

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, 1975b). The microrelief alteration (M) provided a series of ridges and troughs to provide micro-scale 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 (seed mix and microrelief, fencing and control, fencing and microrelief, fencing and seed mix, fencing and seed mix and microrelief).

Six 5m x 5m treatment plots were set up at each site in early July 2002. These were randomly arranged throughout the site, although some plots had to be located randomly within a certain portion of the disturbance 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. The prevailing wind direction is northwest 50% of the time and west the other 50%, and maximum gusts are mainly from the northwest (Environment Canada, 2006). Five metres 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 $1m^2$ 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).

For the seed mix treatment, the top 2.5cm of gravel was removed and a portion of it mixed with 300 seeds $species^{-1}$ (seeding density=1800 seeds m^{-2}) to make it comparable to the rates used by Firlotte (1998), and 30g of SmartCote 12-12-12 NPK (12% nitrogen, 12% available phosphoric acid (P_2O_5), 12% soluble potash (K_2O)) time-release fertilizer (300 kg ha^{-1}). Approximately 2.5cm 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 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 are tolerant of gravel-dominated substrates, perennial, aesthetically-pleasing, 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 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).

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 ≈ 5cm). 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, while the control (FC) in the fenced plots was the reference for the 'fencing only' treatment.

SEEDLING DENSITY, FREQUENCY AND GROUND COVER

In late August 2002-3 the species and approximate location of each individual plant was recorded by placing a 1m^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 is 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%) and 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 1m^2 sampling frame was also used to assess ground cover on twelve (six in each of 2002-3) randomly-located quadrats within the disturbance but outside the reclamation treatments (natural recovery quadrats). In addition there were six 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, 1997b; Munshower, 2000; Streever *et al.*, 2003). However, because this was a short-term study limited by extreme growing conditions other criteria such as increased species richness, colonization by native species or increased plant cover (McKendrick, 1997b; Kershaw, 2003a) 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 because it indicated the plant was present by more than chance, and was 'common' on the study quadrats. A species had to meet at least one of these criteria.

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

TREATMENT ASSESSMENT – LAB METHODS

Density and cover data were natural log transformed to meet the analysis-of-variance assumption of equal variances. After transformation, there were slight deviations from normality (Kolmogorov-Smirnov normality test), however, analysis-of-variance is much more robust to deviations from normality than unequal variances (Clewer and Scarisbrick, 2001). 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. 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 2-2).

The largest proportion of successful species satisfied the density criteria (25 of 26 species) (Table 2-2). Twelve species were density-successful in both years. There was 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. 2-2). Density of the six seeded species increased 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., Poaceae spp.) 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*, with *D. integrifolia* having 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 spp. 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 seeds made it onto the quadrats, that they were not as easily lost to wind or water erosion, and 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 them to germinate and to provide the plant with a long enough growing season for plants to mature and harden off for winter (Klebesadel, 1977; Johnson, 1981; Skriabin, 1981) or in late fall to capture late summer moisture (McLean and Wikeem, 1983). 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, 1974b) 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 spp. category because of their small size and lack of distinguishing features. *Anemone multifida* was not pre-treated despite potentially requiring freezing or spring meltwater immersion to germinate (some *Anemone* spp. require moist chilling (Sorensen and Holden, 1974)). 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. 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 there were high densities of *A. multifida* confirming the requirement for seed treatment 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. 2-3). 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 (Chapter 3). 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. The species composition at Forest

Pit and Tundra Pit was different from that of 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 as on the control and natural recovery quadrats, making the differences due to treatment less noticeable (Fig. 2-3). 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 5cm (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. 2-3) 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 year. There was a difference in the snowpack (7.7cm unfenced vs. 33cm fenced) (Chapter 3), 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 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 except for *L. lewisii* at Tundra Pit, which was 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, 1992b) 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 between the undisturbed, recovery and reclamation treatments. This would be facilitated by several of the species' inherent abilities: it can efficiently capture nitrogen through nitrogen-fixing bacteria in root nodules (Kohn and Stasovski, 1990; Kohls *et al.*, 1994), it has light, easily-dispersed, abundant seeds, it is tolerant of a variety of substrate conditions (Viereck and Little, 1972; Johnson, 1987a), and it has a spreading, mat-forming habit that facilitates its spread. 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 reduces 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} per species) 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 2-3). 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 has 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.

To optimize ecological recovery, disturbance sites should be assessed for the presence of a seed bank through substrate germination experiments or be assessed for adequate seed rain from adjacent areas by examining the surrounding undisturbed plant community and collecting seeds from the species found there. Sites which have adequate seed banks or seed rain potential, 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 which will facilitate revegetation and enhance 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 for 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.

Tables

TABLE 2-1 Reclamation study sites.

Site	Date Abandoned	Location	Description
Forest Pit	c. 1960	58° 40' 22.5"N, 93° 48' 24.0"W	-surrounded by boreal forest -undulating topography
Tundra Pit	1961 (re-disturbed 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 1.5m
Building Pad	1997	58° 42' 56.0"N, 93° 47' 27.3"W	-within open treed area -uniform topography -compacted building foundation pad -raised 0.6m

TABLE 2-2 "Successful" reclamation species. Value denotes species met minimum success criteria in that category on at least one quadrat in either growing season, which is why the averaged value may be less than the criteria. Multiple values per field indicate values for each growing season.

Species	Density (> 10 stems m^{-2})	Frequency (> 20 %)	Cover (> 2 %)
Androsace septentrionalis L.	39.38 / 75.15	0.39 / 0.51	0.16 / 0.97
Anemone multifida Poir.	10.93	0.45	
Arabis arenicola (Richards. ex Hook.) Gelert	6.85	0.22 / 0.29	
Astragalus alpinus L.	3.91		
Brassicaceae spp.	8.67 / 13.00	0.43	0.18
Carex L. spp.	31.45 / 61.55	0.26 / 0.26	0.46 / 0.71
Draba L. sp.	5.22	0.41 / 0.28	
Draba L. spp.	7.89	0.46	
Dryas integrifolia Vahl	5.61 / 7.14	0.47 / 0.68	0.58 / 0.66
Erysimum cheiranthoides L.	12.00		
Euphrasia subarctica Raup	9.17		
Festuca L. spp.	5.71	0.28	
Hedysarum mackenzei Richards.	47.56 / 26.79	0.51 / 0.52	
Linum lewisii Pursh	69.79 / 19.95	0.51 / 0.50	
Minuartia L. spp.	21.04 / 58.31	0.58 / 0.82	
Picea glauca (Moench) Voss		0.22 / 0.25	
Poaceae spp.	13.87 / 13.72	0.43 / 0.56	0.41
Potentilla bimundorum Soják	24.92 / 29.00	0.24	1.67
Potentilla L. spp.	7.75	0.20	
Sagina nodosa (L.) Fenzl	33.90 / 47.54	0.34 / 0.42	
Salix L. spp.	4.67 / 7.29	0.28 / 0.35	0.31
Saxifraga tricuspidata Rottb.	8.00		
Silene involucrata (Cham. & Schlecht.) Bocquet	9.96 / 28.56	0.42 / 0.49	
Stellaria L. spp.	9.11		
unidentified dicot 3	7.81		
unidentified dicot 6	4.08	0.21	

TABLE 2-3 List of species suitable for revegetation in the Churchill, MB. 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)

Figures

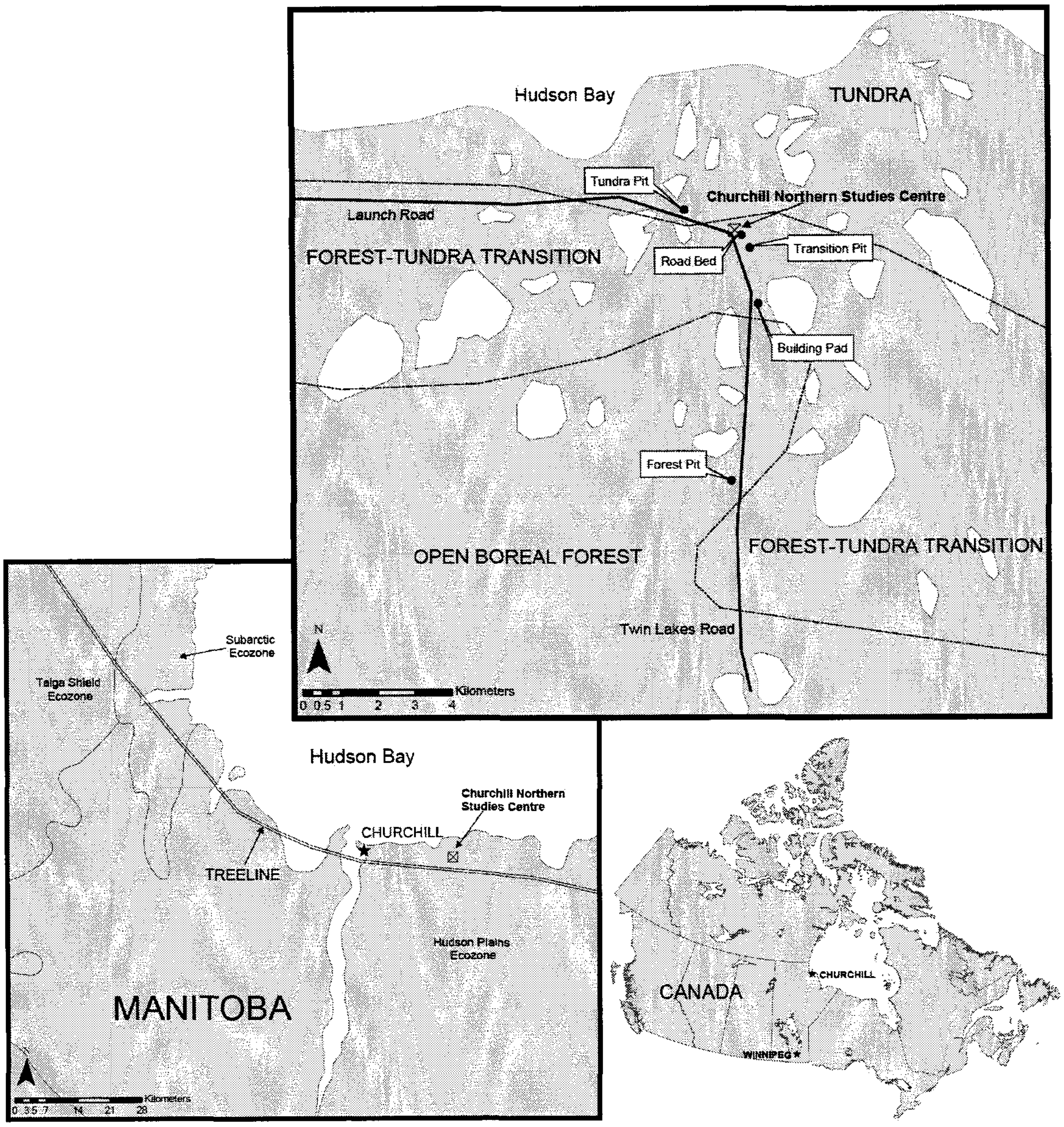

FIGURE 2-1. Location of Churchill, Manitoba study area and revegetation site locations.

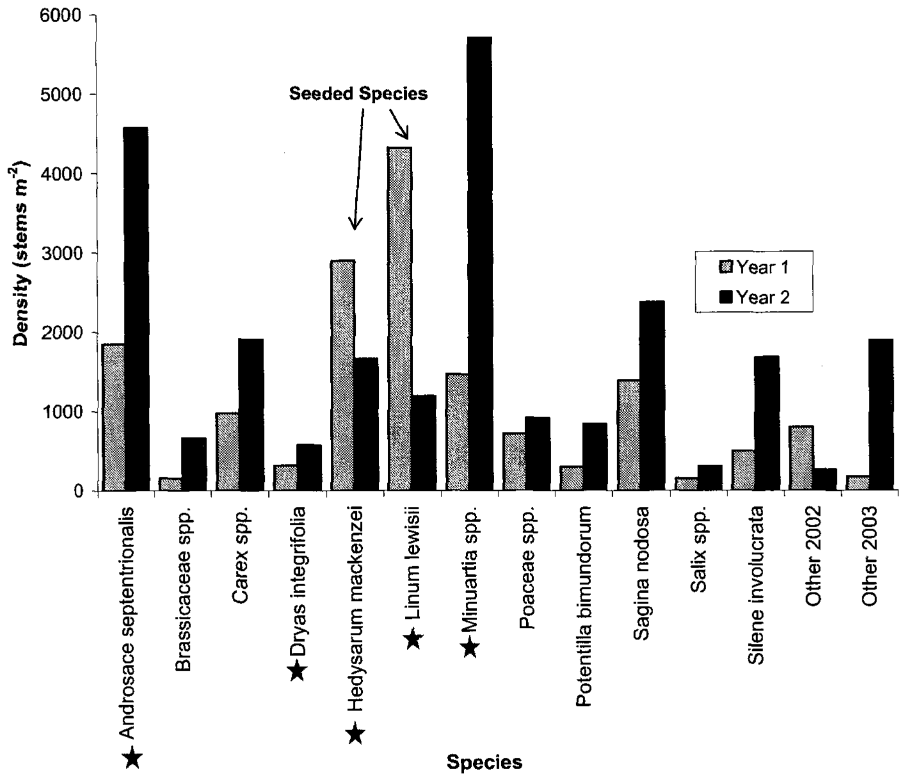

FIGURE 2-2. Total density of successful (density-determined) species: season one and season two. Star denotes significant ($P<0.05$) differences between seasons.

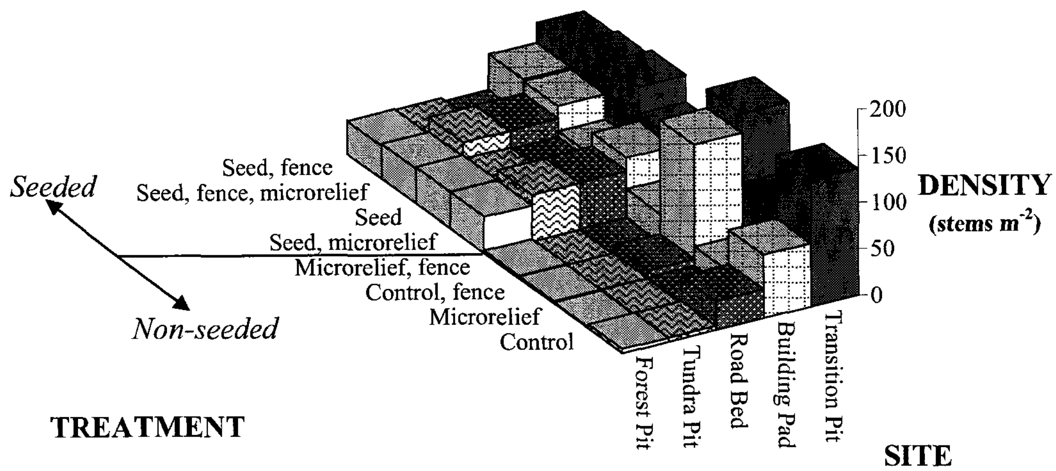

FIGURE 2-3. Seedling density by treatment type and site: growing season one. Building Pad and Transition Pit naturally had more seedlings present regardless of treatment. Treatments which included the seed mix were more effective at increasing density at the three naturally species-poor sites: Tundra Pit, Forest Pit and Road Bed.

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CHAPTER 3 - Use of Organic Amendments and Snow Fencing to Mitigate Substrate Limitations to Revegetation on Gravel-Dominated Human-Induced Disturbances, Churchill, MB, Canada[1]

INTRODUCTION

Conditions dominating substrates such as gravel pits and pads can limit revegetation on these sites (Harper and Kershaw, 1996; Kershaw, 2003a; Lavrinenko *et al.*, 2003). Combining these harsh growing sites with the climatic and environmental conditions of the Arctic and Subarctic (Billings, 1987) further complicates the revegetation process (Webber and Ives, 1978; Arnalds *et al.*, 1987; Stonehouse, 1989). In areas where roads are present, aggregate extraction sites (gravel pits) can make up 40 % of the disturbed area (Johnson, 1987b). This number is made higher by the presence of aggregate deposition sites (gravel pads), such as abandoned roads and building pads. Examples of these types of disturbances can be found in the Churchill, Manitoba area. Many of these are present around the Churchill Northern Studies Centre (CNSC), the site of the former Churchill Research Range. The Churchill Research Range was a rocket launch experiment and testing facility operational from the 1950s to 1980s, and briefly in the late 1990s (Coutts, 2000). Gravel is easily extracted (Groom, 2001) in the region due to the commonness of beach ridges covered with a layer of thin and easily removed soil and vegetation. The ease of access and lack of an enforced permitting process has created a collage of gravel-dominated disturbances with either no attempts at revegetation or no successful revegetation.

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Churchill is located at the transition between the taiga (or boreal) and tundra biomes (Ritchie, 1962; Ecological Stratification Working Group, 1995). Sparse tree cover, the presence of low-lying tundra vegetation and proximity to roads makes these disturbances highly visible. They diminish the natural appearance of the landscape which is especially important to an ecotourism-based economy such as Churchill's. Visitors from across Canada and around the world travel to Churchill providing one billion dollars each year to the local economy (Manitoba Tourism, pers. comm., 2003) to see northern lights, birds, wildflowers, beluga whales and primarily, polar bears (Town of Churchill, 1997). Although some of these gravel disturbances are still active, many have not been used for decades or the usable aggregate has been exhausted. It is these abandoned sites that could be reclaimed in an effort to facilitate recovery to a more ecologically-functional state and to aesthetically blend them with the surrounding undisturbed community.

Limitations to Plant Growth

Leaving sites to naturally recover can be a long process, particularly in the Subarctic (Harper and Kershaw, 1996; Jorgenson *et al.*, 2003; Kershaw, 2003a) where environmental conditions such as severe wind and cold temperatures are the norm for most of the year. Many plants are suited to Arctic and Subarctic conditions; however on human-induced disturbances the combination of the limiting environment with a poor growth substrate such as gravel can considerably extend the natural revegetation process. Gravel-dominated disturbances are nutrient-poor and there are almost no soil micro-organisms to convert nutrients such as nitrogen into forms available to plants (Haag, 1974). Few species can colonize this poor growth medium, and those that can, often have low seed production (Johnson, 1987b). Those that are successful must also withstand increased exposure to wind and wind-driven ice crystals in the winter which has the potential to abrade needles off trees (Scott *et al.*, 1993) and destroy plants and seedlings as if they were heavily grazed (field observation). Gravel extraction sites, particularly those on elevated beach ridges can be exposed to the full brunt of the wind (McKendrick *et al.*, 1992). Snowpack, even as little as ten centimetres can protect plants from winterkill of exposed plant tissues (Leep *et al.*, 2001). Winterkill is one of the three major causes of seedling mortality following germination. The other two are drought and lack of nutrients (Vough *et al.*, 1995), conditions that characterize most gravel-dominated disturbances (Cargill-Bishop and Chapin, 1989).

Substrate Modification

Modification or manipulation of the substrate to provide a hospitable substrate for plants can greatly increase the chance of revegetation success and eventual reclamation of gravel disturbances (Johnson, 1987b). Substrate modifications can facilitate sown species and reduce seeding rates (Johnson, 1987b) which, in the North can alleviate the high cost of procuring native seed. Methods of substrate manipulation include: adding an organic soil amendment; adding biological or chemical fertilizer; alteration of topography (either on a macro- or micro-scale) and reducing wind (which can result in enhance soil moisture).

Organic amendments are used to improve nutrient availability and provide a suitable growth medium while reducing bulk density (Logan, 1978; Land Resources Network Ltd., 1993). Organic amendments, and especially peat moss, are good at improving the water holding capacity (Ontario Ministry of Natural Resources, 1978; Richardson and Evans, 1986; Cole and Spildie, 2000) of the substrate by decreasing the pore size in coarse-textured soils (Puustjarvi and Robertson, 1975) which in turn mediates large temperature fluctuations

(Addison, 1975; Hillel, 1982) and the darker colour helps warm the soil in the spring (Land Resources Network Ltd., 1993).

Organic amendments can consist of the original overburden, commercially produced topsoil, wood chips, peat moss, straw mulch, sewage sludge or fly ash. In areas such as Churchill, use of the original overburden in reclamation projects on existing disturbances is not possible since it was not retained. With current practices there are also problems since beach ridges commonly have thin to discontinuous soil (Dredge, 1992a; Scott, 1996) making stockpiling difficult and impractical.

Straw mulch can be contaminated by exotic seeds (Staniforth and Scott, 1991) and it can be expensive to provide an infrastructure to keep the mulch on the intended site (Chambers *et al.*, 1990). Wood chips decompose very slowly (Schoenholtz *et al.*, 1992), especially in cool climates, and as such would not provide a short-term amelioration of the substrate for seeds and seedlings.

Collecting peat locally can be expensive, time consuming and labour-intensive and will result in the disturbance of peatlands at the extraction site. For these reasons this approach is not normally adopted. Commercial peat moss is often selected over commercial topsoil as an organic amendment since it is often less expensive and more readily available. Although peat moss and topsoil do not require infrastructure to keep the material in place, it is recommended that it be tilled or mixed with the gravel to prevent losses due to wind erosion (Logan, 1978). McKendrick (1997a, pers. comm., 2002) found that over a span of ten years the majority of the topsoil added to plots that were not tilled was lost due to wind erosion while the tilled plots still had appreciable amounts of organic matter.

Another benefit of peat moss is that it can lower the pH of the substrate (Logan, 1978; Reid and Naeth, 2001) which can be useful in situations where the substrate is calcareous and/or alkaline (Land Resources Network Ltd., 1993). Peat also collects capillary water, the portion of soil water that cannot be removed by gravity (Hillel, 1982); of which up to 70 % is available to plants (Puustjarvi and Robertson, 1975). Peat can retain seeds to improve substrate seeding (Gartner *et al.*, 1983). Although peat moss is not a permanent soil amendment, especially if only added once, its slow decomposition of the more resistant organic material (Allison, 1973) provides a suitable growth substrate long enough for plants to establish and in turn improve growing conditions by adding litter (Land Resources Network Ltd., 1993).

Natural fertilizers, such as manure, are useful soil amendments in areas where they are readily available. In Northern areas, where there is no agricultural activity, it would not be cost-effective to import manure. As well, the manure usually contains seeds of species not native to the local area. Thus, chemical fertilizer offers a number of advantages in attempts to increase the nutrient status of the substrate. Decomposition in the North is slow due to lower ambient temperatures so nutrients are not recycled as quickly as they are in southern environments (Johnson, 1987b) increasing the need for additional nutrients especially in extremely well-drained substrates such as gravel pits and pads. Since decomposition is slow and arctic plants have the ability to conserve nutrients once they are obtained, fertilizer can have a long-lasting effect (Klokk and Rønning, 1987). In gravely soils leaching of nutrients from fertilizer is a common problem (Mitchell, 1987; Chambers *et al.*, 1990). Use of time-released fertilizer or application of fertilizer in combination with an organic amendment can extend the period of nutrient release (Logan, 1978).

Alteration of topography, both on a macro- (disturbance) and micro- (plant) scale can encourage plant growth on these disturbances. Although not a consideration for this study as all the sites were relatively flat and uniform in topography, macro-scale modification of gravel-dominated disturbances is recommended to remove steep (>22°) and often unstable slopes which prevent plants from establishing (Borgegard, 1990). Micro-scale topography modifications consisting of small ridges, troughs, or generally uneven or roughed surface help to provide micro-scale wind protection, and collection of moisture in the troughs or lower-lying areas (Johnson, 1981; Densmore, 1987; Mitchell, 1987). Creation of meso-scale ridges or berms, made out of substrate can also help by providing sheltered, moist (relative to the rest of the disturbance) areas for plants to grow in. However, McKendrick *et al.* (1992) and McKendrick (pers. comm., 2002) found that berms did not work well in their revegetation experiments on Alaskan oil drilling gravel pads, but that the same mitigative effect could be had by using more effective snow fencing.

Plastic-mesh snow fencing can be used to accumulate snow drifts which can protect plants and seedlings from the wind (Frey, 1983; Scott *et al.*, 1993). The drifts can also provide enhanced moisture upon snow melt (McKendrick *et al.*, 1992) and an opportunity for roots to collect finer-textured soil particles and prevent their translocation (Walker *et al.*, 2001). The abundance spring moisture can create puddles on still-frozen substrate and cause seed immersion which can be important for low temperature uptake of water – a process critical to germination (Bell, 1975b). Fencing left up through the snow-free season can also provide benefits by trapping wind-transported soil and plant particles, reducing erosion. In addition, sheltering from wind can reduce evapotranspiration and limit damage due to flailing. Any of these micro-scale effects can be important at least until the plants survive the establishment stage (McKendrick *et al.*, 1992). McKendrick *et al.* (1992) used snow fencing that was 1.2 m high and found it collected too much snow, leaving the sites snow covered late into the growing season. Modification of the fencing height to 0.6 m in subsequent experiments was found to provide optimum conditions – sufficient snow but not enough to significantly reduce growing season length (McKendrick, pers. comm. 2002).

Purpose

The purpose of this portion of the study was to determine if key environmental-limiting factors could be alleviated to improve the growth substrate (soil) which will in turn facilitate seedling establishment on anthropogenic disturbances. The environmental factors that were selected for mitigation treatment were wind, soil moisture and soil nutrients.

METHODS

Site Description

Three aggregate extraction (gravel pits – Transition Pit, Tundra Pit and Forest Pit) and two aggregate deposition (gravel pads – Building Pad and Road Bed) disturbances were selected for reclamation testing. Site selection was based on adequate size; lack of plant cover (<10%); accessibility; and flat, uniform topography. Disturbed sites were selected from within tundra- to boreal-dominated plant communities. Tundra Pit was within the predominately tundra area and was the most recently disturbed (2000/2001) after originally being abandoned prior to 1961 (Firlotte, 1998). Transition Pit and Road Bed were adjacent sites, close to the CNSC and were associated with the rocket range. Within the transition of tundra to forest vegetation, Transition Pit was lower than the adjacent surrounding plant community after being re-graded in 1984. Road Bed, a compacted, abandoned road, was approximately 1.5 m higher than the adjacent disturbed and undisturbed areas. Upon the rocket range closure in 1984, it was blocked off from traffic and abandoned. Building Pad, the most recently created disturbance (c. 1997) was a compacted gravel pad about 0.6 m higher than the surrounding undisturbed community, within an open treed area in the forest-tundra zone. Forest Pit was within the boreal forest. It was part of a larger pit that straddled both sides of Twin Lakes Road. Abandoned around 1960, Forest Pit was the oldest of the five study sites.

Treatment Installation

To mitigate the limitations of the gravel substrate, a total of eight treatments were tested at each of the five sites. Quadrats (1 m^2) were randomly located within six 5 m^2 blocks (necessary because of the fencing treatment), with three replicates of each treatment per site (n = 24 per site, 120 total). Three of the blocks had 0.6 m of orange, plastic mesh snow fencing (F) erected along the northwest face of the block, perpendicular to the prevailing wind. The other three blocks were left exposed. Within the blocks the other treatment combinations were installed to further improve the substrate conditions or to provide a reference. Alteration of the topography on a micro-scale was simulated by microrelief (FM and M) treatments consisting of three to five hand-raked and -packed ridges and troughs (about 10 cm ridge to trough) perpendicular to the northwest. Addition of an organic amendment (peat moss), as well as a chemical fertilizer (30 g m^{-2}), was achieved with the seed mix treatment (FS and S), which also included seeds of six native plant species (Chapter 2). For each 1 m^2 quadrat the seed mix treatment (seed mix) consisted of removing the top 2.5 cm of gravel and spreading 2.5 cm of peat moss over the quadrat, and sprinkling most of the removed gravel back over the peat moss. The removed portion of the gravel was combined with seeds (density = 1800 seeds m^{-2}) and 30 g (300 kg ha^{-1}, same as that used by Firlotte (1998) in Churchill) of time-released fertilizer (SmartCote 12-12-12 NPK, 12 % each: nitrogen, available phosphoric acid (P_2O_5) and soluble potash (K_2O)). The mixture was added to the surface of the quadrat and packed down by lightly walking over the surface. The same process was used for the combination treatment of seed mix and microrelief (FSM and SM), except the mixture was not packed down by walking, but rather by hand during the creation of the ridges and troughs. Control, or no treatment, quadrats were placed within both block types for a baseline of no assistance, or natural revegetation (C) and fence only treatment (FC).

Untreated Disturbed and Undisturbed Areas - Year (Growing Season) 1

Five 225 cm^3 soil samples were taken using tin soil sample cans (approximately 6 cm high) from randomly-chosen locations within each pit or pad but outside of the treatment blocks. Surface vegetation was removed and the can pressed evenly into the soil. Soil around the can was excavated and a plaster knife slide underneath. The can was then flipped and the canned sample bagged. Another five samples were taken outside the disturbance in the undisturbed community surrounding each site.

All samples were processed at the Churchill Northern Studies Centre, or the University of Alberta in the Department of Earth and Atmospheric Science soil laboratory. The wet weight of each soil sample was taken using an electronic scale within 24 h of sampling. Samples were oven dried at 60 °C for ~48 h rather than the usual 10-24 h at 105 °C (Hillel, 1982) to prevent burning of organic matter. Samples were weighed to determine dry bulk density, gravimetric water content (mass wetness) and volumetric water content (volume wetness). Organic matter content was determined by burning a portion of each sample (loss-on-ignition, LOI) in a crucible at 475 °C for 1-1.5 h in a muffle furnace until a steady weight was obtained (Scott, 1985). A lower temperature and longer time was used to prevent oxidation of carbonates which could result in an overestimate of organic matter. Samples were dry-sieved to determine the percentage of fines (particles < 2 mm) and to prepare samples for testing of total nitrogen (N), phosphorus (P) and potassium (K). Nutrient content and pH were determined using a Hach NPK-1 Soil Fertility Test Kit (Hach Company, Colorado, USA) (Hach Company, 1992). The Hach NPK-1 Soil Fertility Test Kit was selected to enable field-processing of samples. The presence of carbonates was assessed using a 10 % Hydrochloric Acid (HCl^-) solution. Iteration was assessed as 0 (no reaction, <1 % $CaCO_3$), 1 (slight reaction, 1 % $CaCO_3$), 2 (moderate reaction, 2-6 % $CaCO_3$) or 3 (strong reaction, 6-40 % $CaCO_3$) (Scott, 1985; Soil Classification Working Group, 1998).

Reclamation Treatment Quadrats - Year 1 and 2

A 130 cm^3 soil sample was taken using tin soil sample cans (approximately 3 cm high) in the same manner as the 'Untreated Disturbed and Undisturbed Areas' described above, from the same grid cell in each quadrat (destructive sampling). In quadrats where the treatment included microrelief, a sample was taken from both the ridge (r) and the trough (t) in Year 1 to examine the differences between these two microenvironments. In Year 2, only one sample was taken from each quadrat, regardless of presence of a ridge or trough, and in a different grid cell from the previous year to avoid sampling an already re-disturbed area. Soils were processed as described in the previous section with the exception of carbonate testing which was not conducted on the reclamation soil samples. For soil nutrient, percent fine material and pH there was not enough sample from each quadrat to analyze them separately, so samples from the same treatment at the same site were physically pooled. The three like samples were placed in the same bag and thoroughly mixed to create composite samples.

Snow Sampling - Winter 1 and 2

Blocks at each of the five sites were sampled in the first and second winters (February) after treatment installation. Sampling consisted of taking eleven randomly-collected depth measurements within each block, as well as three snow cores along the northwest edge of the block, using an Adirondack snow corer (Goodison, 1978) to determine snow density. The snow water equivalent (SWE) [1] (Pomeroy and Gray, 1995; Kershaw, 2001) and heat transfer coefficient (HTC) [2] (Kershaw, 1991, 2001) were calculated from the snow density and depth.

$$\text{SWE (mm)} = 0.01\, d_s\, \rho_s \qquad [1]$$

$$\text{HTC } (\text{W}\cdot\text{m}^{-2}{}^\circ\text{K}^{-1}) = k / d_s \qquad [2]$$

where: ρ_s = snow density ($\text{kg}\cdot\text{m}^{-3}$)

d_s = snow depth (cm)

$k = (2.94 \times 10^{-6}\ \text{W}\cdot\text{m}^{-2}{}^\circ\text{K}^{-1})(\rho_s)^2$

Snow cores were melted and filtered for particulate matter and the pH was determined for the filtered water.

Statistical Analysis

For between year comparisons the ridge and trough samples from Year 1 were averaged to compare with Year 2. Data were natural log transformed to meet normality and equal variance assumptions. The natural log transformation was selected because it transforms the data to meet the required assumptions without changing the relationships between the data. In two cases (% organic matter and pH) transformed data still failed the normality test (Kolmogorov-Smirnov) so a rank transformation was performed where the data were arranged from smallest to largest and assigned an integer rank value (SPSS Inc., 2003). All data were tested for a significant difference ($p<0.05$ if not otherwise stated) using one-way and two-way analysis of variance (ANOVA), with the Holm-Sidak multiple comparison test to assess differences among treatments.

RESULTS

Soil - Disturbed and Undisturbed Areas

Bulk density, carbonates and pH were significantly higher ($p<0.05$ and $p<0.001$) in the disturbances than in adjacent undisturbed sites. Gravimetric and volumetric water content, percent fines, percent organic matter, and N and P levels were significantly lower in the gravel disturbances at most sites (Table 3-1). A major exception was Road Bed which was not different in water content, P or pH from the adjacent undisturbed area. The similarity among the K values (Table 3-1) was an artifact of the inability to resolve amounts <77.5 mgL^{-1} using the Hach kit, making them unreliable and excluded from further discussion.

Soil - Reclamation Quadrats

Year differences were almost completely restricted to soil nutrients and water content (Table 3-2). Nutrients decreased at all sites between Year 1 and 2 except for Road Bed where P increased. Water content site-year responses varied due to antecedent conditions at the time of sampling.

In almost all cases when comparing treatments among sites and across sites the seed mix treatments (i.e. FS, S, FSM and SM) were significantly different from the control and microrelief treatments (i.e. FC, C, FM and M). In both years the seed mix treatments had greater water content and percent organic matter while the non-seed mix treatments had greater bulk density and pH. Although this pattern was observed for percent fines, and N and P content in Year 1, the treatments were not significantly different in Year 2 (Table 3-2).

The only significant differences between the fence and no fence treatments were found in bulk density at Transition Pit (FC>C), gravimetric water content at Transition Pit and Forest Pit (FS>S), volumetric water content at Road Bed and Transition Pit (FS>S) and Forest Pit (FC>C and FS>S), percent organic matter at Building Pad (FC>C) and P content at Road Bed (FM>M and FC>C). The fencing treatment caused differences between the fenced and unfenced seed mix quadrats with the fenced seed mix having lower bulk density and higher water content.

Not all among-site differences in Year 1 persisted into Year 2, except for Building Pad and Transition Pit which had higher organic matter and lower pH in both years. Transition Pit also had constantly higher gravimetric water content. Forest Pit on the other hand had high bulk density and low organic matter in both years and Road Bed had high and Building Pad low percent fine material (Table 3-2).

Of the few ridge and trough soil characteristics that differed significantly, all but one fit the predicted pattern of the trough samples being more favourable to plant growth. The volumetric water and N content of the FSMt and SMt treatments were higher than the adjacent ridges. The FMt and Mt treatments collected more fine soil material than the FMr and Mr treatments (Table 3-2).

Snow – Reclamation Blocks

The fenced blocks had significantly greater snow depth (1-14 times deeper in Winter 1, 3-15 times deeper in Winter 2) and SWE, and lower snow water pH than the unfenced blocks. Snow depth was normally consistent and deepest along the fence and gradually thinned with increased distance from the fence along the prevailing wind direction. The exception was Forest Pit where there was no difference between the fenced and unfenced blocks and snow depth was fairly uniform across the entire site.

Density was only different between treatments at Tundra Pit where the snow on the fenced blocks was denser. HTC was greater on the unfenced blocks at Transition Pit in Winter 1 and at Road Bed and Tundra Pit in Winter 2. The fences collected more particulate matter at Forest Pit in Winter 1 and at Road Bed in Winter 2. Snow pH and density varied significantly between winters (Table 3-3).

DISCUSSION

Although the baseline soil characteristics between sites were different, by treating areas of the disturbances (reclamation quadrats) with a peat moss, fertilizer and seed mixture (either alone or in combination with fencing and microrelief alteration) these site differences were moderated and became less important than treatment differences. Thus, with regards to the soil characteristics of these gravel disturbances; the organic amendment was the main factor controlling substrate improvements for plant growth.

Disturbed and Undisturbed Areas

The disturbed areas prior to any treatment were significantly less suited to plant growth than the undisturbed areas. Transition Pit had the lowest bulk density and the greatest percentage of fines. The particle size on the site was visibly smaller than the other sites. Forest Pit had the sandiest substrate but a higher bulk density than Transition Pit because of the sampling procedure where the shallow soil can was easier to fill with smaller-grained substrate and some very large particles escaped being sampled because they did not readily fit into the soil can. The bulk density on the gravel pads was not as high as expected for sites that were mechanically compacted, but this could be due to the depth of sampling. The dense layer or layers can be > 10 cm below the surface (Addison, 1975) while the sampling tin penetrated only 3 cm.

Soil pH was higher in the disturbed areas compared to the undisturbed. The aggregate had a considerable amount of Paleozoic dolomitic limestone and Ordovician limestone (Dredge, 1992b; Bamburak, 2000) which would elevate the pH (Yaalon, 1954; Briggs *et al.*, 1993) while in the undisturbed sites the peaty surface layer composed of litter from ericaceous shrubs, *Dryas integrifolia* L. and spruce needles was more acidic.

Building Pad had the highest N levels while Tundra Pit had very high P values. This could be because P is highly soluble in calcareous soil as the soil to water ratio increases (Olsen *et al.*, 1960; Holford, 1997). Since there is little water available and the substrate is highly calcareous, P was retained. Although not significant, there was more organic matter naturally present in the substrate at Tundra Pit which could have further increased the P present in the samples and P levels can be higher than N in upland tundra communities (Haag, 1974; Holford, 1997).

Water content and percent organic matter were not very different among sites. This explains why the seed mix treatment which mainly influenced the percent organic and water content of the substrate, was also similar across sites. Transition Pit was unusual in that there were more wet areas within the disturbance (possibly from a higher water table) but this was not reflected in the water content of the samples, probably because of the shallow sampling container.

The undisturbed areas had high water content, fine-textured mineral particles and organic matter from naturally-accumulated peat moss, roots and decomposing plant matter. Plant cover was 100 % (Chapter 2) reflecting the suitability of the undisturbed area substrate for plant growth. The undisturbed area adjacent to Transition Pit and Road Bed had less phosphorus than the other sites. Transition Pit, surrounded by boreal forest, had low N, from low quality organic matter (Vance and Chapin, 2001) and high P levels possibly from greater amounts of decomposing plant litter (Shiels and Sanford Jr., 2001). The 'undisturbed' area next to Road Bed was the most different from the others. This area was dominated by a ditch that had naturally revegetated to a point where it was misclassified as an 'undisturbed' area. Sample collection beyond the previously disturbed ditches would probably have yielded results similar to that of the Transition Pit undisturbed areas as these sites were immediately adjacent and surrounded by the same undisturbed plant community. Low P values for the undisturbed area surrounding Transition Pit could also be due to poor sample site selection as there was a zone of re-established vegetation surrounding the pit that was more advanced than that adjacent to Road Bed, that could have been sampled in error.

Reclamation Quadrats – Effects of the Seed Mix Treatment (Peat and Fertilizer)

The addition of the peat, fertilizer and seed mix was the main factor in the improvement of substrate characteristics for plant growth. It lowered the pH and bulk density and increased the water-holding capacity, amount of fines and organic matter. The decreased bulk density and increased amount of fines improves the soil seed bed (Bateman and Chanasyk, 2001) and positively affects germination potential (Down, 1974). In the first year the seed mix treatments contained more nutrients (N, P and K). Year differences were mainly restricted to soil nutrients. Loss of nutrients through leaching, use by seedlings and volatilization resulted in decreased N and K at all sites, and of P at all sites except Road Bed. Natural N or ammonium is usually not lost to leaching, but the highly soluble nitrate from fertilizer additions is easily leached (Hach Company, 1993; Yanan *et al.*, 1997).

The seed mix quadrats had more nutrients than the non-seed mix quadrats in Year 1 but by Year 2 any significant differences between the seed and non-seed mix treatments with respect to nutrients had disappeared. Thus the fertilizer only provided additional nutrients in the first growing season. Subsequent additions of fertilizer would have been needed to maintain or increase the level of soil nutrients in the seed mix quadrats. Other studies found it necessary to fertilize in both the first and second years to compensate for the major loss of nutrients in coarse-grained substrates through leaching (Mitchell, 1987). Hernandez (1974b) and Gartner *et al.* (1983) found N and P contributed most to growth in the first year. However, by the second and third years the effect from the fertilizer was lost because whatever was not immediately assimilated by the plants was quickly lost to immobilization, and/or leaching (Babb and Bliss, 1974; Densmore *et al.*, 1987).

While the nutrients only provided improvement to the substrate in the first growing season the benefits from the peat moss were longer lasting. In addition, the benefits to growth from increased moisture far exceed those of increased nutrients (Jorgenson *et al.*, 2003). Soil water content was different between years but this was likely due to differing weather and soil moisture conditions at the time of sampling rather than a reduction in the water-holding capacity.

Building Pad, Road Bed and Tundra Pit had higher N contents than the other sites. However, these disturbances had naturally higher levels to begin with, so this difference could still be expressing itself despite the treatments. Overall substrate improvements were greatest at Building Pad and Transition Pit. Organic matter and soil moisture were higher and bulk density lower than at the other sites. As well, pH was lower due to the commercial peat moss (Land Resources Network Ltd., 1993; Bateman and Chanasyk, 2001) which normally has a pH of 3.8-5.5 (Land Resources Network Ltd., 1993) which in cases of carbonate-rich soil where nutrients are being made unavailable, is a useful side-effect of using peat moss as an organic amendment. The main exception to Building Pad and Transition Pit being the best suited to growth was percent fines where Building Pad had low levels in both years while Road Bed and Forest Pit had more fine-grained material. This increased amount of fines may have been associated with the increased water holding capacity at Road Bed but this was not seen at Forest Pit, and the fine material did not seem to improve nutrient retention or organic matter content. Forest Pit was also not as suited to growth despite the higher amount of fines, with high bulk density, higher pH and low water content. Forest Pit was the oldest and most sheltered by trees but the most limiting for plants. Organic additions did alter the soil characteristics to those comparable to the seed mix treatments on the other sites. However, the extremely low pre-treatment values out-weighed the benefits of the seed mix treatments in overall site comparisons. Tundra Pit had low soil moisture and percent fines, but its moderate bulk density, percent organic matter and relatively high-to-moderate soil nutrient content made up for these growth deficiencies.

The lack of significant differences between the ridge and trough samples was surprising, especially when field observations one week after treatment installation confirmed obvious visible differences in moisture and amount of fine material. This obvious difference was also observed by Jorgenson *et al.* (1993) but they did not sample and test these areas separately. The troughs were darker and full of small-grained sand and gravel while the ridges were much lighter in colour and had mainly large gravel and rocks along the crest. Peat moss could have helped retain the fertilizer (Logan, 1978) and moisture on the ridges particularly as the ridges were hand-formed after the peat was added creating ridges comprised mainly of peat rather than gravel ridges with a layer of peat. This is supported by the fact that the ridges were less defined in the seed mix quadrats in Year 2 than those on the non-seed mix quadrats after peat erosion and/or settling during the winter and spring. It also helps explain why the FSMr often had more organic matter than the FSMt. The increased moisture in the seed mix troughs (FSMt, SMt) as compared to the seed mix ridges (FSMr, SMr), was likely because the peat moss better retained the water in the troughs and wind more easily dried the more exposed peat on the ridges. On the non-seed mix quadrats, the water drained or evaporated away from both micro-sites until they were not different. Thus, although the water was lost on different time frames, the end result was the same – they were dry.

Reclamation Quadrats - Effects of the Fencing Treatment

The most obvious and significant difference due to the snow fencing treatment was snow depth. Average snow depth on the unfenced blocks was 7.7 cm in Winter 1 and 13.0 cm in Winter 2 when on the fenced blocks it averaged just over 33 cm in both years. This is very similar to unfenced treatments in Alaska which had discontinuous snow cover that averaged <13 cm (McKendrick *et al.*, 1992).

SWE, an estimate of the amount of water released at snowmelt (Pomeroy and Gray, 1995; Kershaw, 2001), was significantly higher on the fenced blocks at all sites except Forest Pit. The average SWE for the fenced blocks was 65.0 mm in Winter 1 and 72.9 mm in Winter 2 while the unfenced blocks had much smaller SWE values of 14.5 mm and 22.6 mm in Winters 1 and 2 respectively. The fenced blocks did not have SWE values as high as McKendrick *et al.* (1992) where the fences trapped about 420 mm SWE and the unfenced 0-

<130 mm, however their fences were twice as high as those in this experiment. If we were to take the square root of the SWE from McKendrick *et al.* (1992) study as the snowpack volume is proportional to the squared height of the fence (Pomeroy and Brun, 2001), then the results would be almost identical (this paper versus McKendrick *et al.* (1992): fenced, ~69 mm vs. 65 mm; unfenced, ~19 mm vs. 0-<36 mm).

HTC is a measure of the potential for heat loss from the snowpack (Kershaw, 1991) where a low value (<1.00 $W \cdot m^{-2} {}^{\circ}K^{-1}$) indicates good snowpack insulation and a high value (>2.00 $W \cdot m^{-2} {}^{\circ}K^{-1}$) increased heat conductivity from the ground to the air. With a low HTC plants and roots would have increased protection from fluctuating and extreme winter temperatures. The HTC was only significantly higher on the unfenced blocks at three of the sites, Transition Pit in Winter 1 and Building Pad and Tundra Pit in Winter 2. Since Building Pad (raised from surrounding area) and Tundra Pit (tundra) were so exposed to wind, it was not surprising that there was a difference in the HTC values when the snowpack was dense and shallow on the unfenced blocks. Even between site comparisons of both the fenced and then unfenced blocks found Building Pad and Tundra Pit to have the highest HTCs and highest densities as compared to all the other sites. The wind was able to pack the snow particles tighter together creating a denser snowpack. The density of the snow must be the main factor influencing these differences since the depths were not significantly different between sites for the same block treatment (fenced or unfenced). Although Transition Pit was relatively sheltered, it had a very high unfenced snowpack density. This was probably the result of an icy ground layer which would have had a greater chance of forming on the unfenced blocks from increased freezing and thawing because of the shallow snowpack and more exposed surface longer into the winter. Other snow studies spanning several winters at Churchill found the HTC in the undisturbed forest to range from 0.12-0.17 and those on the tundra from 2.49-4.35 (Kershaw, 2003b). So the fences made the HTC of the snowpack closer to that of the forest than its previous tundra-like values.

The pH of the snow at the sites was inconsistent between the two winters. The significantly higher pH of the snow on Road Bed and Forest Pit in Winter 1 matched with the higher pH of the substrate at these sites. However in Winter 2, the pH was significantly higher at Tundra Pit and significantly lower at Forest Pit. The low pH at Forest Pit could be attributed to the contribution of needles from the surrounding coniferous trees (Vance and Chapin, 2001; Kahkonen *et al.*, 2002). Tundra Pit has large gravel spoil piles surrounding it, including on the NW (prevailing wind direction) which could explain the higher pH. The increased carbonate-rich dust blown and deposited onto Tundra Pit could have increased the pH of the snow since these piles are not snow covered in the winter. At the other sites, the spoil piles were on the down-wind side of the site.

Although differences in the soil characteristics between the fenced and unfenced blocks were not significant at all sites and for all treatments, slight improvements to the growth conditions of the soil were found. This was noticeable for water content in some of the seed mix treatments, where the additional moisture provided by the snow trapped behind the fence upon melt was better retained by the organic amendment (peat moss) than on the unfenced seed mix quadrats. This can be because the organic amendment better retained the additional moisture collected by the fencing in the form of snow (Jorgenson *et al.*, 1993), or that the fencing provided protection from wind desiccation. Differences between the fenced and unfenced control quadrats were also found at four of the five sites, although for different soil characteristics. Again the fencing alone provided improved plant growth conditions with increased soil moisture, organic material and P. However, greater bulk density on the FC quadrats as compared with the C quadrats was found at Transition Pit. This can be because the bulk density on the C quadrats at Transition Pit was significantly lower than all the other sites and that the greater bulk density of the FC treatment at Transition Pit was more representative of the differences in the placement of the blocks within the pit rather than true treatment differences. This hypothesis was also confirmed by the samples collected from within the pit but outside the reclamation quadrats, where the standard deviation in bulk density at Transition Pit was the largest ($\sigma = 0.20$) among the disturbance samples.

The fencing treatment made the seed mix treatment more suitable to plant growth than the seed mix treatment quadrats without fencing. The fencing enabled the peat moss to collect additional moisture and provided a wind-break so less organic matter and fine material were lost to aeolian transport. Most snowpack meltwater was lost to through-flow and runoff in spring over three to ten days (Jorgenson and Joyce, 1994) unless there is an organic or topsoil amendment to increase the storage capacity of the soil and retain some of this moisture (Kershaw, 1995). Input of moisture from melt water can be almost as much as that from summer precipitation (Jorgenson and Joyce, 1994). Retaining as much of this melt water as possible through use of absorbents, or organic amendments is critical (Jorgenson and Joyce, 1994). Increased snowmelt is useful to plants but it is not as important as storage capacity of the substrate to retain some of this snowmelt (Jorgenson *et al.*, 1993). As well, the spring snowmelt water can aid decomposition which is limited on dry sites (Wein and Bliss, 1974).

The snowpack traps mineral and organic particles such as plant debris. Much of this is lost with melt water, but some is retained by the substrate especially if plant roots can trap these tiny particles (Walker *et al.*, 2001). It was surprising that a greater difference in the amount of particulate matter in the soil was not found, however as the plant roots were removed from the soil samples and not carefully brushed off, much of this fine and organic material would not have been captured in the fines/organic matter content sample analysis. In addition, measures of the particulate matter in the snowpack were similar where only the high density, shallow snowpack of the unfenced blocks at Transition Pit and Tundra Pit (although not significantly more) collected more particulate matter than all the other sites and blocks. It can be that the frequent redistribution of snow particles (and organic particulate matter) is not captured by the snowpack unless certain conditions are present. As well any amounts of particulate matter collected by the snowpack would take a long time to accumulate in the substrate and impact the substrate properties. Unlike McKendrick (1999) there was no significant loss of fines on unfenced plots. However he distributed the fine material over a much larger area so the smaller scale in this experiment provided a less obvious or measurable opportunity for loss.

Once plants grow taller than the snowpack they can be scoured by wind (Scott *et al.*, 1993). Pukak (depth hoar) was observed on all the fenced blocks and not on the unfenced. This confirms the presence of a temperature gradient between the air and ground surface on the fenced blocks where the snowpack provided more moderate temperatures at the ground surface and within the root zone (Kershaw, 1991). It is expected that the snow fences, while not creating obvious differences in the soil characteristics in the short-term, will further improve the growing conditions on the blocks in the long-term by moderating subnivean temperatures and preventing abrasion and desiccation (see also McKendrick, 1991b; Jorgenson *et al.*, 1993; McKendrick *et al.*, 1993; McKendrick, 1997b).

Concluding Remarks

Fertilizer may have been important in the short-term for plant growth, but it was undetectable by the second growing season and there were no plant growth differences to attribute to the presence of the added nutrients. The wind-break fencing should be beneficial to plant growth in the long-term, but it has not become apparent yet. The addition of an organic amendment to the gravel-dominated substrate of these disturbances was the most valuable modification to improve plant colonization and growth potential. The organic amendment (peat moss) provided an improved growth medium in the short-term, and due to its slow decomposition, will continue to maintain this improvement for plants in the long-term. Ease of application and its uncomplicated, relatively cost-effective commercial availability also makes peat moss a beneficial organic amendment for use in the Churchill area and other areas of the North.

TABLES

Table 3-1 – Pre-treatment soil attributes at five reclamation sites. Samples were taken from within the disturbance outside the reclamation quadrats (D), and from the undisturbed area adjacent the disturbances (U). Values given as average (standard deviation). Shading indicates significant difference (light $p<0.05$; dark $p<0.001$) between fence and no fence treatment blocks for that soil parameter. + / ++ indicates a significantly higher (+ $p<0.05$; ++ $p<0.001$) value between sites for that year and soil parameter. - / -- indicates a significantly lower (- $p<0.05$; -- $p<0.001$) value between sites for that year and soil parameter.

SITE / SOIL	Building Pad		Road Bed		Transition Pit		Tundra Pit		Forest Pit	
	D	U	D	U	D	U	D	U	D	U
bulk density ($g \cdot cm^{-3}$)	1.60 (0.10)	0.43 (0.26)	1.31 (0.12)	0.91 + (0.33)	1.30 (0.20)	0.15 (0.06)	1.57 (0.19)	0.44 (0.40)	1.87 + (0.10)	0.34 (0.35)
grav. water content (%)	9.72 (4.16)	217.04 (202.36)	5.33 (1.96)	15.71 - (12.75)	6.84 (1.43)	288.21 (119.99)	6.42 (3.54)	198.32 (150.58)	5.67 (3.54)	240.69 (235.26)
vol. water content (%)	15.20 (5.62)	52.90 (20.10)	6.98 (2.72)	11.00 - (4.94)	8.72 (1.34)	38.80 (17.90)	9.57 (4.42)	43.20 (26.40)	10.70 (6.84)	29.40 (19.20)
fines (%)	38.57 - (3.73)	62.63 (29.30)	50.31 (11.14)	46.49 - (7.98)	55.58 (12.42)	88.03 (26.48)	50.84 (9.21)	83.80 (19.46)	42.30 (1.73)	93.36 (0.16)
organic matter (%)	0.87 (0.21)	35.50 (30.98)	0.45 (0.20)	4.21 - (3.56)	1.02 (0.37)	69.09 (33.27)	1.13 (1.36)	44.24 (39.04)	0.34 (0.14)	56.64 (37.30)
nitrogen ($mg \cdot L^{-1}$)	6.80 ++ (1.59)	4.00 (1.81)	4.52 (0.48)	4.50 (1.00)	3.30 (0.70)	3.20 (1.40)	3.64 (0.76)	4.90 (2.11)	1.20 (1.55)	1.28 - (0.34)
phosphorus ($mg \cdot L^{-1}$)	1.17 (1.22)	17.58 (6.35)	4.29 (2.58)	8.34 (4.41)	2.88 (1.93)	9.92 (5.81)	9.39 ++ (2.33)	23.94 ++ (7.86)	3.21 (2.54)	32.82 ++ (8.92)
potassium ($mg \cdot L^{-1}$)	77.50 (0.00)	77.50 (0.00)	77.50 (0.00)	77.50 (0.00)	77.50 (0.00)	77.50 (0.00)	77.50 (0.00)	78.42 (1.60)	77.50 (0.00)	175.20 (169.22)
pH	8.03 (0.34)	6.94 (0.64)	8.00 (0.10)	7.92 (0.44)	8.57 ++ (0.18)	6.79 (1.08)	8.42 ++ (0.26)	7.34 (0.46)	8.48 ++ (0.08)	6.60 (0.70)
carbonates (ranked scale)	2.6 (0.55)	0.2 (0.45)	2.8 (0.45)	1.2 (0.45)	2.4 (0.55)	0.6 (1.34)	1.6 (0.89)	0.2 (0.45)	2.4 (0.55)	0.0 (0.0)

Table 3-2 – Differences on reclamation quadrats between seed mix (S) and no seed mix (NS) treatments. Values presented as average seed mix quadrats value on the left and average no seed mix quadrats value on the right (average seed mix / average no seed mix). Shading indicates a significant difference (light $p<0.05$; dark $p<0.001$) between seed mix and no seed mix treatments for that year and soil parameter. + / ++ indicates a significantly higher (+ $p<0.05$; ++ $p<0.001$) value between sites for that year and soil parameter. - /-- indicates a significantly lower (- $p<0.05$; -- $p<0.001$) value between sites for that year and soil parameter.

Soil Parameter	Building Pad Year 1 (2002)	Building Pad Year 2 (2003)	Transition Pit Year 1 (2002)	Transition Pit Year 2 (2003)	Tundra Pit Year 1 (2002)	Tundra Pit Year 2 (2003)	Forest Pit Year 1 (2002)	Forest Pit Year 2 (2003)	Road Bed Year 1 (2002)	Road Bed Year 2 (2003)
bulk density ($g \cdot cm^{-3}$)	0.63 / 1.16 -	0.58 / 1.15	0.66 / 1.03 -	0.66 / 1.03	0.75 / 1.24 +	0.69 / 1.14	0.66 / 1.27 +	0.82 / 1.35 +	0.78 / 1.21 +	0.76 / 1.01
grav. water content (%)	11.36 / 3.03	30.18 / 3.93	16.61 / 3.98 ++	28.00 / 6.03 ++	9.17 / 2.31	19.33 / 3.03	12.39 / 1.63	8.37 / 1.29 --	19.33 / 5.66 ++	14.78 / 4.01
vol. water content (%)	6.59 / 3.40	12.26 / 4.52 ++	8.20 / 4.04	12.67 / 6.11 ++	6.20 / 2.78	10.86 / 3.46	7.10 / 1.93	6.04 / 1.74 --	11.46 / 6.78 ++	8.56 / 4.01
fines (%)	36.38 / 7.32 --	39.58 / 5.99 -	48.17 / 1.07	44.07 / 5.09	42.28 / 8.26	45.04 / 2.14	52.12 / 1.86	53.25 / 4.29 +	57.49 / 5.46 ++	52.40 / 48.20 +
organic matter (%)	11.60 / 0.90 +	18.54 / 0.88 ++	14.34 / 1.03 +	12.18 / 1.15 ++	11.08 / 0.76	10.98 / 0.65	11.38 / 0.55 -	6.87 / 0.23 --	10.02 / 0.54 -	10.51 / 0.41
nitrogen ($mg \cdot L^{-1}$)	50.31 / 8.87	3.47 / 1.78 +	46.14 / 5.30	3.48 / 1.00	60.40 / 0.30	6.55 / 2.62 +	60.87 / 3.60	1.07 / 0.50	55.32 / 0.58	3.50 / 3.50 +
phosphorus ($mg \cdot L^{-1}$)	42.17 / 8.63	11.22 / 5.64	62.79 / 1.16	11.39 / 6.66	24.11 / 8.01	9.21 / 5.36	31.74 / 4.42	3.41 / 3.77 --	17.55 / 4.16	50.02 / 9.14 ++
potassium[1] ($mg \cdot L^{-1}$)	109.55 / 7.50 (2)	77.50 / 77.50 (0)	101.42 / 77.50 (1)	77.50 / 77.50 (0)	113.27 / 78.28 (4)	77.50 / 77.50 (0)	86.28 / 77.50 (2)	77.50 / 77.50 (0)	84.62 / 77.50 (1)	77.50 / 77.50 (0)
pH	6.63 / 8.02 -	6.45 / 8.45 -	6.85 / 8.07 -	6.93 / 8.28 -	6.75 / 8.58	6.68 / 8.73	6.53 / 8.53	6.83 / 8.78 +	7.07 / 8.18	7.48 / 8.53 +

[1] Descriptive statistics only. The number of quadrats (out of 24) for each site with a value greater than minimum testable are given in brackets. All were seed mix quadrats.

Table 3-3 – Differences in snow parameters between fenced (F) and no fence (NF) blocks. Values presented as average fenced value on the left and average no fence value on the right (average fence / average no fence). Shading indicates a significant difference (light $p<0.05$; dark $p<0.001$) between fence and no fence treatments for that year and snow parameter. "nd" indicates no data as there was not enough sample to obtain an accurate pH.

	Building Pad		Transition Pit		Tundra Pit		Forest Pit		Road Bed	
Snow Parameter	Winter 1 (2003)	Winter 2 (2004)	Winter 1 (2003)	Winter 2 (2004)	Winter 1 (2003)	Winter 2 (2004)	Winter 1 (2003)	Winter 2 (2004)	Winter 1 (2003)	Winter 2 (2004)
density[1] ($kg \cdot m^{-3}$)	231 / 175	275 / 233	198 / 224	186 / 134	243 / 135	259 / 139	150 / 146	179 / 161	203 / 179	135 / 108
depth (cm)	31.40 / 4.74	35.00 / 3.73	32.96 / 4.98	26.06 / 7.82	56.39 / 4.02	39.73 / 2.64	22.08 / 20.03	35.97 / 41.05	26.17 / 4.63	29.73 / 9.82
SWE (mm)	77.76 / 9.43	102.25 / 9.50	48.99 / 8.15	59.77 / 10.77	85.54 / 6.62	82.09 / 4.08	54.59 / 40.75	79.83 / 76.49	58.32 / 7.64	40.73 / 12.24
HTC ($W \cdot m^{-2} {}^{\circ}K^{-1}$)	0.50 / 1.88	0.61 / 4.76	0.49 / 8.42	0.33 / 1.10	0.69 / 1.33	0.73 / 4.52	0.25 / 0.34	0.23 / 0.18	0.57 / 2.79	0.19 / 0.42
particulate (mg)	15.39 / 10.37	13.46 / 4.66	11.93 / 37.93	9.52 / 3.66	9.99 / 6.67	14.27 / 12.50	11.84 / 4.10	4.19 / 5.36	7.16 / 7.89	8.83 / 3.38
pH	6.38 / 6.85	7.09 / 7.44	6.47 / 6.91	7.12 / 6.88	6.29 / 6.72	7.37 / 7.31	6.81 / 6.69	6.20 / 6.15	7.13 / nd	7.09 / 7.13

[1] Rounded to nearest whole number.

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CHAPTER 4 - Short-term plant and substrate responses to reclamation of gravel-dominated human-induced disturbances, Churchill, MB, Canada[1]

Introduction

Aggregate mining has been occurring in the Churchill region since 1733 with a major surge of extraction (pits) and deposition (pads and roads) in association with the presence of military and research organizations in the area from 1942-1980 (Bamburak, 2000; Coutts, 2000; Groom, 2001). Of the available sand and gravel in the region, about 5 % has already been disturbed and 98 % of the remaining potential aggregate sources are within 2 km of existing roads (Chapter 1). This combined with the thin and easily removed soil and plant cover (Dredge, 1992a; Scott, 1996) makes these sites prone to future disturbance.

The environmental conditions of the Subarctic, such as high wind and low temperature can limit plant growth. When combined with the further limiting conditions (e.g., low moisture, high bulk density, extreme temperature fluctuations, low nutrient status) of the gravel-dominated substrate, natural revegetation of abandoned disturbances is extremely slow (Jorgenson et al., 2003). This leaves sites biologically and visually barren and prone to invasion by non-native species (Staniforth and Scott, 1991; Harper and Kershaw, 1996; Kershaw, 2003a).

The Churchill region (Figure 4-1) encompasses high ecosystem diversity, including tundra, forest-tundra and boreal forest ecosystems within a small geographical area (Ritchie, 1962). The Churchill tourism economy brings in approximately $1 billion annually (Manitoba Tourism, pers. comm., 2003) making preservation of the natural environment –

[1] A version of this chapter has been submitted for publication to Ecoscience.

and thus the visitor's experience – an important consideration when deciding whether or not to revegetate these aesthetically-displeasing sites.

LIMITATIONS TO GROWTH – MOISTURE, NUTRIENTS OR WIND

Natural revegetation, or allowing the surrounding plant community to naturally invade the disturbed area, is a potential method of revegetation. However, the limitations to growth of gravel-dominated substrates make natural revegetation an extremely slow process (Firlotte, 1998; Forbes and Sumina, 1999; Jorgenson *et al.*, 2003). After several years or decades naturally revegetated areas, in comparison with the undisturbed community, will have large areas of bare ground with small patches of a few species, or overall low cover and low species richness (Cargill-Bishop and Chapin, 1989; Borgegard, 1990; Firlotte, 1998; Jorgenson *et al.*, 2003; Kershaw, 2003a). Disturbance itself is not always detrimental to plant growth and can improve species diversity (Harper and Kershaw, 1996), but this is in situations where the seed bank, propagules and soil have not been entirely stripped. In areas where invasion of non-native species is a threat (Staniforth and Scott, 1991) and aesthetics are important (McKendrick, 1991b) to the local economy it is not acceptable to wait the decades (or even centuries) it may take for gravel-dominated disturbances to naturally revegetate. Assisted (human-induced) revegetation/reclamation becomes more desired because it speeds the recovery of disturbed sites and helps them better blend with the surrounding landscape (McKendrick et al., 1992).

Assisted reclamation consists of manipulating the substrate to create a more hospitable environment for incoming native seeds, encroaching vegetation surrounding the disturbance and propagules already present in the disturbance. A disturbance which has been barren for years will not become revegetated on its own without improvements to the substrate (Walker and Everett, 1987). Substrate manipulations (not necessarily mutuallyexclusive) can consist of adding soil amendments (Gartner et al., 1983) such as peat moss, topsoil or straw, adding natural or man-made fertilizers (Klokk and Rønning, 1987), or altering the microtopography to create micro-sites for germination. Seeding or adding of plant cuttings may also be a part of assisted reclamation to speed up the process (Johnson, 1987b).

Of interest in this study was the effect of substrate limitations on assisted reclamation success. We chose to focus on lack of moisture, lack of nutrients, and exposure to abrasive winds since all have been found to limit seedling growth, and thus reclamation success on gravel-dominated disturbances in the Subarctic. This was based on the three major causes of seedling mortality (post-germination) that are characteristic of gravel-dominated disturbances (Cargill-Bishop and Chapin, 1989): drought (Addison, 1975), lack of nutrients (Jorgenson et al., 2003) and winterkill (from desiccation) (Leep et al., 2001).

Soil Moisture

In areas like Churchill where a large proportion of the available moisture falls as snow, the primary source of summer moisture for plants is from the soil (Van Miegroet et al., 2000). Gravel-dominated substrates are rapidly or excessively drained because they are dominated by coarse-grained (>2mm) sediments. Consequently they have low spring and growing season soil moisture availability and retention (Down, 1974; Densmore *et al.*, 1987; Lavrinenko *et al.*, 2003). The large, interconnected pore spaces do not retain moisture and water additions to the soil are lost to through-flow (Briggs et al., 1993). The soil water content of gravel-dominated disturbances such as airstrips, roads, pits and pads, ranges from 3.5-45% (Addison, 1975; McKendrick *et al.*, 1993; Forbes and Sumina, 1999). The low moisture content and lack of vegetative cover associated with these disturbances also contributes to extreme soil temperature fluctuations (Johnson, 1987b; Harper, 1994). The water deficiency reduces carbon assimilation and subsequently, plant growth (Addison, 1975). Seedling germination and growth is also further reduced in substrates with large sized particles due to extreme soil drying and hardening (Down, 1974; Bell, 1975a).

Other studies have determined adding an organic amendment such as peat moss or topsoil to be the best overall treatment for gravel-dominated disturbances (Logan, 1978; Jorgenson and Joyce, 1994; McKendrick, 1999). The organic matter and finer textured mineral particles can absorb infiltrating water and reduce percolation rates to create soil moisture conditions more amenable to plant growth.

Soil Nutrients

Water movement through the soil is also important for plant access to nutrients as they must be in solution to be taken up, and the solution must be available to plant roots (Forbes, 1993). Percolation of soil moisture can transport nutrients and organic particles beyond the reach of plant roots in gravel-dominated substrates (Forbes, 1993). Nutrients speed up plant growth (Skriabin, 1981) but are not necessarily critical to the reclamation of gravel-dominated disturbances. Plants which are able to fix N or easily absorb nutrients are better suited to the gravel-dominated substrate (Kershaw, 2003a), but plants which naturally have low nutrient requirements, as many Arctic species do (Savile, 1972) can also be successful. However, a study on Alaskan gravel pads (Jorgenson et al., 2003) found fertilizer was the most important soil addition because gravel pads are so nutrient deficient that they affect all aspects of growth, while water availability most affected species composition in Arctic sites.

Exposure to Wind

Plants present in wind-swept, snow-free areas, such as gravel pits and pads, have high evapotranspiration rates in the winter (Walker et al., 2001). They can have branches, needles and portions of the stem abraded by wind action (Scott et al., 1993). Uncovered plants are further subjected to plant water loss via cuticular transpiration (stoma are closed) on a sunny winter day. As all available water is frozen, these plants have no way of replenishing lost moisture and experience severe drought stress (Walker et al., 2001) or winterkill (Klebesadel, 1977). Due to the lack of soil moisture in the gravel substrate, the soil temperature can have extreme fluctuations. However, high evaporation (from sun and wind exposure) and abrasive (ice and soil) action are far more limiting to seedling development at high latitudes than soil temperature (Lewis-Smith, 2000).

Snow cover can help protect plants and seedlings from frost damage, ice particle abrasion and desiccation. This is especially important on smooth-surfaced gravel-dominated disturbances where there is little surface roughness to break the wind or accumulate snow (Pomeroy and Gray, 1995). Even short (less than 2cm) plants can be exposed to winter winds on Churchill disturbances. Any ridges or troughs present can also cut the wind speed and increase snow accumulation (Pomeroy and Gray, 1995). In an Alaskan study the creation of ridges and troughs reduced plant winterkill by 57 % (Klebesadel, 1974).

PURPOSE

The potential for the creation of new gravel-dominated disturbances, the limited natural revegetation and aerial extent of existing disturbances and the importance of keeping the landscape natural for ecotourism necessitate the testing and perfection of reclamation techniques suitable for the Churchill region. Testing of some revegetation techniques in the area in 1993-4 (Firlotte, 1998) began the compilation of strategies suitable (and not suitable) for gravel pits. This study builds on, and adds to the options for reclaiming these disturbances by addressing the effect of wind on reclamation success, determining a more effective way to apply the soil amendments to improve plant response and expanding the number of tested species. In addition, the tests were carried out on different disturbance types, ages and locations along a tundra-to-boreal forest transition gradient. Determination of effective techniques is important so that gravel-dominated disturbances can recover some biological function and better blend with the surrounding landscape on a shorter timeframe than letting them naturally revegetate.

Methods

SITE DESCRIPTION

Five gravel-dominated sites were selected for reclamation because they were large enough to house the treatments, had relatively uniform topography and <10% natural plant cover. Two were gravel pads; 'Building Pad' (building foundation) and 'Road Bed' (abandoned road). Three were gravel pits; 'Transition Pit', 'Tundra Pit' and 'Forest Pit'. The five sites differed in location along a vegetation gradient from predominantly-tundra to predominately-boreal forest (Figure 4-2). The sites (disturbances) also varied in size and age since abandonment (Table 4-1).

RECLAMATION QUADRAT TREATMENT

Treatments designed to mitigate the poor growing conditions of the gravel-dominated substrates were installed at each of the selected sites. These treatments included: (1) microtopography alteration (M) consisting of a series of 5-10cm deep ridges and troughs, (2) addition of a seed mix (S) comprised of seeds from six native species (1800 seeds·m^{-2}), fertilizer (30g·m^{-2}, 12-12-12 NPK) and commercial peat moss (2.5cm·m^{-2}), (3) snow fencing (F) installed perpendicular to the prevailing northwest winds (plastic oval mesh, 0.6m high), and (4) no treatment control (C). Combinations were also installed resulting in eight treatments (M, S, SM, C, FM, FS, FSM, FC) with three replicates of each treatment per site (n=120 across all sites). Treatment quadrats of 1m^2 were randomly located within 25m^2 plots (six plots at each site). The 25m^2 plots facilitated use of the snow fencing in larger strips.

The seed mix treatment, with the addition of the peat moss and fertilizer, was used to increase the water holding capacity of the substrate (Logan, 1978; Moskal et al., 2001), and to provide nutrients. Adding fertilizer alone would not have been efficient since there would not be the network of fibres from the peat to prevent translocation of the fertilizer pellets (Logan, 1978; Mitchell, 1987; Chambers *et al.*, 1990; Firlotte, 1998) and any dissolved nutrients through leaching (Johnson, 1987b; Auerbach *et al.*, 1997). Although decomposition in the Arctic and Subarctic is slower than in the South, northern plants have the ability to conserve nutrients once they are made available, so fertilizer can have a long-lasting effect (Klokk and Rønning, 1987). The species selected for inclusion in the seed mix (Table 4-2) were chosen because they were native to the Churchill area (Scott, 1996), perennial, suited to the limited growing conditions of a gravel-dominated substrate, aesthetically-pleasing and available commercially (Blazing Star Wildflower Seed Company, Melfort, SK and ALCLA Native Plant Restoration, Calgary, AB) (Polunin, 1959; Johnson, 1987a; Hardy BBT Limited, 1989). Seeds were included as part of the seed mix treatment because the suite of species present in the surrounding undisturbed plant communities (tundra, tundra-boreal transition and boreal forest) would not be suited to the alkaline disturbances (Borgegard, 1990; Auerbach *et al.*, 1997).

The microtopography treatment was designed to collect additional moisture in the troughs (Johnson, 1981; Densmore, 1987; Mitchell, 1987) and reduce wind at the micro-scale while the snow fencing treatment was installed to do the same on a larger-scale. In addition, the snow fencing collected a protective blanket of snow over the seedlings to reduce wind at the macro-scale, prevent frost scour and desiccation (McKendrick et al., 1992). Snow is six times more efficient at insulating plants from wind and extreme temperature than the same depth of soil because of its high porosity (Pomeroy and Brun, 2001). An additional benefit of snow beds is that they trap mineral and organic particles (such as soil and plant debris) which settle on the ground when melt occurs (McKendrick et al., 1992). Many of these particles are lost with spring meltwater throughflow, but a portion remains within the zone available to plants (Walker et al., 2001) helping to improve soil quality and build soil structure (Sharp et al., 1995).

RECLAMATION AND RECOVERY QUADRAT ASSESSMENT

Vegetation on the reclamation quadrats was assessed in August of 2002 and 2003. Every seedling was counted and identified to obtain plant density on a quadrat basis. Ground cover was estimated visually by the same observer for all 120 quadrats in 5% increments for cover between 10-90% and in 1% increments for 0-10% and 90-100%. Species which covered less than 1% were assigned a cover value of 0.01% (Kershaw and Kershaw, 1987). Cover and species composition were also recorded for 12 'recovery' quadrats at each site. These recovery quadrats were within the disturbance but outside the reclamation treatment quadrats and were used as a site baseline, or estimate of the natural recovery on the site.

Soil samples were taken from each reclamation quadrat in each of the two summer field seasons (and from six random locations from within the disturbance but outside the reclamation quadrats in the first). The samples were processed and analyzed to obtain bulk density, gravimetric (mass wetness) and volumetric (volume wetness) soil water content, organic matter content, percentage of fine material <2mm, nitrogen, phosphorus and potassium content, and pH.

To better determine the effect of the snow fencing, winter sampling was conducted in February 2003 and 2004. Sampling consisted of taking snow cores to determine snow density and depth. From these, the snow water equivalent (SWE) (Pomeroy and Gray, 1995) and heat transfer coefficient (HTC) (Kershaw, 1991, 2001) were calculated. Snow samples were melted and filtered for particulate matter mass.

STATISTICAL ANALYSIS

Descriptive statistics were used for frequency, plant diversity, nutrient and baseline data. Species (plant) diversity was calculated as the number of taxa present on a quadrat out of the 58 taxa found on the reclamation quadrats. Baseline data for analysis were taken from the recovery quadrats (within the disturbance but outside the treatment quadrats) and the control quadrats. Normality (Kolmogorov-Smirnov test) and homogeneity (Levene median test) were tested prior to analysis to ensure assumptions were met. Statistical analysis was conducted using one-way analysis-of-variance (ANOVA) to compare plant density and diversity among treatments, and among sites. The value for reported significance was $P<0.05$.

Hierarchical Clustering Analysis (HCA) was used to reveal any natural groupings in the data set that otherwise might not have been apparent. It was selected over the more common K-means Cluster Analysis because the data set contained a small number of cases (< few hundred). Cases and variable clustering were examined. Clusters were grouped based on centroids and measured using Euclidean distance (straight line). The data were standardized (Z-scores) prior to clustering to equalize the different scales of the data. Discriminant Analysis was also used to explore any additional groupings related to site or treatment.

Outliers and highly correlated variables were removed and linearity tested prior to Principal Component Analysis (PCA). A form of factor analysis, PCA was used to determine variable groupings related to patterns in the data which explain the variance. Factors were extracted if they had an eigenvalue >1, and were rotated using Varimax rotation with Kaiser normalization to enable interpretation of the components (Pimental, 1979; Pielou, 1984; SPSS Inc., 2004).

Results

SITE BASELINE CHARACTERISTICS

Forest Pit had the highest bulk density, but the lowest soil water content (gravimetric and volumetric), nitrogen, natural plant density and plant diversity (Table 4-1). Transition Pit was at the other end of the gradient. Characteristics of the other three sites fell between these two extremes (Table 4-1). The same groupings with regards to plant growth suitability found in the baseline assessment of the sites were carried through to all aspects of the reclamation testing results (Chapter 2) where Building Pad and Transition Pit were better suited to plant growth (lower bulk density, presence of fine material and organic matter, higher soil water content) prior to treatment and Forest Pit the least with Tundra Pit and Road Bed more similar to Forest Pit.

RECLAMATION TREATMENTS

Total average plant frequency and species diversity were significantly greater at Building Pad and Transition Pit than the remaining sites which had less than half their values (Table 4-1). Many of the soil and plant variables were highly correlated ($r>0.76$, $P<0.05$).

Bulk density was used to represent treatment, organic matter and soil pH. Volumetric water content was used for soil water instead of gravimetric because it was more independent of the other variables. Phosphorus and potassium values contributed nothing to the statistical analysis and were removed because of poor nutrient level detection methods in the soil processing. The levels were too low to be accurately measured with the testing equipment available (Hach Soil Testing Kits). Plant density, cover and diversity were all highly correlated so density was selected as the best representative of potential reclamation success (Chapter 2). Transition Pit and Building Pad had significantly higher density and diversity than Forest Pit, Tundra Pit and Road Bed. Quadrats that were treated with the seed mix had significantly greater diversity than those that were not.

Clustering revealed that (1) plant density was most closely associated with water content, (2) fine material with site, and (3) bulk density with treatment (Figure 4-3). Factor analysis of the soil and plant data revealed three main components accounting for 85.6 % of the variance (Table 4-3). Component one represented the soil characteristics of low bulk density (-0.878; component loading) and high water content (0.922). Component two represented low plant density (-0.808) as a result of site (i.e. fine material) (0.939). Component three included year (0.938) and nitrogen content (-0.920) with the second year having lower nitrogen.

Plant density clustered with snowpack HTC. PCA of the snow data with growing season data produced two components which explained 82.8% of the variance. The first component was comprised of high plant density (0.769) and high snow density (0.903), and the second low HTC (-0.777) and high snow depth (0.925).

Naturally occurring N levels at all the disturbed sites were below theoretical plant requirements of 15 $mg \cdot L^{-1}$ (Scott, 1985; Briggs *et al.*, 1993). With the addition of the seed and fertilizer mix all but three of the 60 seed mix quadrats had N levels above the 15 $mg \cdot L^{-1}$

threshold in the first growing season. However, by the second growing season, all of the treatment quadrats were back below this threshold. Phosphorus was naturally present in sufficient quantities (>2 $mg \cdot L^{-1}$) at all five sites. But on a quadrat-specific basis was deficient at six quadrats in each growing season. Potassium levels, natural and treated, were all measured above the required 5 $mg \cdot L^{-1}$.

Discussion

SITE BASELINE CONSIDERATIONS: DISTURBANCE LOCATION, AGE AND TYPE

The sites and treatments that resulted in lower bulk density and higher soil water content had the greatest plant density. Transition Pit was the most successful site of the five, but it was also the site with the greatest natural potential for revegetation. It had the lowest bulk density, highest soil water content, percent organic matter, nitrogen, and the highest natural plant cover, density and diversity. Forest Pit was the least naturally suited to revegetation. These baseline conditions were carried through into the effect of the treatments where quadrats at Transition Pit were quite successful and quadrats at Forest Pit performed the worst. The most interesting site was Building Pad because its baseline conditions were deemed suboptimal: high bulk density, small amounts of fine material, low P, moderate organic matter, soil water content, and N, but it had the second highest natural plant density, diversity and cover and was the second most successful site in terms of revegetation test treatments.

Disturbance Location

Comparison of the sites along a tundra-boreal ecotype gradient revealed no obvious differences, other than the tundra pit (Tundra Pit) and forest pit (Forest Pit) had the lowest species diversities. Each of the two 'extremes' had species not present at any of the other sites. Boreal forest disturbances especially, are naturally more species-poor than tundra disturbances since the range and number of species present in the surrounding undisturbed community are particularly unsuited to colonization of gravel-dominated substrates (Borgegard, 1990). The transition sites, Road Bed, Transition Pit and Building Pad had the benefit of a larger suite of species which were already present on the disturbance or in the surrounding undisturbed plant community.

Disturbance Age

Disturbance age did not appear to be a major factor in the success of reclamation. The oldest site, Forest Pit, which theoretically should have built up fine material and organic matter over the years resulting in increased plant cover, was the least successful. However, the old pit was chosen like the rest of the sites with the criteria that it had to have low pre-existing plant cover, so despite being left relatively undisturbed for over 40 years it had recovered very little on its own further emphasizing the poor growth substrate present. The newest of the disturbances, Building Pad and the second oldest pit, Transition Pit, were the two most successful revegetation sites. Site-specific characteristics apart from disturbance age were more of a factor in site potential for reclamation success.

Disturbance Type

Comparison of the results between pits and pads found no discernable differences. The ability of these two different types of disturbances to be revegetated is more a product of the existing site conditions (including propagules in the substrate) than the disturbance type itself. The expected compaction on the pads did not seem to affect the growth potential of seedlings; however, compaction deeper in the soil profile could become more of an issue once the plants grow mature root systems. It was also expected that the thicker gravel pad (Road Bed) would be more difficult to revegetate than the thinner Building Pad because gravel thickness is related to water content (Jorgenson, 1997) but other factors such as the pond adjacent to Road Bed counteracted this supposition.

The high plant diversity and density at Building Pad can be attributed to the seed (propagule) bank which is a product of the disturbance being the youngest, and an aggregate deposition site. Although gravel- and sand-dominated substrates have little-to-no seed bank (Gartner et al., 1983; Staniforth et al., 1998), 90 % of what is present is in the top 5cm of the gravel (Staniforth et al., 1998). Since gravel was added to Building Pad from different sources, some of which may have been newly created pits, the upper gravel layers from other sites might have included a viable seed bank. The organic matter content was also high at Building Pad, further evidence of "contamination" of the gravel fill with OM and propagules. As well, most natural revegetation of gravel-dominated disturbances is from sexual reproduction rather than vegetative encroachment from the surrounding plant community (McKendrick, 1987). Building Pad in particular had many annual species that were flowering and producing seed each summer, providing a seed source for the next growing season.

LIMITATIONS TO GROWTH

Moisture Availability

The cluster analysis of the treatment quadrats grouped the plant variables; density, diversity and cover, most closely with soil water content. In addition, the sites with the highest natural soil water contents had the highest natural and treated plant density, diversity and cover. The seed mix quadrats had higher plant diversity than the non-seed mix quadrats.

This could not have been all a product of the six seeded species since three of them were found naturally occurring on the sites. But rather, the peat moss in the seed mix treatment decreased bulk density and increased water content which provided a more suitable growing environment for species present on the disturbance which could not grow without substrate improvements.

The factor analysis grouped bulk density and water content, and then bulk density with treatment, which was a result of the addition of the peat moss. The addition of the peat moss increased the water holding capacity of the substrate, creating a water reservoir for plants to access, which had a positive effect on plants in the reclamation treatments.

In a similar study in the Churchill area, Firlotte (1998) found the addition of peat moss inhibited seedling growth 35% more than her other treatments because a crusty surface layer formed. In this project we mixed some of the surface material removed to install the peat moss treatment into the peat prior to applying it to the quadrats to prevent severe drying and wind erosion (Logan, 1978). A slight crust did form when the peat was dried out, but this quickly disappeared with any moisture additions and did not inhibit seedling emergence.

The addition of peat moss decreased the bulk density by almost half, and doubled the volumetric soil water content and increased the gravimetric soil water content by five times. This resulted in a 50 % increase in plant cover and a 33 % increase in plant density. This is similar to results found by McKendrick et al. (1993) where bulk density was halved, water content tripled and there was a 30 % increase in cover. Jorgenson and Joyce (1994) reported that topsoiling doubled the water-holding capacity of their test plots on gravel disturbances in Alaska. Jorgenson and Joyce (1994) found even after four year the organic matter was still maintaining increased water content over the control plots. In a later assessment of his earlier study plots McKendrick (1999) found that all vascular plant species performed better on topsoiled plots and that there was increased litter cover which helped build soil structure.

Increased performance and growth was noted on our study quadrats where individuals on the seed mix quadrats were taller, sturdier, greener and more likely to be flowering.

The combination of the seed mix treatment with the snow fencing collected and retained moisture better than the other treatments because of the ability of the peat moss to capture and store meltwater provided by the snowpack on the fenced quadrats.

However, the micro-relief treatment, found successful in other areas of the Arctic/Subarctic (Densmore, 1987; Mitchell, 1987) and designed to increase moisture in the troughs and provide micro-scale protection from wind, was not successful at least in the short-term. There was visibly moister substrate in the troughs and the majority of the seedlings were found growing there, especially in the quadrats that also had the seed mix treatment. However, plant density, cover and diversity were not greater on these treatments than the seed mix alone or the control plots. Densmore (1987) found the furrows were especially helpful to woody plants of which there were few on our study sites. An external moisture source (other than snow melt or precipitation) could explain the higher soil water content at Transition Pit and Road Bed (especially at Transition Pit where the site was visibly moist, but this extra moisture was not captured in the shallow soil samples). Immediately to the west of these two adjacent sites was a pond with raised banks. The level of the water however, was equal with that of the surface of Transition Pit, and the wetland area to the East of the pit was slightly lower. Lateral percolation from the pond to the wetland could have been supplying these two sites with moisture that was available to plants, but not reflected in the shallow soil samples.

The soil improvements from the peat moss resulted in increased plant cover, density and diversity. This was primarily due to the increase in plant-available water, although additional factors such as improved root distribution and soil stability (Logan, 1978) could also have been a result of the addition of peat moss.

Nutrient Availability

Nitrogen is most available between pH 6-8 and declines outside this range (Hach Company, 1993). The high pH of the calcareous gravel-dominated disturbances created a naturally N deficient environment. The addition of a time-released fertilizer raised the N levels on the treated quadrats to above the minimum required for plant growth (15 $mg \cdot L^{-1}$ (Briggs et al., 1993)) which would have aided the growth of seedlings. However, despite the inclusion of the peat moss to hold the fertilizer and retain any water/nutrient solution, N levels fell below plant requirements, possibly because of the low C:N ratio CEC characteristic of gravel-dominated substrates (Kidd et al., 2006; Stehouwer et al., 2006). The pH of the quadrats treated with the fertilizer and peat mix remained within the optimum zone in the second year (Chapter 3), so any natural N additions from decomposition would potentially still have been available to plants.

Although the dry substrate would have affected the availability of P to seedlings, it is more effectively used by mature plants in the development of roots, formation of fats, cell division and flowering, fruits and seeds. Similarly, K demand from seedlings is low because it is more important to already established plants (Follett and Wilkinson, 1995). As well, the baseline P and K levels at the sites were adequate for plant requirements. Thus, the addition of a complete fertilizer was not as necessary to seedling growth as the addition of N. Seedling growth was still significantly higher on the seed mix treated quadrats in the second year than the non-seed mix treated quadrats despite the decrease in nutrient quantities. So, although the N added in the first growing season could have aided in the initial growth of seedlings on the quadrats, it was not an important factor in the revegetation over the long-term on these gravel-dominated disturbances.

Fertilizer has been found to produce a three-fold increase in plant cover (Hernandez, 1974a), a 200 % increase in production (Babb and Bliss, 1974), increased stem density (McCown, 1973) and enhanced seedling establishment (Hernandez, 1974b) on xeric Arctic and Subarctic sites. However, as in Maslen and Kershaw's (1989) study, we found no effect of the fertilizer. This is because it leached away in the first year despite the addition of peat moss to hold the fertilizer particles, was deflated with soil particles (wind erosion) or was in the plant tissue but was not manifesting itself in plant growth. In the long-term, nutrients from the decomposing peat moss can be added to the substrate, but because of extremely slow decomposition (Logan, 1978), additions will be minimal.

Exposure to Wind

There were visual and measurable differences in the snow cover on the fenced and unfenced quadrats. The average snow depth on the fenced quadrats was 2.5-4.3 times deeper than the snowpack on the unfenced quadrats (Chapter 3). The highest plant densities were found on the deeper, denser snowpack covered quadrats. Although these deeper snowpacks were denser than expected, the low HTC values reflected the protective qualities of the snow. On the fenced quadrats the HTC values were more similar to those of an undisturbed forest snowpack (Kershaw, 2003b).

Very few quadrats were completely snow-free, so at this early stage in the reclamation process, even the unfenced quadrat seedlings had some protective snow cover. Some taxa, such as Brassicaceae spp. (mustard family), Chamerion angustifolium L. (Holub) (fireweed) and Castilleja raupii Pennell (Raup's Indian Paintbrush) were taller than the snowpack on both fenced and unfenced quadrats and had their leaves abraded off on the exposed portion of the plant. Thus, the effect of protection from the wind and abrasive ice particles, which can significantly decrease winterkill (Klebesadel, 1974), can become more important to plant growth as they mature and extend above the snowpack on the unfenced quadrats. At this point they will be subjected to high evaporation and abrasive action (Lewis-Smith, 2000).

CONCLUDING REMARKS

The results from this study support previous research results from other Arctic and Subarctic gravel revegetation projects (Densmore and Holmes, 1987; Elliot *et al.*, 1987; McKendrick *et al.*, 1992) in that addition of a material (such as peat moss) to increase the water holding capacity of the substrate and seeding with native species can increase the rate of recovery in disturbed gravel sites. Although the techniques from locations across the North are not directly comparable, the end results are similar despite these geographical differences. Even within locations, such as Churchill, the site differences dictated different treatment performances. Another consideration in the determination of success is time. Many of the Alaskan studies were conducted over 7-10 years and effects of some treatments such as the snow fencing, were not immediately apparent in the first few years (Jorgenson et al., 1993; McKendrick et al., 1993).

Summary of Findings

1. Fertilizer addition effects disappeared by the end of the first growing season. Although it was added into the same treatment as the peat moss, the increased plant density and cover (particularly in the second growing season) on these plots can be attributed to the peat moss and the increased moisture-holding capacity it provided. It would be more effective to add the fertilizer once the plants were already established to promote increased growth and reproduction.

2. The addition of seeds in a seed mix helped increase density and diversity on sites with naturally impoverished floras (Tundra Pit and Forest Pit).
3. The effect of peat crusting which can inhibit seedling emergence and growth was minimized by incorporating the peat moss into the top 2 cm of gravel rather than laying it on top of the gravel.
4. Snow fencing and micro-relief alteration designed to decrease the effect of desiccating winds and abrasive ice particles had not produced a quantifiable effect after two growing seasons. As with other Alaskan studies it is expected the effect of the snow fencing will become more obvious as the plants mature and grow above the shallow naturally occurring snowpack. The snow fencing did create a minor improvement in the water availability when in combination with the peat moss soil amendment.
5. Firlotte (1998) cited substrate texture as the dominant limiting factor to gravel revegetation in Churchill. We agree with this in that the addition of peat moss decreased the bulk density of the substrate, improving its texture for plants.
6. The main increase in plant response was seen from the increase in the water-holding capacity and alleviation of the limitation to growth imposed by poor water availability on gravel-dominated disturbances.

It would not be financially possible to use every reclamation technique to reclaim these disturbances. The goal is to reach a cost-effective acceptable end point with regards to biological function or aesthetics. Unfortunately, the peat moss was the most expensive part of the project. The cheaper techniques of erecting snow fencing and creating furrows (micro-relief) were not effective, or at least their effectiveness was not yet apparent. However, determination of what is and is not successful based on seedling requirements will reduce the cost and increase the success of future reclamation projects on northern disturbances.

Figures & Tables

Table 4-1. Study site baseline (no treatment) characteristics (mean ± SD).

	Transition Pit	Tundra Pit	Forest Pit	Building Pad	Road Bed
Bulk Density ($g \cdot cm^{-3}$)	1.13±0.14[1]	1.40±0.25[3]	1.59±0.34[5]	1.41±0.23[4]	1.26±0.05[2]
Vol. Water Content (%)	5.50±1.73[1]	4.00±0.82[3]	2.00±0.82[5]	4.00±0.82[3]	5.25±1.50[2]
Grav. Water Content (%)	6.36±1.30[1]	4.20±1.95[4]	2.18±0.71[5]	4.88±1.91[3]	5.07±1.53[2]
Organic Matter (%)	1.55±0.71[1]	0.75±0.13[3]	0.53±0.09[4]	1.32±0.52[2]	0.50±0.18[5]
Fine (<2mm) Material (%)	45.82±6.60[2]	44.47±9.78[3]	39.73±3.93[4]	32.68±7.69[5]	49.21±9.50[1]
Soil pH	8.34±0.13[3]	8.56±0.18[5]	8.46±0.15[4]	8.12±0.13[1]	8.17±0.23[2]
Nitrogen ($mg \cdot L^{-1}$)	11.20±14.04[1]	3.36±0.87[4]	0.42±0.69[5]	5.40±2.82[2]	3.86±1.22[3]
Phosphorus ($mg \cdot L^{-1}$)	4.37±2.54[4]	9.26±3.21[1]	4.98±2.13[3]	2.78±2.97[5]	5.92±3.53[2]
Plant Cover (%)	4.33±2.44[1]	1.04±1.16[4]	2.42±2.92[3]	3.16±1.94[2]	0.33±0.43[5]
Plant Density ($stems \cdot m^{-2}$)	445.42±30.44[1]	15.00±6.86[4]	11.50±3.94[5]	349.58±153.35[2]	80.83±34.70[3]
Plant Diversity (%)	47.42±0.99[1]	23.28±4.98[4]	12.93±2.99[5]	37.94±1.99[2]	30.18±2.98[3]
Year Abandoned	1984	1961*	1960	1997	1984
Disturbance Size (ha)	1.05	1.93	5.73	0.75	1.28
Surrounding Vegetation	Forest patches broken by open tundra	Tundra	Boreal forest	Open treed area	Forest patches broken by open tundra
Additional Information	-adjacent to Road Bed	-along main highway -same pit used by Firlotte (1998)		-building pad -raised 0.6m	-adjacent to Transition Pit -old road bed -raised 1.5m

[1-5] Site ranking (1=good, 5=poor) based on suitability for plant growth for each characteristic, if applicable.

* Tundra Pit was re-disturbed in 2000/2001.

TABLE 4-2. List of species selected for seeding on reclamation test quadrats.

Species	Common Name	Family
Anemone multifida Poir.	Cut-leaf Anemone	Ranunculaceae
Castilleja raupii Pennell	Raup's Indian Paintbrush	Scrophulariaceae
Chamerion angustifolium (L.) Holub	Fireweed	Onagraceae
Hedysarum mackenzei Richards.	Northern Sweetvetch	Fabaceae
Hierochloe odorata (L.) Beauv.	Sweetgrass / Vanillagrass	Poaceae
Linum lewisii Pursh	Lewis' blue flax	Linaceae

TABLE 4-3. Factor analysis (Rotated Principal Component Analysis) of soil and plant data.

	Component		
	1	2	3
% Variation Explained by Component	31.722	28.415	25.464
Cumulative %	31.722	60.137	85.601
Year	.170	-.039	.938
Site	-.014	.939	.070
Ave. Bulk Density	-.878	.144	.152
Ave. Volumetric Water Content	.922	-.082	.078
Ave. % Fines <2mm	.617	.653	-.019
Ave. Nitrogen	.252	.005	-.920
Ave. Plant Density	.357	-.808	.145

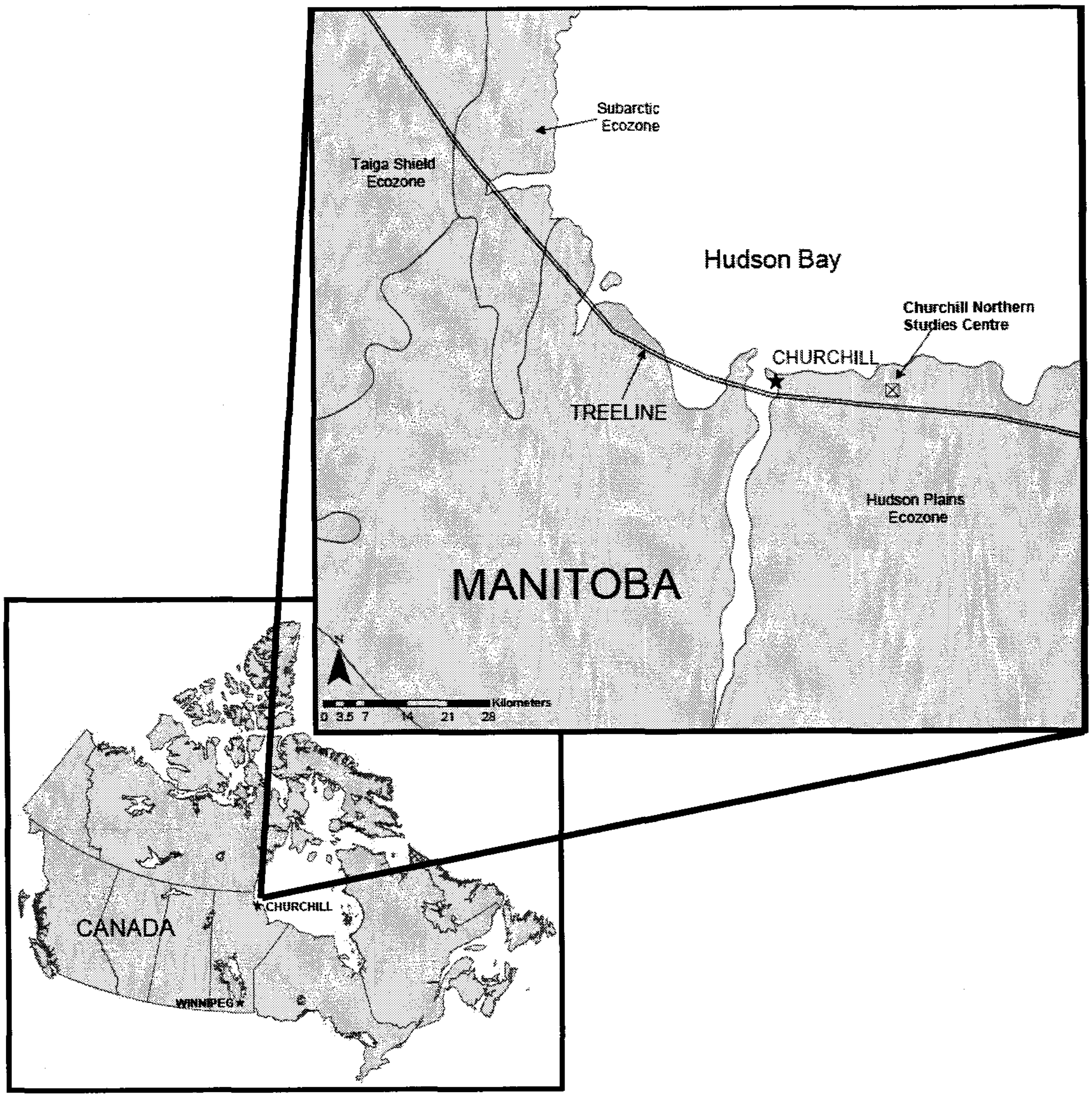

FIGURE 4-1. Location of general study area, Churchill, Manitoba, Canada.

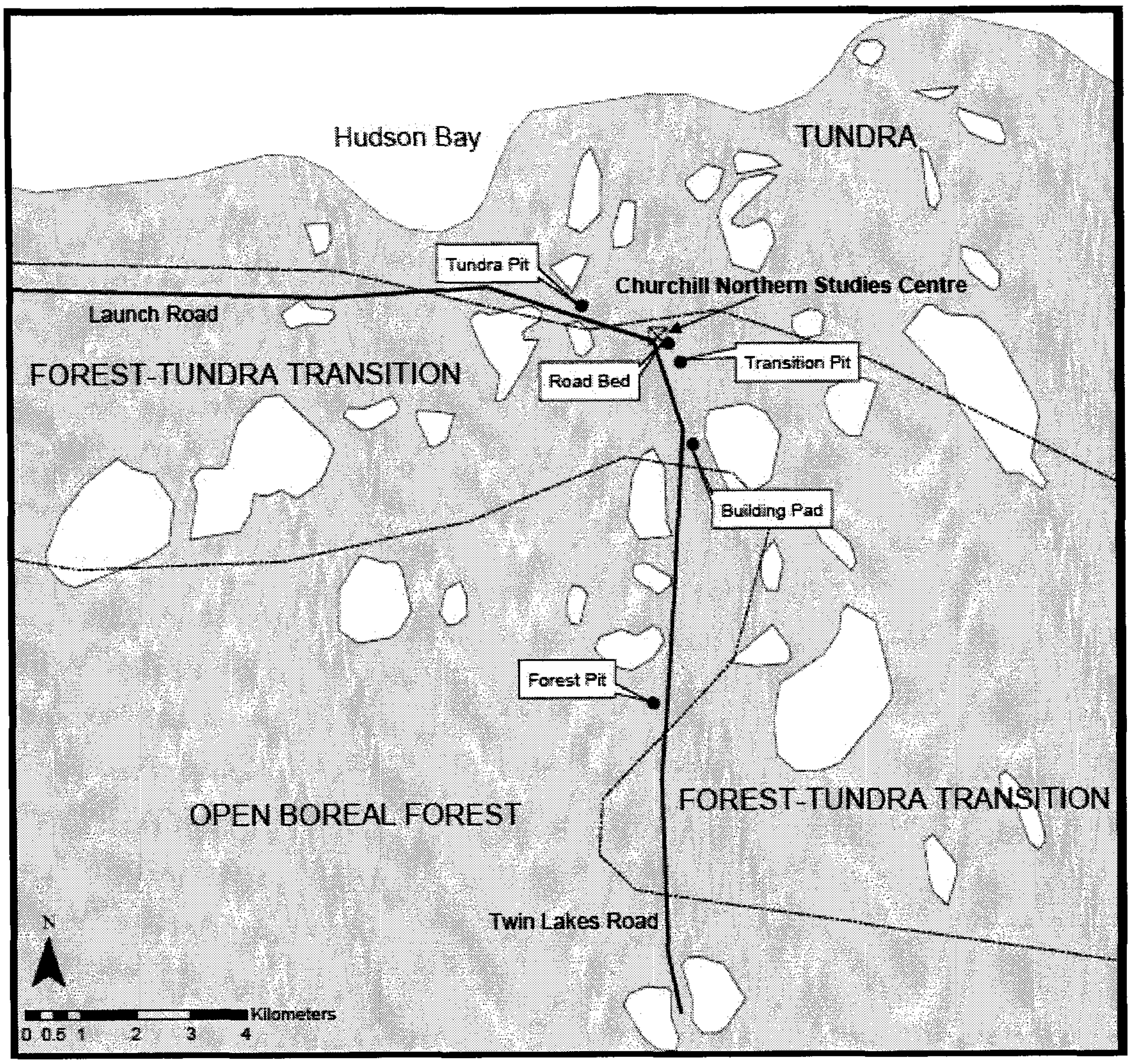

FIGURE 4-2. Location of study sites.

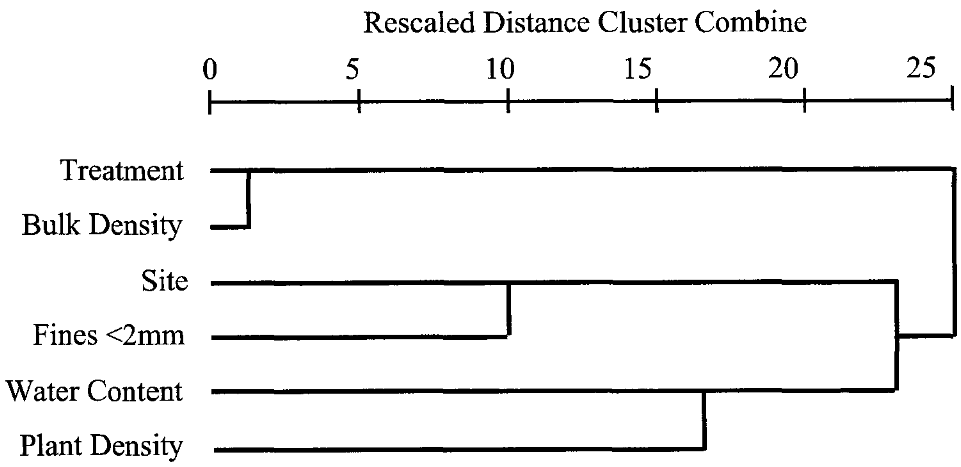

FIGURE 4-3. Hierarchical Cluster Analysis dendrogram relating soil and plant variables. Variables which combine with shorter line lengths (closer to 0) represent stronger associations. With looser clustering criteria all variables eventually group into one cluster (at 25). The rescaled distance at which clusters were combined preserved the ratio of the distances between steps. Treatment and bulk density were combined first and most closely.

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CHAPTER 5 - Conclusion: Study Considerations, Findings and Recommendations and Project Evaluation

INTRODUCTION

Reclamation of gravel-dominated disturbances at Churchill, Manitoba is important for eco-tourism. Although the plants that grow on a disturbance in the process of reclamation will not be the same species growing in the adjacent undisturbed plant community, they will still add aesthetic appeal to the site. In addition, they will prevent encroachment by non-native weedy species, and help improve the substrate making it more hospitable for plant growth. This study combined techniques from previously conducted revegetation experiments in Churchill (Firlotte, 1998) along with techniques from long-term Alaskan studies (Densmore and Holmes, 1987; McKendrick *et al.*, 1992; Jorgenson *et al.*, 1993) and expanded the study sites to include those in the treed transition between tundra and boreal forest ecozones. The results from the separate chapters in this thesis have been synthesized in this final chapter to give a summary of the overall study problems, findings and recommendations for implementing reclamation at these gravel-dominated sites on a larger scale.

STUDY CONSIDERATIONS

Influence of Weather

This project spanned two growing seasons, the first (2002) was similar to the climate normals (1971-2000) for Churchill while the second (2003) was much warmer (Table 5-1). The year 2002 was slightly cooler than normal on an annual basis, but when the growing seasons (June – September) were compared, there was little temperature difference. The second year, 2003, was a much warmer year both on an annual (+1.3°C) and growing season basis (+2°C). Precipitation was almost identical between the two growing seasons, but 2003 had more snowfall. The most interesting difference between the two seasons and years was in terms of Growing Degree Days (GDD>5°C) and the first GDD of the year. This showed that 2002 was not much different from normal, but that 2003 had far more GDDs than 2002 and the normals.

Since the growing seasons were not cooler or drier than normal it is expected similar results could be obtained if the project were repeated on other gravel disturbances in the Churchill area. The warmer second growing season may have been helpful to the seedlings that over-wintered and the new seedlings that emerged during the second growing season in that there were more GDDs. Although warmer than average years may have been helpful to seedling emergence and growth by providing a warmer and longer growing season, the overall project success is not solely due to the warmer than normal second growing season. It would have been interesting if one of the years had greater precipitation than the other to see if there was a difference due to rainfall, especially with respect to the peat moss treatment and its ability to retain moisture additions.

Identification Difficulties

A large problem with seedling identification was the grass species. All grasses were grouped together unless they could be positively identified. Unfortunately this means *Hierochloe odorata* seedlings, if present, were not recorded independent of other grass species until they were large enough (most *H. odorata* seedlings were identifiable in the second growing season). This made determination of *H. odorata* success as a seeded species for reclamation difficult. Another identification problem was several members of the Brassicaceae family. Due to the early stage in growth of many of these seedlings where there were no flowers or seed pods to aid in identification, it was difficult to determine the species and in some cases even the genus of the mustards.

Wildlife Interference

The only problems encountered with wildlife were Arctic Foxes at Building Pad. Any disturbance to the quadrats (e.g. taking a soil sample) resulted in the fox digging in the disturbed area. Luckily the seedling counts and identification were completed prior to the sampling and fox digging, so it did not unduly influence the data, although the corner of the quadrats dug up may have had more difficulty growing back for the next season since the seedlings were covered up. Other wildlife influences on the study were ptarmigan eating seedlings, and caribou and dogs walking on the quadrats which could help spread seeds around the disturbances once the current seedlings reproduce.

Project Maintenance

The only part of the project that required constant maintenance was the snow fencing. Despite using heavy-weight winter-grade fencing, it was still easily shredded by the wind. The use of rebar as the support may have added to this because it was textured, however, this texture also helped keep the fencing from sagging down the poles. Fencing was easily repaired with cable ties, however fencing should be replaced annually (probably towards the end of the summer prior to snowfall since most of the shredding occurred in the summer) to prevent failure. Degradation of the plastic with the wind and the snow made the fencing brittle and more prone to damage.

There was some general public interest from the community of Churchill about what the project entailed and its reason for taking place, which was sparked by the very visible orange snow fencing and signage. Public awareness of the project and the ongoing maintenance of the sites by Churchill Northern Studies Centre employees probably reduced unintentional disturbance or vandalism. Further public involvement could be encouraged through a seed collection program and larger scale implementation of the study quadrats. Volunteers from outside the community (from Earthwatch) helped install the treatments and with a funding grant, local volunteers from the general public and the school could be recruited and encouraged to take ownership of reclaiming disturbed areas in the vicinity of the community.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Findings

1. Overall site success is determined by the pre-existing conditions of the disturbance. I.e. sites which were species rich, had a more suitable growth substrate, or a seed source (from seed rain, or the minimal propagule bank) were more successful.
2. Species-poor disturbances benefited more from the addition of seeds in a seed mix, while they were less important to success at the naturally species-rich sites.
3. Disturbance type, age and ecotype had no influence on reclamation success other than disturbances in at the two ecotype extremes (primarily tundra and primarily boreal forest) were more species poor than the disturbances in the transition ecotype. These sites also had a different suite of species present.
4. Peat moss, when properly applied (by mixing it into the gravel substrate) increased plant density (33%) and cover (50%) by reducing the bulk density by half and doubling the volumetric water content of the substrate.
5. Adding the peat moss and fertilizer mix improved the substrate conditions for growth by lowering the pH and bulk density, increasing the water holding capacity, amount of fine material and organic matter.
6. Seedlings growing on the peat moss treatment were larger, greener and in some cases flowering.

7. All of the nutrients added to the substrate through the time released NPK fertilizer were lost by the second growing season. This may have been through either leaching or uptake, but since the treatment was not applied on its own, it is difficult to determine where the nutrients went. However, the lack of fertilizer in the second growing season had no effect since seedling densities were greater in the second growing season.
8. Snow fencing had no quantifiable effect on seedling success or substrate improvements in the short-term despite the fenced plots having significantly greater snow depth and snow water equivalent and lower heat transfer coefficient (greater insulative properties). It is suspected it will become more important as plants grow and protrude beyond the naturally shallow snowpack. Alaskan studies have found the snow fencing does not have a measurable positive effect on reclamation success until the seventh or eighth growing season. This could be due to the slow plant growth response to the milder winter temperatures (Walker *et al.*, 1999) and slight improvements each year to plant canopy height, diversity and abundance which are not obvious on a year-to-year basis, but are measurable over a longer time period (Wahren *et al.*, 2005).
9. The micro-relief treatment alone was not successful. It lowered species density and cover as compared to the controls because of the intense disturbance to the substrate without any amelioration to offset the disturbance. As well, differences in the substrate characteristics were not measurable which was unexpected.
10. Twenty-four taxa have been identified as suitable for revegetation projects in the Churchill region from this study and that of Firlotte (1998) (refer to Table 2-3).

11. Dryas integrifolia was the most successful naturally-occurring species. Its ability to fix nitrogen, its tolerance of xeric substrates and light, easily dispersed seed and mat life form make it an ideally suited species for growth on gravel-dominated substrates.

12. Seeding of species suited to the gravel-dominated substrate, such as *Anemone multifida*, *Linum lewisii* and *Hedysarum mackenzei* and the addition of a water-retaining soil amendment were found as the best methods with which to reclaim gravel-dominated disturbances in the Churchill region.

Recommendations

1. Disturbances should be assessed prior to large-scale application of reclamation techniques for natural species richness from the propagule bank and seed rain. This could be done through seed collection and soil germination tests. Species-rich sites do not require seeding, while species-poor sites do.
2. Peat moss must be incorporated into the substrate to prevent severe drying which causes crusting. This crusting prevents seedling emergence.
3. If fertilizer is going to be used it must be added annually to compensate for losses between years.
4. Snow fencing should be maintained on the sites and assessed in a few years to determine if it is finally having an effect on plant success.
5. Seeding rate of applied species should be doubled to compensate for seed loss to wind and water erosion and seed desiccation and seedling winterkill due to the nature of the well-drained, coarse-grained substrate.

   The seeding rate applied was 300 seeds·species^{-1}·m^{-2} (total = 1800 seeds·m^{-2}).
6. *Dryas integrifolia* seeds should be harvested locally and tested as a species suitable for revegetation.

PROJECT OBJECTIVES

1. Determine the major limiting factor to seedling emergence.
    a. The major limiting factor to seedling emergence with respect to moisture, nutrients or wind, was moisture, although the way in which the treatments were designed makes it difficult to determine if the nutrients provided in the first growing season aided seedling emergence. Many of the seedlings had a reddish discolouration perhaps from fertilizer chemical burn.
    b. Effects of wind and particle abrasion does not affect seedling emergence.
2. Determine the major limiting factor to first winter seedling survival.
    a. The major limiting factor to first winter seedling survival and subsequent second growing season success was moisture.
    b. The fertilizer was gone by the second growing season, so it was not the major limiting factor. However, the nutrients which may have been taken up in the fall by seedlings, could have helped them survive the first winter and prosper the following spring. As the fertilizer treatment was not applied independently of the peat moss it is hard to determine its true effect on survival.
    c. Again there was no measurable effect from wind and particle abrasion on first winter survival and second growing season success.
3. Determine the suitability of each of the six seeded species for revegetation in the Churchill region.
    a. *Hedysarum mackenzei* was very successful. Its large seed size ensured seeds were not lost to wind erosion or water translocation and they did not desiccate. SUCCESSFUL AND RECOMMENDED FOR FUTURE USE.

b. *Linum lewisii* was very successful for the same reasons as for *H. mackenzei*. It readily flowered by the second growing season and was green, lush and attractive. SUCCESSFUL AND RECOMMENDED FOR FUTURE USE.

c. *Anemone multifida* did not germinate in the first year but did well in the second growing season. It is likely that it needed to be cold stratified to germinate and if this had been done it is suspected *A. multifida* would have been as successful as *L. lewisii* and *H. mackenzei*. SUCCESSFUL, NEEDS COLD STRATIFICATION.

d. *Hierochloe odorata* was not found in the first year, probably due to mis-identification. However, individuals identified in the second growing season were large and robust but not plentiful. SUCCESSFUL, INCREASE SEEDING RATE TO COMPENSATE FOR SEED LOSS.

e. *Castilleja raupii* individuals were found flowering in the second growing season and were attractive and noticeable. However, they were also quite rare. This may have been because of the small seed size, or its hemi-parasitic nature. UNSUCCESSFUL. MORE TESTING REQUIRED TO DETERMINE CAUSE OF RARENESS.

f. *Chamerion angustifolium* was quite rare except at the two most successful sites. The small seed size or the seed variety may have been the cause. UNSUCCESSFUL. SHOULD BE TESTED AGAIN USING LOCALLY COLLECTED SEED AND THE SEEDING RATE INCREASED TO COMPENSATE FOR SMALL SEED SIZE.

4. Consideration of other factors in success.

   a) Aesthetics

i. The 'pretty' treatments on the disturbances were limited to the peat/seed mix quadrats.

ii. At Tundra Pit, one of the species-poor sites, the taller, green growth from the *Linum lewisii* and *Hedysarum mackenzei* was very attractive. Especially since many of the *L. lewisii* plants were flowering.

iii. At Building Pad, the peat moss/seed mix treated quadrats were already quite obvious and more visually appealing from the rest of the gravel pad because again, there was much more plant growth, taller individuals were present and some were flowering.

iv. The peat moss/seed mix treatments would have to be applied across the entire disturbances to make a significant improvement to site aesthetics and to help the disturbances blend in with the surrounding undisturbed landscape.

b) ease of application/labour and equipment needs

i. The peat moss was relatively expensive (~\$1.70m^{-2}) compared to the micro-relief and snow fencing treatments, but it was easy to obtain and apply, did not require any maintenance and resulted in good seedling growth.

ii. The species selected for seeding were the only ones available commercially in sufficient quantities and were not available from any Manitoba retailer. The seeds for the project cost about \$10m^{-2} and it is recommended future projects increase the seeding rate, making costs as high as \$20m^{-2}. Locally collected seed would not only be cheaper and provide work income to a few locals, but also likely increase germination success because the seeds would be the local variety.

iii. The snow fencing was fairly inexpensive. Several lines of fencing across the entire disturbance at any one of the sites would be about \$100-200. The main input to the fencing treatment is in maintenance. The fences need checked and repaired about once a month.

5. Determination of project success.
    a. By the list of quantified success measurements outlined in Chapter 1, none of these sites have been successfully reclaimed. This is as expected given the early stages of the project. However, there are some promising signs in that species diversity has increased and density on the successful treatment plots is higher than the surrounding untreated areas. Finally, although not on the initial list, the public is aware of the program taking place and has not re-disturbed these sites with extraction or ATV traffic. Awareness in the community of the reclamation projects at these sites has decreased subsequent disturbances at these sites. Since Firlotte (1998) found frequent re-disturbances of many gravel-dominated disturbances in the area, it is a positive measure that these sites have been left alone for over three years (summer 2002 to winter 2006).
    b. Evaluation of these sites should be done around 2008-2010 to determine if the treatments are continuing to be successful and if they are spreading to the untreated areas.

CONCLUDING REMARKS

Gravel extraction and depsoiton for infrastructure is a necessity of modern human life. Roads and other associated gravel sites are important to our economic and recreational needs and wants. However, with this comes the associated impact on the environment. Gravel disturbances will always be present in northern regions, but it is important that we:

- use proper planning to reduce the number of new sites being created,
- use proper management to minimize their negative effects,
- encourage policy creation to introduce and enforce legislation to reclaim abandoned sites and,
- have a prepared set of tested methods and techniques for gravel-dominated disturbance reclamation that are logistically and economically feasible.

TABLES

Table 5-1: Climate values for the project's two growing seasons, 2002 & 2003 (Environment Canada, 2005a,b). *Difference from normal was calculated using Environment Canada's (2005a,b) Climate Normals from 1971-2000.

Year	Mean Temp. (°C)	Difference from Normal* (°C)	Total Precip. (mm)	Difference from Normal* (mm)	Growing Degree Days (> 5°C)	Difference from Normal* (GDD>5°C)	First GDD	Last GDD
2002 (Annual)	-7.4	-0.5	536.3	104.7	608.7	14.0	June 2nd	Oct 10th
2003 (Annual)	-5.6	1.3	545.0	113.4	847.3	252.6	May 12th	Oct 11th
2002 (June-Sept.)	9.3	0.3	75.5	17.5	606.9	32.7		
2003 (June-Sept.)	11.0	2.0	75.4	17.4	792.9	218.7		

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Appendix A – Species List

Table A-1: Complete list of species found at disturbed and undisturbed study sites.

Species Name (with origin)	Former Name	Common Name	Family
Achillea millefolium var. *nigrescens* E. Mey.		common yarrow	Asteraceae
Andromeda polifolia L.		bog rosemary	Ericaceae
Androsace septentrionalis L.		pygmyflower rockjasmine	Primulaceae
Anemone multifida Poir.		cutleaf anemone	Ranunculaceae
Arabis arenicola (Richards. ex Hook.) Gelert		sand rockcress	Brassicaceae
Arctostaphylos alpina (L.) Spreng.		alpine bearberry	Ericaceae
Arctostaphylos rubra (Rehd. & Wilson) Fern.		red fruit bearberry	Ericaceae
Astragalus alpinus L.		alpine milkvetch	Fabaceae
Bartsia alpina L.		Velvetbells	Scrophulariaceae
Betula nana L.	*Betula glandulosa*	dwarf birch	Betulaceae
brassicaceae spp.		various mustards	Brassicaceae
Carex maritima Gunn.		curved sedge	Cyperaceae
Carex spp. L.		Sedge	Cyperaceae

Species Name (with origin)	Former Name	Common Name	Family
Castilleja raupii Pennell		Raup's indian paintbrush	Scrophulariaceae
Cerastium alpinum L.		alpine chickweed	Caryophyllaceae
Chamerion angustifolium (L.) Holub	*Epilobium angustifolium*	Fireweed	Onagraceae
Descurainia sophioides (Fisch. ex Hook.) O.E. Schulz		northern tansymustard	Brassicaceae
Draba breweri var. *cana* (Rydb.) Rollins	*Draba cana*	cushion draba	Brassicaceae
Draba sp. L.		whitlowgrass	Brassicaceae
Draba spp. L.		whitlowgrass	Brassicaceae
Dryas integrifolia Vahl		mountain aven	Rosaceae
Empetrum nigrum L.		black crowberry	Empetraceae
Epilobium palustre L.		marsh willowherb	Onagraceae
Equisetum sp. L.		horsetail	Equisetaceae
ericaceae sp.		unknown ericaceae	Ericaceae
Erigeron elatus (Hook.) Greene		swamp boreal-daisy	Asteraceae
Erysimum cheiranthoides L.		wormseed wallflower	Brassicaceae
Euphrasia subarctica Raup	*Euphrasia arctica*	arctic eyebright	Scrophulariaceae
Festuca sp. L.		Fescue	Poaceae

Species Name (with origin)	Former Name	Common Name	Family
Fungi spp.		Mushroom	Fungi
Gentianella propinqua ssp. *propinqua* (Richards.) J. Gillett	*Gentiana propinqua*	fourpart dwarf gentian	Gentianaceae
Hedysarum mackenzei Richards.	*Hedysarum mackenzii*	northern sweetvetch	Fabaceae
Hierochloe odorata (L.) Beauv.		sweetgrass	Poaceae
Juncus arcticus Willd.		arctic rush	Juncaceae
Juncus spp. L.		Rush	Juncaceae
Ledum palustre ssp. *decumbens* (Ait.) Hultén	*Rhododendron decumbens*	marsh Labrador tea	Ericaceae
Lesquerella arctica (Wormsk. ex Hornem.) S. Wats.		arctic bladderpod	Brassicaceae
Leymus arenarius (L.) Hochst.	*Elymus arenarius*	sand ryegrass	Poaceae
Linum lewisii Pursh		Lewis' flax, blue flax	Linaceae
Minuartia sp. L.		Sandwort	Caryophyllaceae
Minuartia spp. L.		Sandwort	Caryophyllaceae
Moneses uniflora (L.) Gray		single delight	Pyrolaceae
Oxytropis campestris (L.) DC.		northern yellow locoweed	Fabaceae
Amerorchis rotundifida (Banks ex Pursh) Hultén	*Orchis rotundifida*	roundleaf orchid	Orchidaceae
Packera paupercula (Michx.) A. & D. Löve	*Senecio pauperculus*	balsam groundsel	Asteraceae

Species Name (with origin)	Former Name	Common Name	Family
Parnassia palustris L.		grass-of-parnassus	Saxifragaceae
Pedicularis flammea L.		redrattle	Scrophulariaceae
Petasites sagittatus (Banks ex Pursh) Gray		arrowleaf sweet coltsfoot	Asteraceae
Picea glauca (Moench) Voss		white spruce	Pinaceae
Pinguicula vulgaris L.		common butterwort	Lentibulariaceae
Platanthera obtusata (Banks ex Pursh) Lindl.	*Habenaria obtusata*	northern small bog orchid	Orcidaceae
poaceae spp.		various grasses	Poaceae
Potentilla bimundorum Soják	*Potentilla multifida*	staghorn cinquefoil	Rosaceae
Potentilla spp. L.		Cinquefoil	Rosaceae
Pyrola grandiflora Radius		large flowered wintergreen	Pyrolaceae
Pyrola sp. L.		wintergreen	Pyrolaceae
Rhododendron lapponicum (L.) Wahlenb.		lapland rosebay	Ericaceae
Rubus chamaemorus L.		Cloudberry	Rosaceae
Sagina nodosa (L.) Fenzl		knotted pearlwort	Caryophyllaceae
Salix athabascensis Raup		Athabasca willow	Salicaceae
Salix calcicola Fern. & Wieg.	*Salix lanata ssp. calcicola*	woolly willow	Salicaceae

Species Name (with origin)	Former Name	Common Name	Family
Salix pedicellaris Pursh		bog willow	Salicaceae
Salix reticulata L.		net-leaf willow	Salicaceae
Salix spp. L.		willow	Salicaceae
Saxifraga caespitosa L.		tufted alpine saxifrage	Saxifragaceae
Saxifraga oppositifolia L.		purple mountain saxifrage	Saxifragaceae
Saxifraga tricuspidata Rottb.		three-toothed saxifrage	Saxifragaceae
Trichophorum caespitosum (L.) Hartman	*Scirpus caespitosus*	tufted bulrush	Cyperaceae
Shepherdia canadensis (L.) Nutt.		russet buffaloberry	Elaeagnaceae
Silene involucrata ssp. *involucrata* (Cham. & Schlecht.) Bocquet	*Melandrium affine*	arctic catchfly	Caryophyllaceae
Solidago multiradiata Ait.		mountain goldenrod	Asteraceae
Stellaria spp. L.		starwort	Caryophyllaceae
Taraxacum officinale ssp. *ceratophorum* (Ledeb.) Schinz ex Thellung	*Taraxacum lacerum*	common dandelion	Asteraceae
Tofieldia pusilla (Michx.) Pers.		scotch false asphodel	Liliaceae
Vaccinium uliginosum L.		bog blueberry	Ericaceae
Vaccinium vitis-idaea L.		lingonberry	Ericaceae

Nomenclature: Integrated Taxonomic Information System, 2006. ITIS on-line database: Smithsonian Institute and United States Government. Available at <http://www.itis.usda.gov>. Accessed 2006.