A culture is no better than its woods.

-Wystan Hugh Auden-

University of Alberta

Forest floor protection during drilling pad construction and its benefits for natural regeneration of native boreal forest vegetation

by

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Abstract

I tested forest floor protection techniques in the construction and reclamation of temporary drilling pads to restore native boreal canopy and understory cover. By covering and delineating the forest floor I hoped to reduce damage to the vegetative propagule bank, so clonal species such as aspen (*Populus tremuloides*) can quickly re-establish from root sprouts after being cut on disturbed sites. These were compared to the current soil salvage and replacement operations, assessing density, height and survival of aspen regeneration, as well as associated understory cover and richness. After re-contouring and soil placement, I measured the extent of surface disturbance, slash cover, soil temperature, soil bulk density and nutrient status in the four treatments and control plots. Aspen and understory recovery was prolific in protected sites and exceeded that of salvaged sites. Only little soil compaction from covering and moderate soil surface disturbance in forest floor protection sites were detected.

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Chapter 1. Introduction

1.1 Alberta's oil resource development and its implications

Alberta's total proven oil reserves in 2012 were 170.2 billion barrels and about 99 percent of them accounted for crude bitumen found in the oil sands (Energy Resources Conservation Board 2013). This made it the third-largest source of proven crude oil reserves in the world, next to Saudi Arabia and Venezuela (U.S Energy Information Administration 2013). The oil sands industry affects many Canadian jobs, both directly and indirectly.

Alberta's oil sands are mainly recoverable using in situ methods (Alberta Chamber of Resources 2011). In situ production techniques such steam assisted gravity drainage (SAGD) disturb less land per unit of production than surface mining, but its spatial footprint is more dispersed, which increases landscape fragmentation (Schneider and Dyer 2006). Using a life cycle analysis, Jordaan et al. (2009) showed that the land area influenced by in situ technology is comparable to land disturbed by surface mining, when fragmentation and upstream natural gas production are considered. Rapid expansion of oil sands exploration (OSE) and extraction activity have already resulted in increases of industrial disturbances dealt to boreal forests (Schneider et al. 2003).

This land use pattern for energy development in Alberta creates a societal dilemma, because the oil sands provide economic and social gains while at the same time altering ecosystem services that humans value and depend upon (Foley et al. 2005). As a result, oil sands development has been debated by a wide range of environmental organizations (e.g. Schneider and Dyer 2006, United Nations Environment Programme 2008).

In situ development involves the construction of numerous OSE drilling and wellsites and it creates many linear features that extend across the lease area such as seismic lines, access roads and pipelines. Each OSE drilling pad may be 0.5 to 1 ha in size, depending on the construction approach. This results in forest fragmentation, which affects the biodiversity value and other values society places on land (Jordaan et al. 2009).

If a forest is fragmented, species therein will be exposed to conditions of a different ecosystem (Saunders et al. 1991). Fragmentation can either increase or decrease local biodiversity, however some species can be negatively affected at a larger scale (Saunders et al. 1991, Wilcove 1987). Certain species will use anthropogenic edges to their advantage, such as carnivores like wolves, which may use linear features to facilitate travel and predation (Latham et al. 2011). Species that require niche habitats will most likely be adversely affected by habitat fragmentation (Fahrig 2003). In Alberta's boreal forest, Woodland caribou have been found to avoid anthropogenic edges such as wellsites at distances of up to 1 km and up to 250 m from roads and seismic lines, depending on the time of year (Dyer et al. 2001). Further, Nielsen et al. (2007) showed that the occurrence of 6 out of 14 species surveyed in Alberta's boreal forest was significantly related to road density.

The impact of fragmentation depends not only on the area and intensity, but also on the lifespan of the industrial features on the landscape (Jordaan et al. 2009). Many linear features become access points for recreation and hunting (Weber and Adamowicz 2002) and human access may therefore propagate edge effects over time (Jordaan et al. 2009). Therefore, the overall need to improve and speed up the reclamation process in this ecosystem calls for innovative and more ecologically sound approaches and techniques in both construction and restoration of drilling sites and associated disturbances.

1.2 Boreal forest ecology

Boreal forests are complex in the environmental factors required to understand their ecology and the interactions among these factors (Bonan and Shugart

1989). The different natural processes driving boreal forest development can provide important information for its restoration (Macdonald et al. 2012).

My study focusses on the boreal mixedwood forest, which exists as a patchwork of stands with varying compositions of coniferous and broadleaf trees, hosting the most diverse understory communities of the North American boreal forests (Hart and Chen 2006 & 2008). Within this mosaic, stands with mixed conifer-broadleaf canopies have the greatest diversity of understory plants (Hart and Chen 2006, Macdonald and Fenniak 2007) and other biotic groups such as birds (Hobson and Bayne 2000) and arthropods (Work et al. 2004, Buddle et al. 2006).

Mixed species stands may support higher plant diversity, because they provide more resource heterogeneity in the understory and allow for resource demanding vascular plants to coexist with more tolerant, yet less competitive species, such as ericaceous shrubs and bryophytes (Hart and Chen 2006). At their most diverse, boreal overstory communities may consist of six tree species, whereas up to 77 plant species can be present in the understory (La Roi 1967, Qian et al. 2003). Therefore, understory plant communities make up a larger proportion of the plant diversity in boreal forest ecosystems than the overstory species (Craig and Macdonald 2009). Understory plant community composition and diversity are strongly influenced by canopy composition and stand age (Hart and Chen 2006, Macdonald and Fenniak 2007). Accordingly, changes in canopy composition or structure will have an associated effect on understory vegetation communities. Vascular plant cover is highest under deciduous stands and decreases with higher conifer content (Légaré et al. 2002).

Although light is considered the most important environmental variable affecting understory vegetation (Légaré et al. 2002), soil type and slope position can influence soil fertility and therefore affect understory abundance, composition and diversity. With the removal of trees, higher light transmission to the forest floor increases soil temperature and mineralization rates (Hart and

Chen 2006). This shows the great interconnection between these factors, since soil fertility itself is in turn affected by overstory composition (Hart and Chen 2006).

Understory plants are also important in the prevention of erosion following disturbance (Oliver and Larson 1990). Chapin (1983) estimated that the annual turnover of biomass and nutrients in boreal understory vegetation is 34–43% compared to only 2–5% in trees. Therefore, Kolari et al. (2006) suggest that the contribution of the understory vegetation to momentary CO_2 exchange and C balance (Morén and Lindroth 2000 and Strömgren 2001) may also be large.

1.2.1 Forest restoration

There is a great need for scientific investigation to advance the understanding of boreal ecosystem restoration (Macdonald et al. 2012) as well as finding the practical analogy to translate this knowledge into goal directed management tools. The boreal forest is a disturbance-prone ecosystem, which is affected by disturbances of varying extents and intensities (Rydgren et al. 2004). The efforts to restore natural processes such as natural disturbances, succession and nutrient cycling seem limited, except for the use of fire, which has seen widespread adoption in some regions (Burton and Macdonald 2012). Many policy makers, environmentalists and forest managers have emphasized the need to develop practices that emulate wildfire at the landscape and stand level (Duchesne 1994), because much of the boreal forest plant life is adapted to wildfire and commonly regenerates directly from sprouting of rhizomes and roots following disturbance (Greene et al. 1999, Rydgren et al. 2004, Macdonald et al. 2012). In fact, most perennial herbaceous species in the boreal understory have vegetative regeneration organs (Rowe 1956) and are capable of recovering in post-disturbance communities because of their elaborate rooting systems (Whittle et al. 1997).

In general, almost any fire intensity can stimulate sprouting from vegetative propagules (Whittle et al. 1997). The recovery of vegetation depends on the propagule availability, which is predetermined by the species composition of the stand prior to disturbance (Pennanen et al. 2004, Johnstone and Chapin 2006). It is argued that very intense anthropogenic disturbances (like soil stripping) normally favours the establishment of plants from seed rather than vegetative parts (Rydgren et al. 2004), because they are likely to remove a high percentage of aboveground plant parts along with roots and rhizomes (Roberts 2004). Fire also drives changes in forest floor quality, including its carbon composition and ability to retain nutrients (Thiffault et al. 2006). Replacing wildfire by clearcut harvesting may influence the chemical properties of the forest floor and its capacity to cycle and supply nutrients, with possible implications for forest productivity (Thiffault et al. 2006). Depending on environmental conditions and the extent of disturbance, recovery of the forest floor following clear cutting can take anywhere from 5 to 80 years (Preston et al. 2000).

1.2.2 Forest floor & propagule viability

Prescott et al. (2000) state that "the vitality of an ecosystem is connected to the energy and nutrient status of the forest floor, which has the most biologically active portion of the soil and often the largest reservoir of nutrients." The forest floor may also promote water retention and can improve soil structure which buffers against nutrient deficiencies (Welke and Fyles 2005). The forest floor is a thin organic horizon which consists of fresh identifiable litter (L), fragmented and fermenting litter (F) and humus (H) (Soil Classification Working Group 1998) with small amounts of moss in upland forest (Paré et al. 1993). The forest floor thicknesses in natural, mature (80–140 years old) aspen stands from the boreal forest of Northwestern Alberta, typically ranges from 6.3 to 9.0 cm (Kishchuk 2004).

Apart from nutrient storage and habitat for microorganisms, the forest floor also provides a diverse source of propagules for vegetation recovery on reclaimed sites (Mackenzie and Naeth 2010), since it contains buried seeds and vegetative propagules (bud bank), which are the primary sources of revegetation in postdisturbance plant communities (Whittle et al. 1997). The comparably thin forest floor layer can contain about 73% of the total propagules (Mackenzie 2013). Harper (1977) defined the seed and bud banks as hidden populations of dormant seeds and meristems, respectively, which differ from established vegetation in species composition and abundance. While differences in species composition between the seed bank and present vegetation can be large (Leck et al. 1989), this contrast is normally less pronounced in the bud bank (Lee 2004).

Seeds are relatively mobile and may persist in the soil even after the parent plant dies (Leck et al. 1989), whereas the presence of vegetative propagules is almost always associated with the persistence of parent plants (Bond and Midgley 2001). Buds are usually numerous, kept dormant by correlative inhibition and are not dispersible. The bud bank resembles a long-term persistent seed bank, however bud longevity usually does not exceed that of the parent plant (Klimešová and Klimeš 2007). Though, one has to bear in mind that the life-span of bud-bearing organs is not necessarily bound to that of the whole plant.

Dormancy in the bud bank is regulated by correlative inhibition, which is represented mainly by apical dominance (Klimešová and Klimeš 2007). Through this mechanism, actively growing apical buds prevent growth of axillary and adventitious buds situated below the apical meristem. Thus, the buds remain available for vegetative regeneration until an injury disrupts the apical dominance (Schier 1981, Stafstrom 1995, Frey et al. 2003). After correlative inhibition is broken, adventitious buds on roots start to sprout similarly to axillary buds on rhizomes (Horvath et al. 2002), or are formed de novo (Bosela and Ewers 1997). This type of imposed dormancy has no analogy in seeds (Klimešová and Klimeš 2007).

Depletion of the bud bank can be caused by propagule mortality due to predation, pathogens, failed germination and sprouting, and deep burial

(Stafstrom 1995). When propagules germinate too deep underground they may not reach the surface before running out of nutrients or do so much later than competitors placed closer to the surface and therefore be disadvantaged in competition for light. To avoid bud bank depletion it seems beneficial to protect the forest floor during anthropogenic disturbance (like OSE activity) to obtain the best results in restoring boreal forest plant and tree species. This way, the fragmentation and burial of root propagules, as well as seed loss could be avoided, since the original soil structure stays intact. Understanding how the forest floor is affected by certain disturbances such as soil movement and storage might give us insights and new management tools for the reclamation of OSE drilling pads.

1.3 OSE legislation & drilling pad construction

Reclamation in the Alberta Oil Sands Region is regulated by the Environmental Protection and Enhancement Act (EPEA) of the Government of Alberta (GOA), which states that 'industrial operators are responsible for conservation and reclamation of the lands affected by their operations' (GOA 2009). According to Alberta's EPEA, 'the objective of conservation and reclamation of specified land is to return the specified land to an equivalent land capability' (ACR 2011). Equivalent land capability is defined in the Conservation and Reclamation Regulation as "the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical" (GOA 2010). Under current EPEA regulations, operators are required to create reclaimed soils and landforms that are "capable of supporting a self-sustaining, locally common boreal forest," and then to "revegetate the disturbed land to target the establishment of a self-sustaining, locally common boreal forest, integrated with the surrounding area. . .The expectation is that reclaimed sites should be like natural boreal landscapes in appearance and ecological function" (Cumulative Environmental Management Association 2006).

To understand the challenges in reclaiming industrial sites like OSE drilling pads and restoring them according to regulation one must familiarise themselves with the specific reclamation criteria and current OSE drill pad construction procedure. However, there seems to be no coherent legislation for construction and approval of OSE projects. The current regulatory framework for OSE approvals is not easy to track, as it has several acts, fact sheets, information letters, regulations and an Alberta Environment (AENV) code of practice. In contrast to conventional oil and gas exploration, no detailed legislative and regulatory scheme for approvals for OSE exists. Yet, it is exempted from the conventional exploration regulation (Vlavianos 2007). Requirements on how to construct an OSE drilling pad can only be found under the Soil Conservation Requirements of the Code of Practice for Exploration Operation (AENV 2005) and the Reclamation Criteria for Wellsites and Associated Facilities for Forested lands (AENV 2010).

For each OSE pad, of which more than 16 wells could be drilled in the areas of the lease (Osko and Glasgow 2010), a patch of forest big enough to accommodate a drilling rig, is cut. As the pad needs to be level for the drilling to occur, bulldozers and back hoes smooth the surface. Any terrain features higher than the desired level will be cut and pushed into lower spots. Therefore, the bulldozers will have to dig up and rip out tree stumps and roots that impede the process.

According to Section 5.1 of the Code of Practice for Exploration Operation which stipulates the Soil Conservation Requirements, all topsoil must be salvaged from the area where the drill pad or access road will be constructed, and redistributed once the pad is reclaimed (AENV 2005). Therefore, appropriate site preparation will salvage the forest floor material (FF) including the LFH and all appropriate mineral soil horizons such as Ah, Ahe and Ae (AENV 2010). 'It shall be salvaged and stockpiled separately from subsoil. A principle in salvage and redistribution of topsoil is not to dilute and/or bury the nutrient rich LFH and A horizons by over- or under-stripping (Alberta Sustainable Resource Development [ASRD 2007]). 'The intent would be not to mix the nutrient rich layers (LFH, Ah, Ahe) with the less nutrient rich Ae horizon. Two-lift stripping (LFH, Ah, and Ahe) and (Ae) is recommended as it helps to ensure all organic rich and texturally valuable topsoil is available for reclamation' (AENV 2010). Furthermore, topsoil should be only stockpiled on topsoil; and subsoil must be stockpiled on an area from which all topsoil has been salvaged (AENV 2005).

Although these regulations were surely crafted with the best intentions of protecting topsoil from industrial spillage and contamination, they create several problems: Due to the construction of very small 'minimal disturbance' pads little or no space is left on site to properly store topsoil. It is either stored on the edge of the drilling pad or even buried on site, which makes it harder find during reclamation.

Salvaging FF material can provide propagules of upland species that are not commercially available (Alberta Native Plant Council 2010, Mackenzie and Naeth 2010). Salvage is demanded on the entire drill pad, although the lower parts of a sloped site may not need to be cut or disturbed at all. It should be elective to salvage topsoil if it can be protected and not stripped, thereby protecting the bud bank for regeneration. Two-lift stripping can be detrimental to root systems of various boreal plant species, especially aspen, since their roots are usually found at depths between 4 cm and 15 cm (Wachowski et al. 2014) . Although AENV (2003) provides considerations for no-strip production wellsites, the potential contamination of topsoil around wellhead, pipeline risers and tanks during the production operations still leads AENV to advise using reduced disturbance versus no-strip techniques. However, reduced disturbance is actually just a descriptor, rather than a technique meaning that only partial topsoil stripping takes place. 'If leveled areas required for the rig and soil storage do not exceed 50% of the surveyed wellsite area, the development can be regarded as reduced disturbance' (AENV 2003).

Finally, factors such as slope and aspect can play an important role in the design of reconstructed landscapes after mining (Badia et al. 2007) and can affect energy input, microclimate, soil moisture and other processes, and are therefore significant drivers of vegetation establishment and growth in reclaimed mining landscapes, particularly in northern latitudes (Macdonald et al. 2012). Often times, operators will attempt to stabilise recontoured slopes (see AENV 2005, Code of Practice 5.1.9) by driving over it with the heavy machinery and compacting the topsoil. The idea to prevent erosion could prove counterproductive if slope stabilisation leads to soil compaction and in consequence decreases water infiltration (Arnup 1998), thereby increasing runoff and erosion. In fact, minor variations in topography on reclaimed areas can often enhance conditions that will moderate environmental extremes and promote forest vegetation species recruitment, survival and growth (ASRD 2007). Some reclamation criteria even seem to contradict each other: In ASRD (2007) it is said that large woody debris or rocks may enhance protection from excess wind or sun and/or to provide a vegetation-free space for plant development. 'Creation of a flat lease during reclamation can often retard vegetation development and is undesirable' (ASRD 2007), whereas in the 2005 AENV criteria it is less clear if or if not to leave debris such as rocks or wood on the lease (see AENV 2005, Code of Practice 5.2.2).

Understandably, fine chipped woody debris such as mulch can be detrimental to soil thermal conditions, the C:N ratio and plant recruitment (ASRD 2007). Yet, as it decomposes, woody debris can contribute to soil litter and organic matter content and provide habitat requirements for smaller species. For the revegetation of natural recovery sites, reclaimed after June, 2007, following criteria must be met: "A minimum of 25% canopy cover of herbaceous species; and a minimum of 25% canopy cover of woody species or a minimum stem/plant count of 5 stems per $10m^2$ circular assessment plot" (AENV 2010). Also, "preventing aggressive herbaceous colonizers that could inhibit or preclude the recruitment and/or development of the target forest community is desirable" (ASRD 2007).

1.3.1 Effect on propagules and plant regeneration

For each drilling pad, the loss of aboveground biomass resulting from tree harvesting is inevitable, since rig setup and leveling require the site to be cleared. The major problem of site leveling is the disturbance of belowground propagules through earthworks and traffic. These buds and seeds are however needed to re-establish native plant cover via natural regeneration. Plant species richness usually declines after FF salvage and re/spreading (Rollback) compared to the existing forest, likely due to losses of viable seeds after stripping and stockpiling (Fair 2012, Iverson and Wali 1982). In terms of seeding, Koch et al. (1996) found cumulative declines in viable seed density after stripping (26%), stockpiling (69%), and re-spreading (87%). Other studies have found reduced plant establishment with increased depth of propagule burial (Grant et al. 1996, Tacey and Glossop 1980). Salvage depth of FF influences the regeneration success, because dilution of the upper strata may decrease the density of propagule in the materials which are spread in reclamation (Tacey and Glossop 1980, Iverson and Wali 1982, Putwain and Gillham 1990, Rokich et al. 2000).

Furthermore, nutrient status, microbial biomass and soil fauna will be also affected by salvage depth (Mackenzie 2013). Soil microbe activity for example declines in disrupted soil layers and is slow to resume independently (Sheoran et al. 2010). The viability of mycorrhizas can decrease considerably when stored and may drop to 1/10 of those in undisturbed soil (Rives et al. 1980). Storage also affects other biological, topsoil chemical and physical properties in negative ways. FF stockpiles that are moist when stripped will potentially have conditions that promote decomposition, anaerobic conditions and in situ germination that can lead to propagule death (Rokich et al. 2000).

Loss of seed may also be attributed to attack by microorganisms and predation by vertebrates and invertebrates (Koch et al. 1996). Stockpiling and associated disturbance from earth moving equipment increase soil bulk density and reduce aggregate stability causing degradation in soil structure (Hunter and Curie 1956). Finally, placement depth of salvaged FF may affect propagule burial. Some studies have shown thick applications result in greater plant biomass and cover than shallow applications due to increased nutrients, organic matter, and available moisture (Bowen et al. 2005). However, if placement depth exceeds salvage depth, FF material itself will ultimately be depleted.

Machine traffic in both pad construction earthworks and recontouring and soil replacement can exert heavy ground pressure, causing soil compaction and damage roots and propagules in the forest floor, as documented for aspen (Renkema et al. 2009a). Depending on traffic intensity, direct root damage from compaction might also cause an immediate loss of root area. Soil compaction reduces air-filled porosity, which is hypothesized to restrict soil aeration, change soil morphology and water retention (Startsev and McNabb 2009). Compaction resulting from skidder traffic can impair the regeneration capability of aspen, since it does not grow well in poorly aerated soils (Landhäusser et al. 2003). Increases in soil resistance to penetration and reduction in air-filled pore space reduces root growth in most species, while reduced soil aeration in turn increases root mortality as oxygen for respiration is limited (Landhäusser et al. 2003).

1.4 Aspen as a key reclamation species

The knowledge of boreal forest regeneration ecology and of the regulatory framework for OSE operation provides the opportunity to understand what limits or enhances the restoration of mixedwood stands on OSE drilling pads. To establish a functioning forest ecosystem which provides services we desire, restoring native canopy species is crucial, because they drive long-term successional- and understory plant development (De Grandpré et al. 2003, Hart and Chen 2006, Roberts 2004). The forest canopy can also prolong the availability of regeneration microsites, thereby facilitating development of a more diverse and possibly more natural forest plant community over time (Macdonald et al. 2012). A rapid formation of a dense tree canopy will also encourage buildup of the litter and facilitate soil redevelopment (Klinka et al. 1990).

Furthermore, trees influence environmental variables such as temperature and especially light, which is considered the most important factor influencing understory vegetation (Lieffers 1995, Légaré et al. 2002). However, little is known about seedling production techniques for boreal tree species such as tamarack, aspen, and birch, nor are there reviews concerning assessment of quality in conifer seedlings. Establishment of boreal forest tree species through direct seeding on reclamation sites is rare and irregular (Macdonald et al. 2012) as key requirements such as microclimatic conditions and substrate available may not be ideal for seedling establishment due to nutritional imbalances or other limitations (Landhäusser et al. 2010, Pinno et al. 2012, Wolken et al. 2010). In this context, trembling aspen (*Populus tremuloides* Michx.) lends itself as a key reclamation species since it is an abundant and resilient pioneer species that can seed in disturbed or abandoned habitats, as well as resprout prolifically after clear cutting or wildfire (Frey et al. 2003). It is of considerable importance in providing habitat and browse for wildlife (Weber 1991) and can be commercially used for pulp and paper production, as well as oriented strand board (Peterson and Peterson 1992). It has high demands for light availability and if granted sufficient sun, it is fast growing and competitive. Aspen may have great potential as a reclamation species for mining sites in the boreal forest, but planting stock has shown poor field performance after outplanting (Landhäusser et al. 2012).

1.4.1 Vegetative reproduction and reclamation potential

Without aboveground disturbance, the roots of a healthy aspen tree rarely develop new sprouts (Wan et al. 2006). Though, when the stem portion of the aspen tree is killed, regeneration occurs through root sprouts (suckers) that are produced by adventitious buds on lateral roots (Maini and Horton 1966a, Steneker 1976, Frey et al. 2003). Suckering is triggered by a disruption of the apical dominance, which is a change in the hormonal balance induced by the loss of the above ground portion of a tree. More specifically, suckering is thought to be related to the ratio of auxins to cytokinins (Schier 1973). Auxins are produced in aboveground tissues like twigs and buds and are transported basipetally through the stem to inhibit the growth of lateral buds (Schier 1972). Notably the auxin named indole-3-acetic acid (IAA) is thought to be involved in this. Long-distance transport of IAA can occur in both mature phloem elements and through other living ray cells in stems (Lomax et al. 1995). Accordingly, the organ with the largest influence on root suckering appears to be the stem. After Farmer (1962b), Wan et al. (2006) proved exogenous application of IAA on excised stumps to inhibit root suckering, basal stem sprouting and the development of sucker buds.

In contrast, cytokinins are produced in growing root tips and are transported towards the stem (Frey et al. 2003). It has long been speculated that substances like cytokinins and inorganic nitrogenous compounds that accumulate in the stumps and roots after removal of the aboveground stem, help induce root suckering in aspen (Farmer 1962b). Navratil and Bella (1988) stated that citokinins degrade auxins and therewith decrease their inhibitory effect on suckering. Accordingly, high concentrations of cytokinins promote the development of stem buds and shoots (Schmülling 2002). Once the flow of auxins into the roots is interrupted the hormone ratio will change in favour of cytokinins (Navratil and Bella 1988). However, there is only limited empirical evidence to support this theory (Fraser et al. 2004). Wan et al. (2006)

demonstrated that cytokinin application improves the rate of aspen sucker initiation, while (Schier 1981) reported no effect. Also, the direct role of auxin in the apical dominance of plants is largely refuted in the wider plant physiology literature (e.g. Wareing and Philips 1979).

Sucker regeneration can turn out to be very vigorous, if the roots are healthy and undamaged by traffic (Frey et al. 2003). The parental root system initially provides the essentials for the sucker growth. Until suckers have developed their own root systems, they depend on that parental root system for moisture and nutrients. Therefore the loss of parts of the root system is likely to have negative effects on the growth and performance of new sprouts in *P. tremuloides* (Landhäusser and Lieffers 2002). However, cutting the entire aboveground portion of a clonal tree or isolating it by abscission can also leave the large root system without the support of leaf area. If the root system is still alive then, it will also continue to consume resources for its survival. Landhäusser and Lieffers (2002) showed that the respiratory demands of the large root systems appear to have higher priority for allocation of carbohydrates over sucker height growth. A portion of the root system of aspen is unique among forest tree species as it is usually much older than the sucker-origin stems that they support and stems are interconnected to a common parent root system (Strong and La Roi 1983a, Peterson and Peterson 1992). Therefore, aspen clones are able to accumulate great amounts of root biomass (Strong & LaRoi 1983a). The lateral roots of aspen may extend for more than 30 m into adjacent open areas and Aspen suckers have been observed up to 21 m from the nearest bole (Barnes 1966). Roots typically concentrate in a zone between 5 and 20 cm below ground surface (Strong and La Roi 1983a). It is for this reason that the upper 20-25 cm of the soil surface is of such importance to boreal mixedwood silvicultural treatments (Peterson and Peterson 1992).

Historically, trembling aspen is dependent upon stand-replacing fire disturbances for successful and prolific regeneration (DeByle et al. 1987). This is due to favourable site conditions for aspen suckering following burning. The forest floor thickness is typically reduced, which tends to increase the depth at which aspen roots will produce suckers (Brown and DeByle 1987).

Distribution of roots capable of suckering is also important. Rooting depth is thought to reflect a decline in sucker initiation controlled by soil temperature (Frey at al. 2003). There is great variation in literature, since various papers suggest that most suckers occur in shallow depth near the surface (Farmer 1962a, Navratil and Bella 1988) whereas others suggest the majority of suckering is in a depth between 8-15cm (e.g. Peterson and Peterson 1992, Navratil 1996). Of course, roots may appear in much greater depth, especially in coarse-textured soils, but they would be highly questionable to produce many emerging suckers. Lieffers and Van Rees (2002) argue that aspen suckers mainly occur from parental roots located in the LFH layer. The mean depth to sucker initiation from the parent root would then range between 2.1cm and 4.6cm. Considering a total LFH depth of around 10cm, the great majority of suckering would happen very near the soil surface. According to Lieffers & Van Rees (2002) only 7% of suckers originate from below the LFH layer. It seems to be rather important how deep the LFH layer actually is and probably affects rooting and sucker depth. The longer distance suckers have to penetrate through the soil, the more likely it is for them to deplete their nutrient reserves and get a late start in competing for growing space and light. Also, root depth is likely to implicate how susceptible roots are to mechanical damage. Since the LFH layer constitutes the border between soil and air phase, it is highly influenced by climatic conditions and temperature. Therefore aspen suckering can be linked back to soil temperature. A theory that explains the different influence of rooting depth is presented in Frey et al. (2003). They hypothesize that suckering can be equally frequent on roots at deeper depths, but are less likely to become established because growth may be slower as a result of cooler temperatures or insufficient carbohydrates for emergence above the soil surface. The development may even be halted because of reestablishment of apical dominance by suckers from more shallow roots.

1.4.2 Effects of root wounding

Disturbance or injury inflicted to the clonal root system of aspen has been indicated as a mechanism that may influence the rate and vigor of suckering following disturbance (Maini and Horton 1966b, Fraser et al. 2003). The suckering response to injury is somewhat unclear in literature, as some studies have suggested that root injury can increase suckering (Farmer 1962, Maini and Horton 1966b, Fraser et al. 2004), while others have come to the opposite conclusion (Zahner and DeByle 1965, Fraser et al. 2006). Some literature suggests that wounding affects the hormonal balance of the root system, which can lead to an increase in suckering density and growth (Farmer 1962, Fraser et al. 2004), because damaged tissue produces more growth hormones or the transport of growth inhibitors is interrupted. Therefore, suckering could even be stimulated by light scarification from harvesting (Navratil and Bella 1988) or mechanical site preparation (MSP) (Shepperd 2001, Fraser et al. 2003). It is also possible that root fragmentation due to site construction or other preparation measures leads to the complete disconnection of clonal root mass from remained ramets or stumps, which ultimately stops auxin transport and decreases apical dominance. Fraser et al. (2004) used 1-m sections of trembling aspen and subjected them to scraping and severing. Results indicate that injured roots produced more suckers per root, and these suckers were taller and had a greater leaf area index. Further, only 31% of control roots produced suckers, compared with 48% of scraped roots and 57% of severed roots. Suckers near wounds were also taller and had more leaves with greater leaf areas than suckers on unwounded roots (Fraser et al. 2004). These results suggest there was greater mobilization of reserves following root wounding, which confirms the observational findings by Farmer (1962), Fraser et al. (2003) and the review by Frey et al. (2003).

Yet, Fraser et al. (2004) also observed little difference in the suckering response between the distal and proximal sides of roots for any of the measured variables. The movement of both hormones should have been disrupted by wounding, particularly by severing. It has long been suspected that cytokinins may accumulate at a wound site following mechanical injury and more suckers would be generated on the distal side (Farmer 1962, Maini and Horton 1966a). However, it is unlikely that normal transport processes would continue following disturbance, even though cytokinins can be transported in both phloem and xylem tissues. If the auxin to cytokinin ratio was driving the suckering response, Fraser et al. (2004) should have observed significantly reduced suckering on the proximal sides of the sever injury, as no cytokinins would have been able to bypass the injury site. Since this was not the case, their study does not support the hypothesis that the auxin to cytokinin ratio controls suckering around root injuries.

Studies by Renkema et al. (2009a,b) conclude that wounding from heavy machine traffic can amount to 40% to 50% mortality in living roots, while adding slash to simulate log deck conditions would drastically increase mortality (>90%). This in turn would lead to a decline in root total non-structural carbohydrate, total dry mass and sucker numbers according to the root area lost. Further, the study reveals that initiated suckers are much greater in number when wounding the root system, which does not necessarily mean they are able to emerge above ground, e.g. due to the lack of total non-structural carbohydrate reserves. However, the drawback of shallow rooting is also exemplified by the vulnerability of fine roots to logging damage. Ultimately, root wounding may initiate the formation of more sucker buds, presumably due to hormonal changes, but also damages and kills portions of the root system and thereby reduces sucker growth (Renkema et al. 2009a). Therefore, the number of initiated suckers is related to loss of root area rather than decline in root carbohydrates per se. When wounding occurs more initiated suckers must share fewer resources from a smaller root area, which is very likely to result in reduced emergence. In conclusion, there is no concrete quantification of how much wounding or cutting of roots is increasing suckering in the literature.

However, scuffing, crushing, or fragmenting of large and fine roots can also reduce the ability of the clone to supply water and nutrient to suckers (Navratil 1996) and any wounding also introduces a higher risk of infection for any plant and plant organ. Especially fungi are known to be able to kill trees after infection. Frey et al. (2003) states that even where suckering is stimulated there may be negative consequences of site preparation for growth and wood quality. Therefore, the mechanisms controlling increased suckering associated with site preparation are not completely clear (Frey et al. 2003).

A number of studies have assessed the effects of MSP on first-year aspen suckering and the results indicate significant increases in sucker densities relative to untreated areas (Maini and Horton 1966b; Fraser et al. 2003; Frey et al. 2003). Long term impacts of such treatments show different results, though. The impacts of heavy site preparation on the fragmentation of roots leads to the assumption that roots get isolated from the rest of the clone, so short root fragments are likely to have diminished sucker growth and survival (Zahner and DeByle 1965). After 9-12 years, aspen stem density and height are generally lower in MSP-treated areas relative to untreated areas (Fraser et al. 2006). It appears that the density increases observed in previously mentioned studies immediately following MSP are not maintained a decade later. However, it does not appear to seriously harm the aspen either.

1.4.3 Effects of soil surface and temperature conditions

The emergence of aspen suckers is strongly influenced by the depth of burial and soil temperature. Increased sucker production has been attributed to soil temperature increases accompanying soil disturbance (Maini and Horton 1966b). High temperatures promote an increase in cytokinin production by root meristematic tissues, which in turn enhances auxin degradation. Accordingly, the auxin ratio drops and suckering increases. Therefore, soil surface conditions can significantly affect soil temperature and soil temperature fluxes (Lieffers and Van Rees 2002). Evidence for variation in this behavior was provided by Fraser et al. (2002) and Landhäusser et al. (2006) who found that roots and root segments produced nearly the same numbers of suckers between soil temperatures of 12°C and 20°C. Though, at lower temperature sucker initiation was delayed by 12 days compared with the warmer regime. Thus, cold soils might result in poor regeneration from suckers not because buds are not initiated but because these buds fail to develop into suckers of a significant size (Landhäusser et al. 2006). Under field conditions, it is likely that soil temperature and nutrient availability work together to encourage aspen suckering. Winter season soil temperatures generally have little effect on aspen growth unless they reach extremely low temperatures harmful to the root tissue (Lieffers and Van Rees 2002), which however could be applicable to stockpiled soil.

Low soil temperature can be a result of an insulating layer such as thick LFH or slash and other woody debris that block radiation from penetrating. Although slash might reduce compaction during machine traffic, it can also negatively affect aspen suckering (Steneker 1976, Bella 1986). Especially if branches are cut on site to prepare for transport, harvest operations may leave excessive amounts of slash. Indeed, Lieffers and Van Rees (2002) correlated slash loading to decreasing soil temperature and number of suckers produced, as well as smaller leaf area index. Studies by Renkema et al. (2009a,b) examined aspen roots impacted by slash showed drastically increased sucker mortality. Lieffers and Van Rees (2002) found that daily mean soil temperatures during the growing season were significantly lower under higher levels of slash. As a result, this would shorten the length of the growing season itself. For heavy slash loading Lieffers and Van Rees (2002) found mean daily temperatures in April still below 0°C, whereas on unloaded surfaces all frost would already be gone. Aspen is also highly sensitive to cold soil conditions, slowing the development of new roots, as well as reducing root activity and water flow (Lieffers and Zwiazek 2000). Accordingly, root water flow is declining with decreasing soil temperatures, since it is strongly dependant on how many new roots were developed (Lieffers and Zwiazek 2000). Hence by mediating early growth, temperature can affect the competitive ability of emerging suckers and thus potentially affect sucker survival, which also suggests an indirect role of temperature on suckering (Fraser et al. 2002).

Over the long term, Bella (1986) found slash retention to reduce initial sucker density in harvested stands, but by year five the effect of slash retention was less evident. As noted by Frey et al. (2003) slash removal might result in higher initial densities of suckers in some cases, although the longer-term consequences of slash removal on the nutrition of regenerating aspen stands are not known. A practice commonly used on industrial sites is satellite chipping (Corns and Maynard 1997), which is supposed to increase the amount of usable fibre from a site and returns organic matter (chipped branches and bark) to the site by the spreading of chip residue not suitable for pulp. It is also used on in-situ oil extraction sites for insulation purposes. Corns and Maynard (1997) tested sucker density after such application and found any application with more than 10 cm residue resulted in aspen densities of less than 50% of untreated control values, further declining (50%) by year two (Corns and Maynard 1997). Therefore, differences in how soil surface and substrate are handled, disturbed and reclaimed can be a determining factor for aspen regeneration.

1.4.4 Grass competition

A common observation of young aspen stands from sucker origin is that even after good initial growth in the first years, seedling growth can slow down significantly on grass-dominated sites (Landhäusser and Lieffers 1998). The presence of *C. canadensis* significantly reduces total biomass, plant height, and root collar calliper of aspen (Landhäusser and Lieffers 1998). In the phase immediately after suckering, competition for light and rooting space may inhibit aspen growth, too. The suppressive effect of *C. canadensis* on aspen seedlings is likely due to the accumulation of thick grass litter which can keep soil temperatures relative low throughout the growing season (Hogg and Lieffers 1991). Heavy thatch could also be responsible for an allelopathic suppression of aspen because of the presence of phenolic compounds, which have been found in other graminaceous species (Guenzi and McCalla 1966). Landhäusser and Lieffers (1998) also found a significant interaction between *C. canadensis* litter and nutrient regime, inducing inhibitory effects on aspen seedling growth. Landhäusser et al. (2007) separated the effects of sod and litter in *C. canadensis* and found that the sod did not affect the initiation of suckers, but resulted in 30% fewer suckers emerging above the soil that were smaller and had 40% less leaf area. *C. canadensis* also delayed emergence by 10 days (Landhäusser et al. 2007). Both grass sods and aboveground litter likely act as physical barriers to the emergence of root suckers. When suckers were forcing their way through the litter, they were chlorotic and the delay in photosynthesis probably prolonged their dependence on root reserves for growth. In some circumstances it may even be possible to have a stable grass community that resists the establishment of trees (McMurtrie and Wolf 1983).

1.5 Objectives

The overall objective of this study was to determine ways to improve OSE drilling pad reclamation with native boreal plant species that regenerate naturally after reclamation. Recognising the negative impacts of the currently used FF stripping and rollback, I wished to develop an ecologically sound approach to reclaiming disturbed OSE sites. Using the regeneration potential of the surface soil bud bank, which includes most of the aspen root propagules, I proposed to protect the original forest floor during OSE drill pad construction and operation. Emphasis was put on aspen as a foundation species in boreal forest restoration, since it is well known for its resilience to above-ground disturbances.

In chapter 2 I investigate the benefits of forest floor protection on vegetative aspen (*P. tremuloides*) regeneration, as a fast means to recover upland OSE drilling pads. I compared aspen regeneration following the standard technique of stripping off the FF surface soil and replacing it on the site (Rollback) during the reclamation phase with a technique that minimises disturbance to the forest floor layer during the drilling operation. Here, subsoil from stripped sites was used on top of the forest floor to level the drilling pad, protect the original forest floor and test three different ways of delineating the subsoil, so that it could be effectively removed by backhoes during the recontouring of the pad in reclamation.

In chapter 3, the effect of the above treatments on understory plant recovery is presented. Conditions affecting establishment, cover and diversity were studied to explore the impact of forest floor disturbance compared to the protected and controlled treatments. Also, the vegetation response in different functional groups was assessed.

In chapter 4, I evaluate the overall study success, its application and propose possible amendments and future investigations.

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Chapter 2. Forest floor protection during drilling pad construction and its potential to promote resprouting of aspen

2.1 Introduction

The increasing amount of Oil Sands Exploration (OSE) drilling in the Athabasca basin of Alberta results in significant forest fragmentation from the numerous temporary drilling pads used for OSE and their access. Drilling usually requires flat areas roughly 1 ha in size on which the rig equipment can be established. In most cases these drilling pads may only be needed for less than a month and then can be reclaimed. Currently, upper soil layers including the forest floor (FF) material of the entire site are pushed to the side of the pad prior to leveling the drilling pad, as regulations demand the salvage of all LFH and A horizon soil or even B horizon up to 15 cm if considered suitable. This material can then be redistributed back onto the surface of a re-contoured drilling pad after its use (Rollback). Such FF salvage, however, is still an aggressive mitigation measure that may not be necessary on the entire drilling pad.

Plant species richness usually declines after FF salvage and Rollback compared to the existing forest, likely due to losses of viable seeds after stripping and stockpiling (Fair 2012, Iverson and Wali 1982). Others argue that intense disturbance like soil stripping normally favours the establishment of plants from seed rather than vegetative parts (Granström 1986, Rydgren et al. 2004). Koch et al. (1996) found large cumulative declines in seed density after stripping (26%), stockpiling (69%), and re-spreading (87%). Most boreal forest plants regenerate directly from sprouting of rhizomes and roots following disturbances such as logging and fire (Greene et al. 1999, Rydgren et al. 2004, Macdonald et al. 2011), in particular aspen (*Populus tremuloides* Michx.) which is well known for its vigorous root suckering after disturbance (Maini and Horton 1966a, Kemperman 1978, Frey et al. 2003). This resprouting potential provides aspen forests with a high resiliency to disturbance, if the root system stays mostly intact during the disturbance (Frey et al. 2003). To take advantage of this regenerative potential in the reclamation of drilling pads, ways need to be found to operationally protect this layer during the construction and loading of the drill pad.

Severe disturbance of the aspen root system can cause a reduction in suckering due to wounding and extensive fragmentation of roots which limits the ability and vigour of resprouting (Zahner and DeByle 1965, Renkema et al. 2009). It can also allow for pathogens to enter and attack the root system (Jacobi and Shepperd 1991, Peterson and Peterson 1992, Pankuch et al. 2003). Salvage of FF along with a thick layer of about 15cm of the upper mineral soil may also reduce the regeneration success, because the seeds and propagules of the FF are diluted in the material spread (Tacey and Glossop 1980, Iverson and Wali 1982, Putwain and Gillham 1990, Rokich et al. 2000). Furthermore, stockpiling and long term storage (> 10 month) of FF material decreases propagule viability by in situ germination and degradation under anaerobic conditions (Iverson and Wali 1982, Rokich et al. 2000, Mackenzie and Naeth 2010).

In the building of a level drilling pad, particularly on sloping ground, one part of the disturbed area is cut while the other part is filled. On the cut portions (upper slope) of the pad the removal and then the eventual replacement of the upper soil layers and propagule bank are likely the only strategy for the recovery of such heavily-disturbed sites. On the fill side (lower slope) of the disturbed areas, however, it is likely unnecessary to disturb the seed and propagule bank of the original forest floor. An alternative to stripping off the FF and rollback is simply not to disturb the original forest floor on the lower half of the pad by covering the lower portion of the slope with the cut material during the leveling of the pad (as has been suggested by Osko and Glasgow 2010). Once the drilling is complete the lower slope will be uncovered and the materials pushed back onto the upper slope, thereby re-contouring the hill. The operators of large machines must be able to remove the cut material without causing damage to the protected forest floor underneath. Therefore, the delineation of the protected forest floor from the fill material is important; however the gain of using special measures to delineate the forest floor vs. simply covering and carefully removing fill material is unknown. Machine traffic which is exerting heavy ground pressure can cause soil compaction and damage roots and propagules in the forest floor (Renkema et al. 2009). Depending on traffic intensity, direct root damage from compaction might also cause an immediate loss of root area.

This study focused on the re-establishment of aspen after the winter-time construction of temporary drill pads in the boreal mixedwood forest, using different reclamation techniques. The stripping and subsequent rollback of FF on the upper half of the drill pad was compared to three different strategies for forest floor protection on the lower side of the drill pad. Finally these four different strategies for construction and recovery of the drilling site were compared to aspen regeneration following operational clear-cut logging on the site. To complement the data set, underlying factors for aspen regeneration such as soil temperature, soil disturbance, retention of woody debris and compaction were also measured in each treatment.

2.2 Methods

2.2.1 Study site

The study site is situated in North Eastern Alberta in the Central Mixedwood Subregion of the Boreal Forest Natural Region of Alberta (Natural Regions Committee 2006). The climate in this subregion is cool and moist with cold winters and short wet summers. Monthly mean temperature on site varies from -17°C in January to +17°C in July, while daily extremes can vary from -48°C in January to +36°C in June (Devon 2012). Mean annual precipitation is 475mm with 71% occurring as rain and 29% as snow (Devon 2012). The study site has a rolling terrain with low relief. As patchy forest fires are common in this subregion, stands are usually even-aged, thus creating a mosaic of patches of different size, ages and composition (Greene et al. 1999).

The research site was a 40 ha cutblock, previously harvested by Alberta-Pacific Forest Industries Inc. The block also belongs to the Devon pike lease and is located South-east of Conklin, Alberta (55°24’N, 110°44’W). It can be accessed from Highway 881 East towards Kirby airstrip at kilometer 40. The site lies in the Sandy river catchment area, where soils are silty sandy luvisols. The terrain type is a Glaciofluvial Veneer over Morainal till. The local terrain of the study site is slightly sloped, facing South-South East.

According to the Pike project Environmental Impact Assessment, the soils on site are low in organic matter and susceptible to wind and water erosion. It was also categorized as class 4 by Land Capability Classification, which is defined as conditionally productive and limited by low buffering capacity. It was also attested poor reclamation suitability because of associated low pH level and low moisture holding capacity (Devon 2012).

The experimental site was a modal ecosite (lowbush cranberry, aspen - d1) of the boreal mixedwood natural subregion (Beckingham and Archibald 1996). Prior to harvest the stand was dominated by 80 year old trembling aspen with some interspersed white spruce (*Picea glauca* (Moench) Voss) both in the overstory and understory. The trees in the mature aspen stand were on average 20 m tall and had a diameter at breast height (DBH) of 20 cm.

The stand was harvested in late November of 2011 during non-frozen soil conditions using tracked feller buncher and wide tire grapple skidders. All areas selected for the drilling pad experiment had no residual living aspen trees that could decrease suckering response (Lennie et al. 2009). The drill pad experiment was started in late January 2012. It was set up with five treatments in six blocks; in each block the ‘drilling pad’ was 40 x 60 m and corresponds to approximately half the area used for a conventional drilling pad. The experimental blocks were selected from areas that were dominated by aspen and situated on a slightly sloped site to allow for the usual cut and fill sides of the pad necessary for accommodating the questions of this experiment.

2.2.2 Treatments

Each pad was divided into four treatment plots. On the upper half of the pad, a 20 x 60 m plot was laid out for the FF salvage and Rollback treatment (Figure 2-1). The lower half of the pad was divided into three 20 x 20 m plots each assigned to a different forest floor protection treatment (Figure 2-1). In these plots the original forest floor was not stripped off and different treatments were used to protect and delineate it during the leveling (filling) of this side of the pad. A fifth plot (20 x 20 m) was selected adjacent to each pad to serve as an untreated harvested Control, thereby completing the block.

For the Freezing treatment, water was applied with a water truck holding about 14 m^3 of water. The original 33 cm of snow were first track-packed so a more compact layer of snow-ice mix would eventually form. Water was then hand sprayed on the treatment plot. In total, each Freezing plot received four full truckloads of water, the equivalent of 56 m^3 of water, resulting in a 12-17 cm layer of compacted and hard frozen snow-ice mix, which was verified by drilling and measuring the depth to the soft forest floor layer. In the Geotextile treatment a tough woven plastic mat was rolled out on the 20 x 20 m plot. The No Barrier (NB) treatment did not receive any special treatment to protect the forest floor except for 33 cm of snow; this snow was eventually compacted to 10-13 cm by the subsoil application (see below).

In the upslope half of the pad (20 x 60 m) about 20 cm of surface soil material was stripped off with a $D6R_{xw}$ caterpillar bulldozer and stockpiled on the upper edge of the pad (Fig. 2-2A). An attempt was made to remove these soil horizons in one lift, so that horizontal roots were not laterally sheared during the stripping. During the leveling process of the entire pad, the remaining B and C horizons of the upper half of the pad were then used to cover the three forest floor protection plots on the lower half of the pad (Figure 2-2B). The bulldozer pushed the subsoil from the upper slope down onto the forest floor protection plots of the lower slope. The cat padded its way into the protected plots over the spreading subsoil. Once leveled with subsoil, the forest floor protection plots were uniformly trafficked with a fully loaded 30 ton rock truck to imitate the use of heavy vehicles on the pad during rig operation.

To assess capping thickness and compaction I staked out three transects perpendicular to the slope in each plot; each had four sample points 4 m apart. The thickness of subsoil application on each sample point was determined by subtracting pre and post construction elevation. Elevation was assessed with a total station (Leica Flexline Ts09, St. Gallen, Switzerland). It was set up in a safe, marked location, offsite the actual experiment plots and referenced to permanent corner points. Station height was subtracted from reflector height and the offset entered in the machine. The standard reflector height was 2 m. All sample points were re-established after re-contouring by referencing the total station to the corner points, so all measurements were taken at the exact same spots. On average, subsoil was filled to a depth of 74 cm up to 125 cm (1^{st} to 4^{th} sample point, respectively) and was compacted by about 8 cm during the truck traffic on the pad.

After lying idle for about three weeks, the level pads were deconstructed to uncover the original forest floor beneath the subsoil and the entire upper slope was re-contoured. Accordingly, a back hoe (Komatsu PC200) fitted with a toothless, finishing-bucket peeled off the subsoil (and Geotextile) until it uncovered the original forest floor; the subsoil was then moved and dumped upslope. The bulldozer spread the subsoil on the upper side of the pad and re-contoured the slope. Finally, the salvaged FF material was rough dumped back onto the re-contoured upper slope; care was taken to minimize machine traffic on the FF during the spreading.

2.2.3 Measurements

In spring after deconstructing the pads, the positions of the three transects, with their four sample points were re-established on each of the five plots, of each block, before regrowth. A 1 x 1 m quadrat was centred over each sample point and in each I estimated percentage cover of slash and subsoil residue, and used categorical evaluation (yes/no) for wheel rutting, breaking through the LFH to the mineral soil (gouging) and root exposure.

Woody logging debris, further referred to as slash, was assessed digitally in its cover. Photographs were taken straight downward (90° angle against the slope), at each of the 360 subplots using a standard height and with a 12 Megapixel camera (Pentax Optio W90 Mississauga, Ontario); picture dimension 4000 x 3000 pixels and 72 dpi resolution. As a prerequisite for digital analysis, the images were given square shape and the content outside of the 1 x 1 m square was eliminated using GNU Image Manipulation Program (GIMP). An Image Analyser (GSA v3.9.5, Rostock, Germany) was used to distinguish between colours coded as desired objectives (slash) and their percentage cover was calculated.

HOBO data loggers (Onset Computer Corporation, Bourne, Mass.) were programmed to record soil temperature in 1 hour intervals and then sealed in heavy duty ziplock bags, together with an activated desiccation pack. After taking out a spade depth of intact soil, a horizontal pocket was dug into the side of the hole and the logger was inserted at a depth of 10 cm and soil was repacked. In total, 30 units were installed, one per treatment at each block. After digging up the HOBO units in mid-September 2012, temperature data in degrees Celsius (°C) were downloaded using BoxCar Pro 4.3 software.

Soil bulk density of the mineral soil was assessed at 10 cm depth, in the second subplot (at 8 m), in each transect of the main treatments (Rollback, No Barrier and Control). Additionally, the bulk density was assessed in all remaining subplots within the No Barrier plots; these data were correlated with subsoil depth loaded onto the lower half of the pad. I used the core method (308 cm^3 stainless steel rings) to determine bulk density (Blake and Hartage 1986). Soil samples were bagged, weighed wet in the laboratory and then oven dried at 107°C for three days. After recording the dry weight, roots and rocks greater than 4.76 mm (mesh No.4) were removed by sieving, weighed separately and each component was subtracted from the total volume of soil by means of density calculations. The remaining dried soil was weighed again and bulk densities were calculated as g/cm^3. From the weight loss between wet and dry samples, volumetric soil moisture content was calculated.

Measurements of mean sucker density, mean and maximum height were also taken at the same 12 sample points, at the end of the first growing season. The number of aspen and balsam poplar (*Populus balsamifera* L.) suckers were counted in circular 10 m^2 (1.78 m radius) regeneration plots, centred over each sample point. The 10 m^2 plots were used for assessment of density and stocking. A tally of stem density was also made in 1 m^2 subplots, used for correlations with edaphic data. Height was measured for each sucker in the 1 m^2 subplots, whereas the tallest sucker was chosen and measured within each 10 m^2 plot. Since balsam poplar constituted less than 1% of the suckers found, they were added to data on aspen suckers and not separately analysed. In August of the second growing season, all measurements of aspen regeneration were repeated for the Rollback, Control and No Barrier treatment.

Basal area and number of aspen stumps were recorded to evaluate their influence on sucker density. For basal area, all stumps of former aspen trees were measured in each applicable treatment (not in Rollback), recording 2 perpendicular diameter measurements.

2.2.4 Data analysis

To test treatment effects on sucker density and height, all sub- or regeneration plots (1 m^2 or 10 m^2) within one treatment plot were averaged (n = 6) before running ANOVAS in Statistical Analysis System (SAS 9.2, Cary, North Carolina).

First and second year data on sucker regeneration were compared using repeated measures ANOVA to determine the change over time, as well as differences among treatments. Sucker density and maximum height did not meet the assumptions of normality (using Shapiro-Wilk test) or homogeneity of variance (using Levene's test). After log transformation homogeneity of variance criteria were met. Density data were analysed using Mixed Models in SAS to allow for the appropriate partitioning of variance (and resulting increase in model power). Maximum height data were successfully log-transformed and analysed as simple ANOVA via GLM, just as mean sucker height. Contrasts were used to carry out comparisons among the Rollback, NB and Control, as well as among the three forest floor protection treatments. Stocking was determined as the percentage of regeneration plots (10 m^2) within each treatment unit that contained at least one sucker.

Mortality was calculated as the percentage of suckers which died within the one year period after the first density assessment. Growth was assessed as the difference between 2012 and 2013 sucker height measurements, pertaining to both mean and maximum height.

The effect of the slope position and subsoil fill depth on sucker density or height was only assessed on protected forest floor and analysed with one-way ANOVAs. Comparisons of all edaphic and disturbance factors among treatments were also analysed by one-way ANOVAs. Aspen regeneration response to edaphic factors and soil disturbances were assessed with simple linear regression analysis, based upon mean values per treatment plot (n = 30). Categorical data such as wheel rutting and LFH gouging were also averaged to obtain the percentage of plots with disturbance present. For regression analysis of LFH gouging, subsoil residues, fill thickness and bulk density, I excluded the Rollback treatment, because the effects of these variables were not applicable in the mixed up Rollback soil (n = 24).

The influence of basal area and number of aspen stumps per ha on suckering density was assessed by regression analysis. For statistical analysis only data from the Control treatment were used to prevent confounding results by treatment effects (see Appendix).

Mineral soil moisture content at 10 cm depth was analysed with mixed model ANOVA. Minimum and maximum values did not conform to the assumptions of homogeneous variance and were log transformed (see Appendix). Mean, minimum and maximum soil temperatures were calculated for the period from early June until leaf off in October. Minimum temperature did not conform to the assumptions of homogeneous variance and couldn't be normalised; it was therefore analysed with non-parametric procedure (Kruskal-Wallis k-sample-and Multtest). A significance level of $\alpha = 0.05$ was used for all analyses.

2.3 Results

2.3.1 Comparison of Rollback, No Barrier and Control

Aspen sucker density was 8,736 stems/ha in the Rollback treatment at the end of the first growing season; this was much lower than 59,347 stems/ha in the Control plots ($p < 0.001$) and 89,722 stems/ha in the No Barrier (NB) treatment ($p < 0.001$). Sucker density in NB plots was higher than the Control ($p = 0.006$; Figure 2-3). However, the percentage of 10 m^2 regeneration plots that contained at least one sucker (stocking) was 98.6% in Rollback and Control. Yet, in the stocked plots of the Control treatment suckering was much more densely clustered with densities as high as 171 suckers per 10 m^2 regeneration plot, whereas clumps in the Rollback yielded only up to 41 suckers. The degree of stocking in the NB treatment was 100% and 10 m^2 plots yielded clumps of up to 261 suckers per plot.

Sucker density in the second year was 4,333 stems/ha in the Rollback treatment and this was still much lower than in the Control plots which averaged

44,277 stems/ha ($p < 0.001$) and also lower than the NB treatment with 60,277 stems/ha ($p < 0.001$). Sucker density in NB plots was even higher than the Control ($p = 0.032$; Figure 2-3). Compared to the density of the 1st year, both the Control ($p < 0.001$) and No Barrier ($p < 0.001$) were much lower in the 2nd year. Sucker mortality from year one to two (% decrease in density) was 46 % in the Rollback compared to only 20% in the Control ($p = 0.001$) and 30 % in NB resulting in a significant year by treatment interaction ($p < 0.001$). Mortality in the Control compared to No Barrier treatment was similar ($p = 0.135$). The Percentage stocking in the Rollback treatment dropped to 91.7% in year two ($p = 0.078$).

Mean and maximum sucker heights of the first year in the Rollback were 10.1 cm and 19.3 cm respectively, while Control heights were 37.4 cm for the mean, and 112.1 cm for the maximum ($p_{mean} < 0.001$, $p_{max} < 0.001$; Figure 2-4). Mean and maximum sucker height in No Barrier was 40 cm and 137 cm, respectively (Figure 2-4). Mean sucker height in NB treatment was not different from the Control ($p = 0.390$), but greater than in the Rollback treatment ($p < 0.001$; Figure 2-4). Maximum heights were significantly greater in the NB treatment compared to the rolled back treatment ($p < 0.001$) and Control ($p = 0.003$). In fact, maximum height in NB averaged more than 1 m higher than the Rollback.

Mean height growth was 37.9 cm in the Control and 36.4 cm in the NB treatment indicated no difference between the two ($p = 0.968$). However, growth in the Rollback treatment which averaged only 8.5 cm was much lower than the other two ($p < 0.001$). Tallest suckers in the Control treatment grew 48.4 cm and 48.8 cm in the NB treatment, which were very similar ($p = 0.964$).

2.3.2 Comparison of forest floor protection treatments

Among the forest floor protection treatments, aspen density ranged from 69,250 stems/ha in Geotextile (GT), 77,347 stems/ha in Freezing (FR) to 89,722 stems/ha in No Barrier; planned comparison showed the No Barrier was marginally different from the Geotextile ($p = 0.054$) and not different from the FR treatment ($p = 0.234$; Figure 2-3). Similar trends were found for sucker height. Mean height was not different among the three treatments ($p = 0.407$); while the maximum height of suckers in the NB treatment was on average 26 cm greater compared to the FR treatment ($p = 0.026$), yet no different than the GT treatment ($p = 0.150$; Figure 2-4). An interesting observation, specific to the NB treatment in fall 2012, was that aspen in this treatment had lost all foliage by October 15th whereas in all other treatments leaves had just started to turn brown.

During re-contouring work of the original slope, back hoe operation to remove deposited subsoil in the GT treatment was very slow, since even with careful stripping of subsoil the weight of soil on the cloth induced tearing of the geotextile when it was pulled back. Subsoil would remain on site wherever it fell through the tears in the cloth. According to the operators it would take at least twice as long as to remove the fill from the GT plots than from the NB treatment plots. Freezing plots were reclaimed the fastest and required the least attention by the operators.

2.3.3 Role of edaphic factors in aspen sucker response

Soil bulk density in the Rollback (1.54 g/cm^3) was not different from the Control (1.59 g/cm^3) and NB treatment (1.60 g/cm^3; $p = 0.637$, Figure 2-5) and did not affect sucker density ($p = 0.266$) or mean sucker height ($p = 0.639$). This was also mirrored in the results for soil deformation, such as wheel ruts ($p = 0.146$). In the forest floor protection plots soil bulk density increased with greater subsoil fill thickness down slope ($R^2 = 0.291$; $p = 0.001$, Figure 2-6). Yet, on average there was no clear trend of bulk density in relation to the slope position ($p = 0.396$; Figure 2-7). Thus, differences in subsoil thickness among slope position did not influence mean sucker height ($p = 0.371$) or density ($p = 0.358$). Accordingly, there were no differences in mean sucker density ($p = 0.657$) or mean height ($p = 0.837$, Figure 2-8) among slope positions.

LFH gouging and root exposure were very different among treatments ($p < 0.008$). Gouging was highest in the No Barrier and lowest in the Control treatment (Table 2-1). LFH gouging increased sucker density ($R^2 = 0.191$; p = 0.033), whereas sucker height was not affected by gouging ($R^2 = 0.062$; p = 0.241). As can be expected LFH gouging also increased the exposure of roots ($R^2 = 0.571$; p <0.001). Root exposure was highest in the Rollback (95.9%) followed by the No Barrier (44.4%) and was lowest in the Control treatment (18.3%; Table 2-1).

In all of the applicable treatments, sucker density was not influenced by the cover of residual subsoil (p = 0.559) nor was mean height (p = 0.180). Having said so, however, most plots had less than 14% residual subsoil cover (Table 2-1). Slash cover was significantly influenced by the treatment effect (p <0.001), where the Control retained the highest slash cover (40%) and the Rollback treatment the lowest (10%). Slash cover in forest floor protection ranged from 18.1% in NB to 29.1% in GT treatment (Table 2-1). Sucker height was not related to slash cover (R^2 =0.015; p =0.574). Sucker density was not influenced by slash cover either ($R^2 = 0.102$; p = 0.122).

Soil temperature in the rooting zone (10 cm depth) was negatively influenced by slash cover ($R^2 = 0.574$; p <0.001; Figure 2.9). Following this trend, the highest mean (16 ℃) and maximum (28.3 ℃) soil temperatures were found in the Rollback treatment. However, Rollback plots also had the greatest temperature fluctuation as it displayed significantly lower minimum values (2 ℃) over the period observed (Table 2-2 and Appendix).

Basal area did not affect sucker density (p = 0.113) and neither did number of stumps (p = 0.184). Pre harvest stem density among blocks ranged from 50 to 1075 stems per ha (see Appendix).

2.4 Discussion

In the first year of assessment, there were more than 10 times as many aspen suckers in the No Barrier plots and these were at least three times as tall as in the Rollback of FF salvaged plots, which is the current approach for reclaiming these pads. Further, the density on the forest floor protection exceeded the density of the Control (normal clear cut plots) by ~ 30,000 stems/ha. Both trends continued in the second year of assessment. Protection of forest floor and its healthy aspen roots during the winter construction of OSE pads will therefore improve the speed of aspen recovery and with that the overall forest restoration because it provides abundant, intact and healthy roots that receive the additional stimuli for suckering (Frey et al. 2003); provided that the pad is deconstructed and rolled back prior to the growing season. Small lateral roots (< 2 cm in diameter) produce many suckers (Kemperman 1978, DesRochers and Lieffers 2001) and these roots are normally susceptible to disturbance (Frey et al. 2003). Maintenance of the original root system, including their fine roots may also increase access to C reserves and nutrient supply (Landhäusser and Lieffers 2002, Landhäusser et al. 2012). Total-nonstructural carbohydrate (NSC) reserves are considered to be essential for the elongation and above ground emergence of aspen suckers following disturbance (Landhäusser and Lieffers 2003). This is because suckers depend on root reserves until they reach the surface and establish photosynthetic area (Schier and Zasada 1973). Intact root systems increase the chances for long-term growth and success of suckers, since intact roots access more water and nutrients.

The high leaf area produced from the many suckers within forest floor protection plots will likely maintain much of the original clonal root system (DesRochers and Lieffers 2001, Landhäusser and Lieffers 2002) thereby bringing the stand onto a rapid growth trajectory. Also, rapid development of leaf area in high density stands (Lieffers et al. 2002) will shade the site and reduce the establishment of undesirable competing vegetation (Landhäusser and Lieffers 1998).

Suckering response in the Rollback plots clearly shows stunted and less dense aspen regeneration and growth. However, 98% of stocking on Rollback plots indicates that the relatively few suckers were well dispersed in the first year. My observations were that the Rollback treatment fragmented the original root system and caused severe root wounding, fragmentation and root exposure. Therefore, mortality in the Rollback treatment may have been caused by the loss of root area, and excessive wounding could have increased infections and root decay. Such damage likely leads to root death, accompanied by a decrease in sucker density (DesRochers and Lieffers 2001, Renkema et al. 2009). Sucker development is limited on small root segments, because of the limited availability of NSC reserves (Steneker and Walters 1971). Further, short root fragments will also lack the hormonal stimulation of cytokinin needed for shoot elongation (Schier 1981) and suckers have less access to water and nutrients needed for growth (Zahner and Debyle 1965, Fraser et al. 2002, Landhäusser and Lieffers 2002). After another growing season, almost 50% of suckers in Rollback plots had died. This could point towards the depletion of nutrients as suckers allocated resources to rebuild their root system.

While sucker performance in the Rollback treatment was lower than desirable, it is an improvement over the current operationally-built pads in the vicinity where I observed lower sucker regeneration 2 years after abandonment. On these sites the FF and part of the upper mineral soil horizon is stripped in very shallow layers, likely resulting in more root damage and lower sucker densities. Another reason for the improved regeneration in the experimental Rollback could be the rough dumping of FF material with no further compaction. A soft and irregular surface provides more microsites and allows penetration of water that is likely beneficial to establishing plants (Johnson and Fryer 1992, Macdonald et al. 2011). In the long run, surface conditions might also influence nutrient supply, microbial energy reserves, root growth and air balance (Corns and Maynard 1997).

Both sucker density and mean height were not statistically different among the three forest floor protection treatments, but there was a strong trend for more suckers in the No Barrier treatment (p = 0.054). Maximum height and density however, were depressed in Freezing in comparison to the No Barrier treatment. Possibly, suckering was delayed in Freezing plots since low soil temperatures inhibited sucker initiation (Maini and Horton 1966b, Zasada & Schier 1973) for a longer time compared to other treatments. Therefore, suckers were smaller and less numerous, because they had less time to emerge and grow (Landhäusser and Lieffers 1998, Landhäusser et al. 2006).

The No Barrier treatment displayed slightly greater LFH gouging from back hoe operation, resulting in lower slash cover and higher soil temperatures. Light to medium scraping might have caused greater suckering, since light wounding of an intact and connected root system can stimulate sucker initiation (Fraser et al. 2003 and 2004, Renkema et al. 2009). This explains the trend for higher sucker densities in the No Barrier treatment compared to the Control. Since there was no scraping in the Control plots, slash was retained in this treatment. The only feature of concern in the No Barrier treatment was the early senescence of suckers, compared to the Geotextile or Freezing. This could point to an effect of nutrient depletion, because less LFH and slash was available for decomposition/mineralisation or because higher temperatures speeded up the annual processes and growth was completed earlier. Sucker height growth in the second year was lower in the No Barrier compared to the Control treatment. This aspect may require further monitoring.

Higher slash loading was found to reduce soil temperature; however it could not be linked to sucker regeneration in my study. Higher slash can inhibit soil warming and hinder suckers from penetrating to the surface (Brown and DeByle 1987, Lieffers and van Rees 2002, Mulak et al. 2006) and lower soil temperature, limit root growth and respiration (Maini and Horton 1966b, DesRochers et al. 2002, Landhäusser et al. 2006). Yet, in my experiment sucker growth was not related to slash cover.

Sucker growth was not influenced by subsoil loading, therefore using subsoil to build the pad and as a buffer to protect the forest floor was successful in the regeneration of aspen. Soil loading in this study was likely not associated with root crushing or heavy wounding. Even exceptionally high amounts of subsoil loading in some blocks did not cause sufficient compaction of the protected forest floor underneath to influence suckering. Many studies link lower sucker densities with soil compaction (Bates et al. 1993, Shepperd 1993), whereas Renkema et al. (2009) observed small increases in bulk densities to increase sucker density while decreasing height growth. Heavy loading caused some compaction, but I did not test a thin loading zone, which may not have provided sufficient depth of subsoil to bear the weight of the machines. Therefore, compaction could actually play a role in much lesser loaded sites. I speculate that the greatest difference in soil bulk density originates from the harvesting operations rather than subsoil loading. Accordingly, special precaution must be paid to carefully harvesting future protection sites and using only Rollback sites as log deck and loading areas. Subsoil fill residue left on top of the forest floor after re-contouring was generally very low in this study. My assessment of the effects of residual subsoil only tested the low end of the range of possible conditions following cleanup - nowhere was there a large amount of subsoil left. This points to the skillful operators of machinery in my study. I assumed that large amounts of subsoil residue would have impacts similar to excessive slash and resulting in poor suckering.

2.4.1 Conclusions and management implications

Among the protected forest floor sites, suckering results were best in the No Barrier treatment. Certainly, the Geotextile treatment compares to No Barrier in terms of sucker regeneration, but due to the higher costs and effort of application and reclamation it is not as economical, provided that there are motivated and skilled operators available. The Freezing treatment with its thick and hard snow-ice mix was very easy for the operator to scrape, because it would offer a resistant barrier on top of the forest floor for the bucket to slide against, allowing for very rapid and thorough cleanup of subsoil. Since water is commonly available in Alberta, freezing-in the soil and snow treatments remain a viable option. Furthermore, the generation of snow via snow cannons should be considered for all OSE operations starting prior to natural snow fall.

It would be interesting to investigate the economics of trucking in subsoil from close by sites to increase the area that could be protected, thereby speeding up reforestation. Vegetative regeneration of aspen is very fast compared to planting, and it will quickly capture the site and can suppress competing vegetation such as graminoids or exotic weeds. Woody slash cover resulting from harvesting significantly reduces soil temperature and should not intentionally be increased. Debris spread should be in the form of whole logs and non- mulched debris. When available tree tops of species with serotinous cones might improve seedling establishment in the rollback areas, but should not cover up the forest floor protected areas.

Since I tested the effect of basal area on aspen regeneration density it might justifiable to propose using my technique even in conifer dominated stands, as long as there are some remaining aspen. Indeed, Navratil and Bella (1988) mention that only one tree may restock an area of about 400 m^2, which very well corresponds to the size of my treatment plots (where vigorous suckering occurred even with no aspen stump inside the plot).

In conclusion, the use of FF salvage and Rollback over the entire OSE pad is only appropriate on areas that will be cut down in the leveling of the pad. Here, careful salvage and rough dumping of the FF in the Rollback can be moderately effective in restoring aspen stands. Admixing of the FF with upper soil layers (without an inclusion of unsuitable soil horizons such as heavy clays) should be tolerated in order to provide the right substrate around the roots (Wachowski 2012). Forest floor protection should be applied to the lower positions on the pad. Furthermore, operator training to create the understanding of the value of forest floor and how to identify it during pad cleanup is crucial. In my study, both hoe and bulldozer operators were motivated and reacted quickly to training. Without careful training the Freezing treatment might be needed in order for workers to detect the original forest floor.

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Tables

Table 2-1. Percent surface area disturbed by machine traffic, covered with slash or subsoil residue in relation to recovery treatment.

For gouging, exposed roots, and wheel ruts are based on the proportion of subplots within a treatment plot that contained these conditions. Means with different letters indicate statistically significant differences (α=0.05). Capital letters indicate differences among the three main treatments (Control, Rollback and NB), while small letters indicate differences among the three FF protection treatments.

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
FF gouging	$13_{\mathbf{B}}$	NA	$43_{\mathbf{Ax}}$	$28_{\mathbf{y}}$	$24_{\mathbf{y}}$
Exposed roots	$18_{\mathbf{C}}$	$96_{\mathbf{A}}$	$44_{\mathbf{Bx}}$	$24_{\mathbf{y}}$	$31_{\mathbf{xy}}$
Wheel ruts	$30_{\mathbf{B}}$	$61_{\mathbf{A}}$	$40_{\mathbf{ABx}}$	$32_{\mathbf{x}}$	$22_{\mathbf{x}}$
Residual subsoil	NA	NA	14	9	8
Slash residue	$40_{\mathbf{A}}$	$10_{\mathbf{C}}$	$18_{\mathbf{Bx}}$	$27_{\mathbf{y}}$	$29_{\mathbf{y}}$

Table 2-2. Mean, maximum and minimum daily soil temperatures (°C) in relation to recovery treatment.

Data were collected from June 7th to October 7th. Means (± S.E.) with different letters indicate statistically significant differences (α=0.05).

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Mean	$12.3_{\mathbf{C}}$ (0.3)	$16.0_{\mathbf{A}}$ (0.2)	$13.8_{\mathbf{Bx}}$ (0.3)	$13.0_{\mathbf{y}}$ (0.2)	$13.1_{\mathbf{xy}}$ (0.2)
Maximum	$18.7_{\mathbf{C}}$ (0.6)	$28.3_{\mathbf{A}}$(0.9)	$21.7_{\mathbf{Bx}}$ (0.7)	$18.7_{\mathbf{y}}$ (0.4)	$20.2_{\mathbf{xy}}$ (0.5)
Minimum	$6.2_{\mathbf{A}}$ (0.2)	$2.0_{\mathbf{B}}$ (0.6)	$5.8_{\mathbf{Ax}}$ (0.2)	$6.6_{\mathbf{x}}$ (0.2)	$6.2_{\mathbf{x}}$ (0.2)

Figures

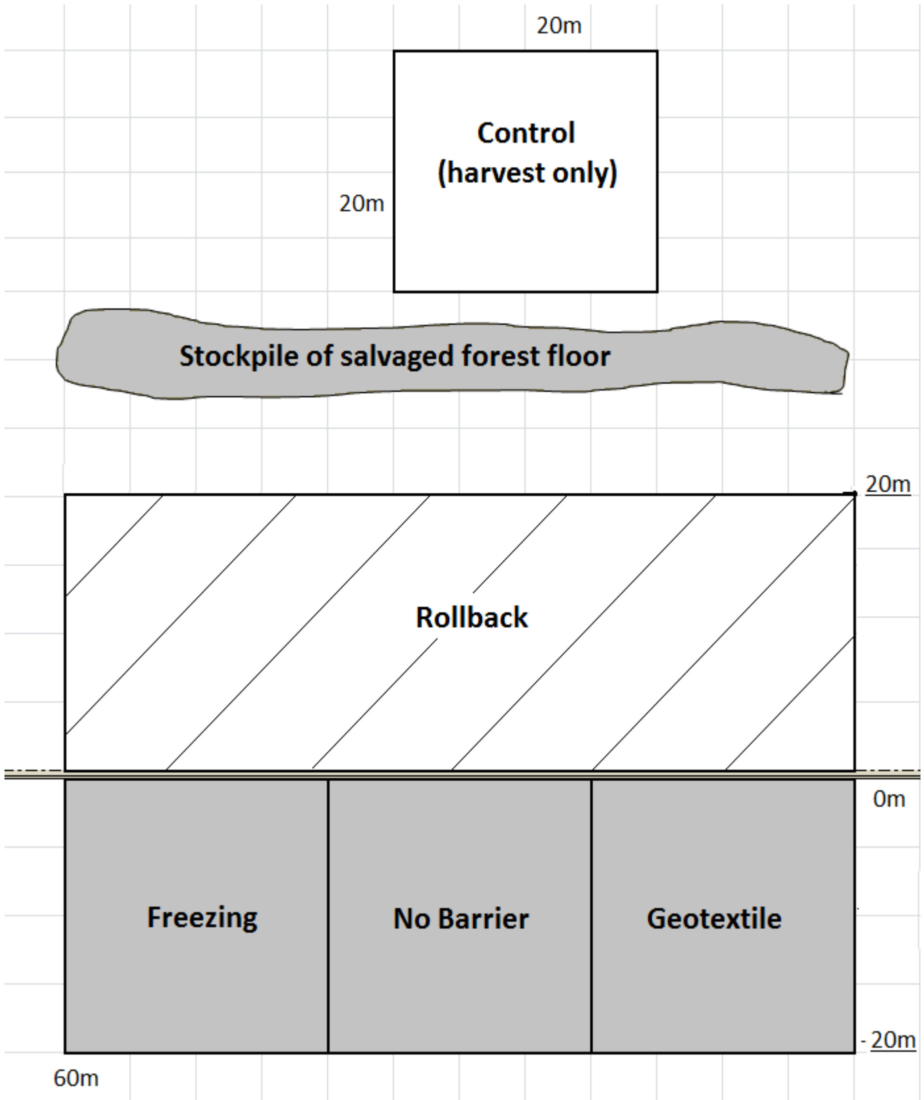

Figure 2-1. Experimental block design with all treatments.

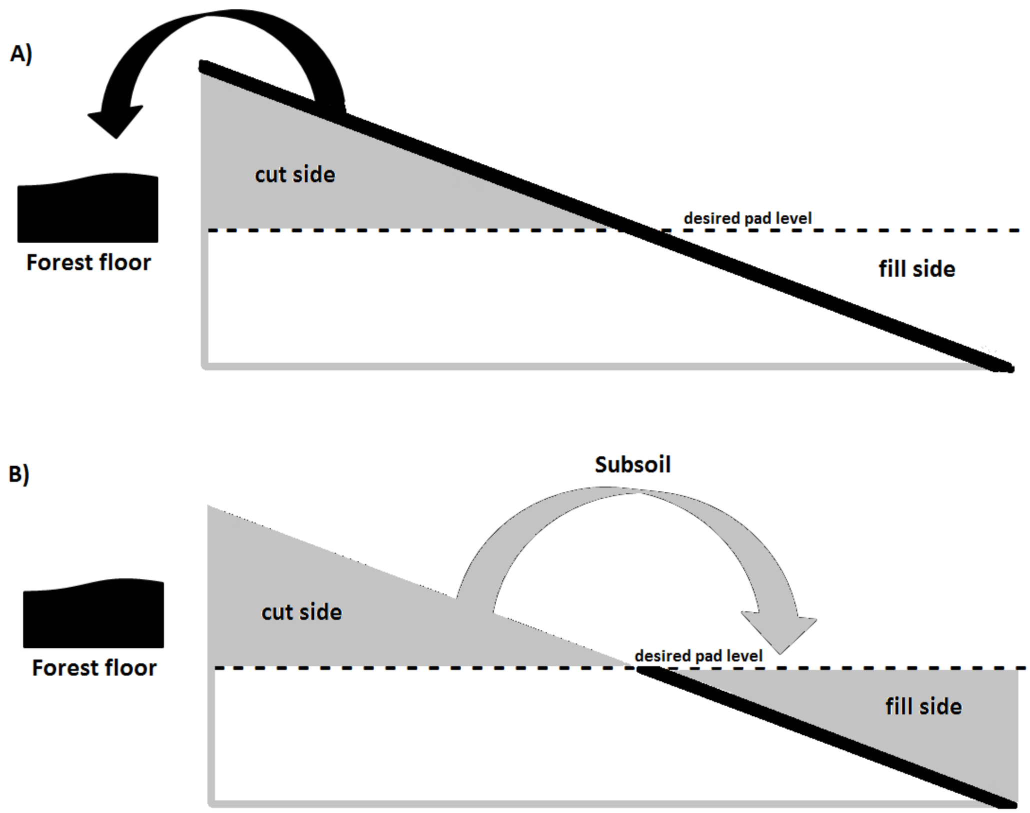

Figure 2-2. Schematic of drilling pad leveling procedure and FF handling.

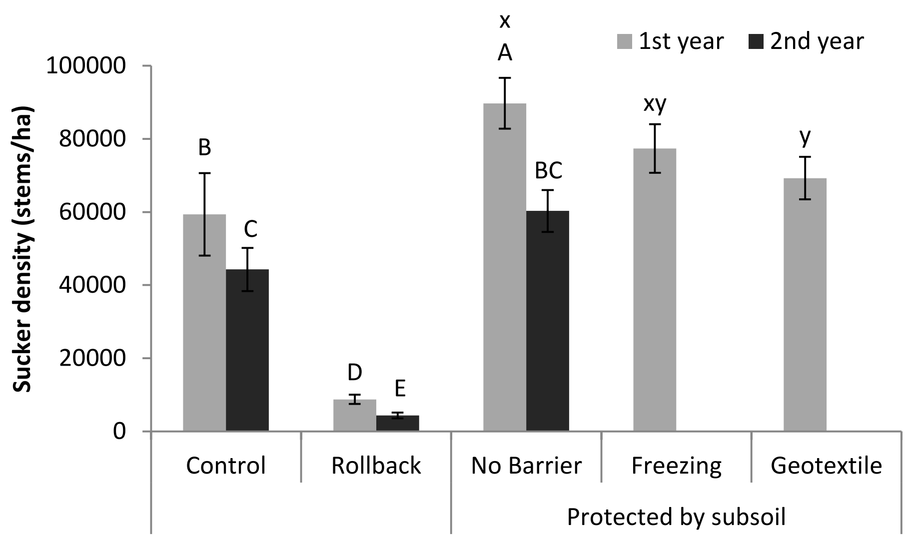

Figure 2-3. Mean density of aspen suckers (± S.E.) in relation to treatments based upon the 10 m^2 plots.

Means with different letters indicate statistically significant differences (α=0.05). Capital letters indicate differences among the three main treatments for year 1 and year 2 (Control, Rollback and No Barrier). Small letters indicate differences among the forest floor protection treatments; all based on planned comparisons.

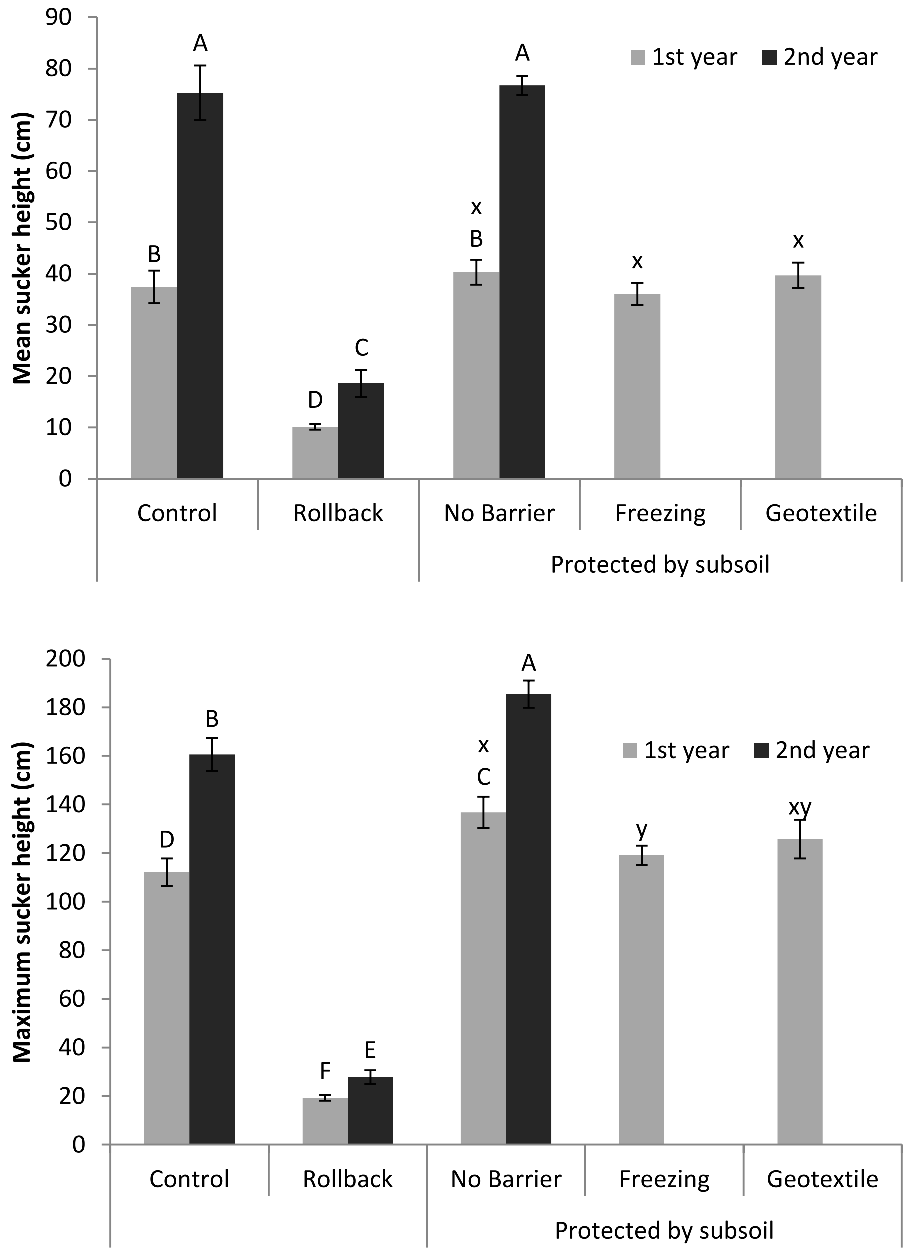

Figure 2-4. Mean sucker height (± S.E.) based upon the 1 m^2 subplots and maximum sucker height (in 10 m^2 plots) in relation to recovery treatments.

Means with different letters indicate statistically significant differences (α=0.05). Capital letters indicate differences among the three main treatments for year 1 and year 2 (Control, Rollback and No Barrier). Small letters indicate differences among the forest floor protection treatments; all based on planned comparisons.

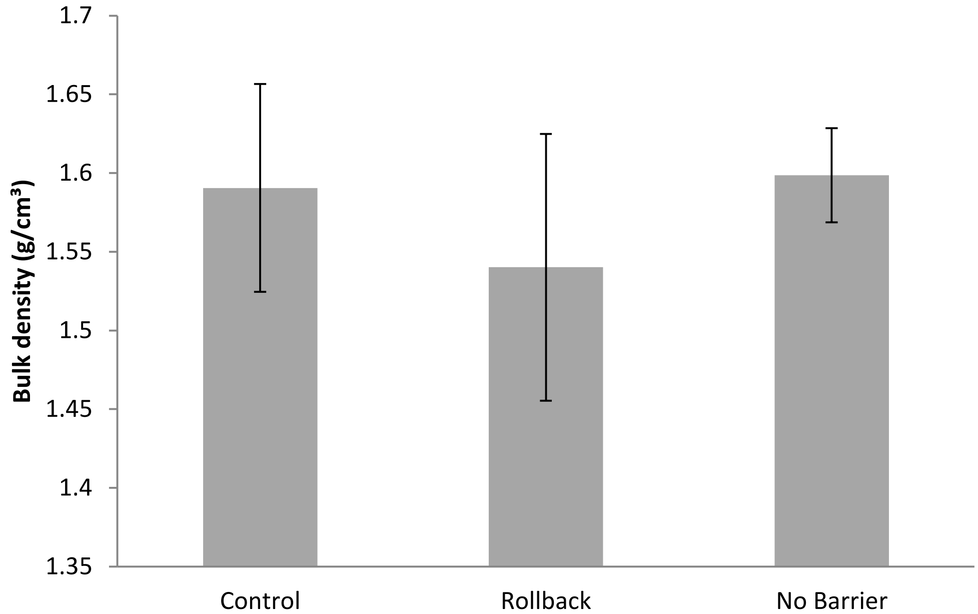

Figure 2-5. Mean soil bulk density (± S.E.) in relation to selected treatments.

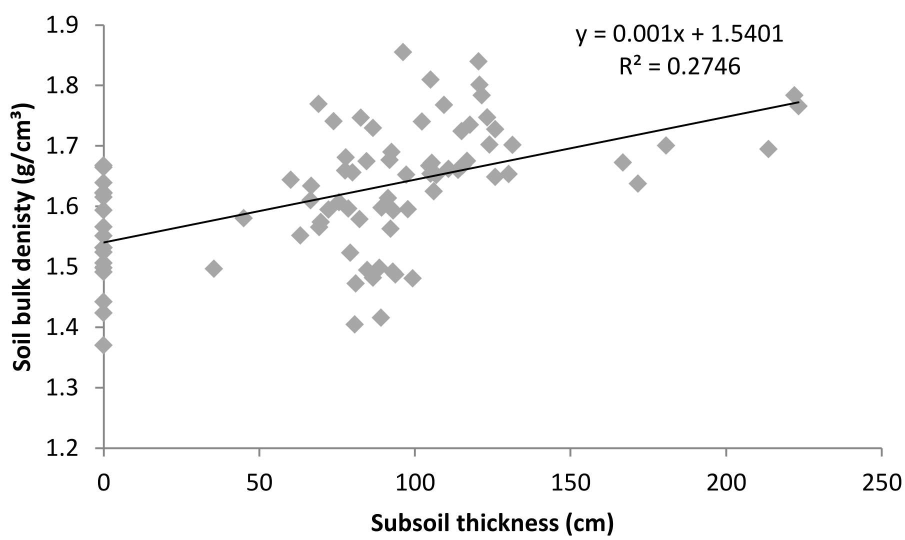

Figure 2-6. Soil bulk density in relation to thickness of the subsoil fill.

All data originate from the Control and NB treatment (n=86).

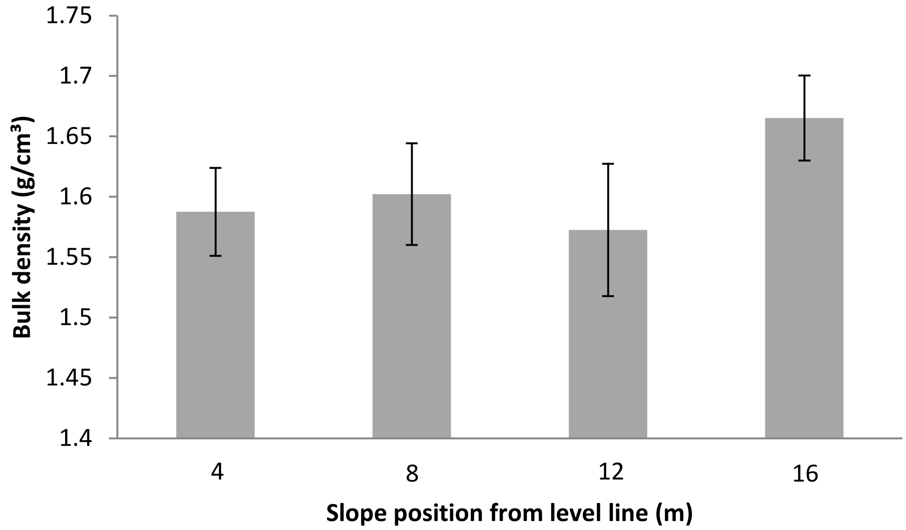

Figure 2-7. Mean soil bulk density (± S.E.) in relation to slope position in the No Barrier (FF protection) treatment.

Position 16 was lowest down slope with most material deposited.

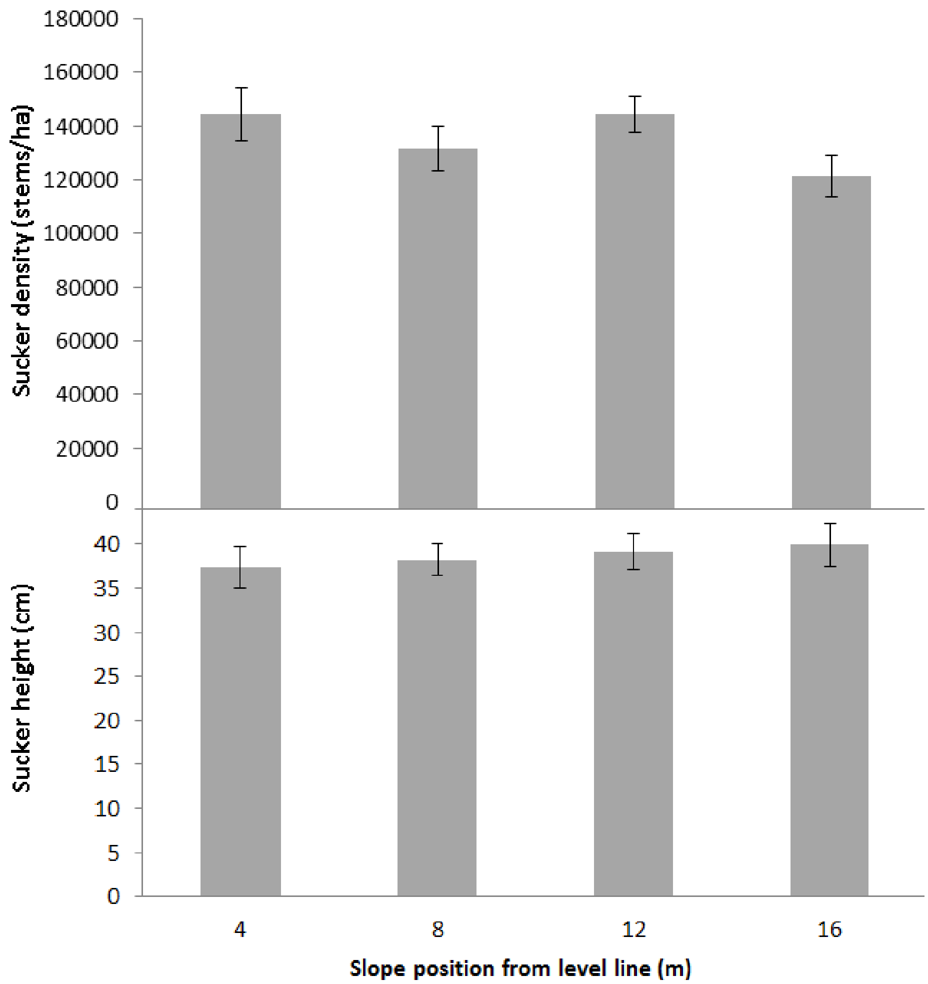

Figure 2-8. Mean density and height (± S.E.) of 1st year aspen suckers in relation to slope position in the forest floor protection treatments.

Position 16 was lowest down slope. There were no statistical differences across slope position.

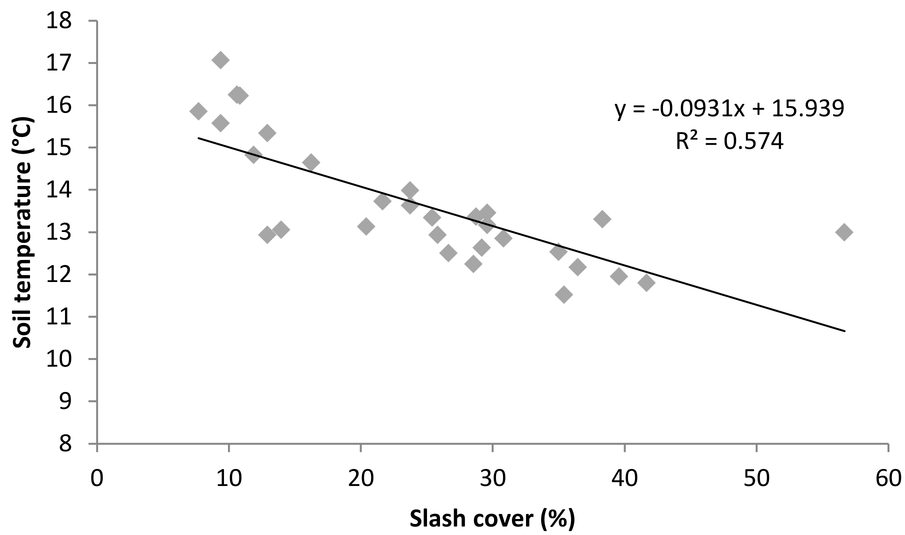

Figure 2-9. Mean soil temperature in relation to slash cover.

Each data point represents a seasonal average over the treatment plots (n=30).

Chapter 3. Understory vegetation response to salvage and forest floor protection techniques on temporary drilling pads

3.1 Introduction

Plant diversity in boreal forest ecosystems is largely driven by the understory plant communities (Craig and Macdonald 2009). Understories provide habitat and food for wildlife (Økland and Eilertsen 1996, Craig and Macdonald 2009) and play key roles in nutrient cycling (Dearden and Wardle 2008), forest succession, and long-term stand productivity (Nilsson and Wardle 2005, Hart and Chen 2006 & 2008, Kolari et al. 2006, Gilliam 2007). It is estimated that the annual turnover of biomass and nutrients in boreal understory vegetation is 34–43% compared to only 2–5% in trees (Chapin 1983).

The boreal forest is a disturbance-prone ecosystem (Rydgren et al. 2004) and the understory composition is related to disturbance severity, with more severe disturbances causing greater changes (Roberts 2004). Much of the boreal forest plant life is adapted to wildfire and commonly regenerates directly from sprouting of rhizomes and roots following disturbance (Greene et al. 1999, Rydgren et al. 2004, Macdonald et al. 2012). Wildfire often burns the organic surface layer and exposes the mineral soil, therewith preparing the seedbed for recolonisation and providing stimulation to intact roots and rhizomes (Whittle et al. 1997, Purdon et al. 2004, Hart and Chen 2008). In fact, most perennial herbaceous species in the boreal understory have vegetative regeneration organs (Rowe 1956) and are capable of dominating post-disturbance communities because of their elaborate rooting systems (Whittle et al. 1997).

Forest harvesting and Oil Sands Exploration (OSE) practices represent anthropogenic disturbance processes that are rather different from wildfire. Harvesting operations export most of the tree biomass, whereas OSE activity results in surface soil stripping and mixing. This can result in post reclamation understory communities being different from those observed after natural disturbances. For example, post logging understory composition may be comparable to the pre-disturbance communities, but rather different compared to those resulting from wildfire (Rees and Juday 2002). Replacing wildfire by clearcut harvesting may also influence the chemical properties of the forest floor and its capacity to cycle and supply nutrients, with possible implications for forest productivity (Thiffault et al. 2006).

OSE drilling pads on forested land are currently constructed by stripping off the upper forest floor materials (FF) and stockpiling them beneath or near the pad. The FF material is a mixture of the organic L-F-H horizons and the A horizon. After operations have ceased on the pad, the FF material is placed back on the surface of the pad (Rollback) for reclamation (Alberta Environment 2005). Plant species richness usually declines after FF salvage and Rollback compared to the existing forest, likely due to losses of viable propagules (seeds and vegetative tissues) after stripping and stockpiling (Fair 2012, Iverson and Wali 1982). It is argued that intense disturbance like soil stripping normally favours the establishment of plants from seed rather than vegetative parts (Granström 1986, Rydgren et al. 2004), because stripping is likely to damage propagules from roots and rhizomes (Roberts 2004), which otherwise could greatly contribute to plant establishment in boreal forest reclamation (Mackenzie 2013). In terms of the seedbank, Koch et al. (1996) found a cumulative decline in viable seed availability after stripping (26% loss), stockpiling (69% loss), and re-spreading (87% loss). Furthermore, machine traffic can exert heavy ground pressure, causing soil compaction and damage to the roots and propagules in the forest floor, as documented for aspen (Renkema et al. 2009a).

Likely, such heavily disturbed rollback sites will be initially dominated by a semi-stable community of early to mid-successional forb and grass species (Landhäusser and Lieffers 1998, Maundrell and Hawkins 2004). If tree regeneration is retarded, shade intolerant understory species might not establish. Although soil disturbance can increase microsite availability for plants to germinate, it may also enable invasive or problematic species' establishment, resulting in different community structures (Lieffers et al. 1993). Undesirable species may persist in the understory of developing forest stands, where they can impede the establishment of species typically found in natural understory communities (Macdonald et al. 2012). Some species such as bluejoint reedgrass may interfere with natural overstory succession if they start altering the temperature or light environment in a way, which some trees are intolerant to. It is important to restore disturbed sites with high species richness, because a diverse understory plant community will likely lead to increased ecological stability, creating a more resilient plant community (Tilman 1996) and resisting environmental stresses (Macdonald et al. 2012). Since seeds are not commercially available for the vast majority of native forest understory species, (Alberta Native Plant Council 2010), retaining viable propagules during industrial disturbance is very important.

A viable alternative to stripping and rollback of FF is the protection of the forest floor during the construction and drilling of the OSE pad (see also previous chapter). The vegetation recovery using this technique has never been compared with that of conventional harvesting and the stripping and rollback techniques currently applied on these sites.

The objective of this study was to evaluate the recovery of understory vegetation after OSE pad construction in the boreal mixedwood region. This was compared to conventional clearcut harvesting and the different reclamation techniques as described in the previous chapter. Further, I wanted to investigate if the same factors that influence aspen regeneration, as well as soil nutrition have an effect on understory recovery.

3.2 Methods

3.2.1 Study site

The research site was located on the Devon Pike lease south-east of Conklin, Alberta (55°24’N, 110°44’W). It is situated in North Eastern Alberta in the Central Mixedwood Subregion of the Boreal Forest Natural Region of Alberta. This subregion is characterized by a mix of aspen-dominated (*Populus tremuloides* Michx.) deciduous stands, mixed aspen-white spruce (*Picea glauca* (Moench) Voss) forests and some upland jack pine (*Pinus banksiana* Lamb.) stands (Natural Regions Committee 2006). The site lies in the Sandy River catchment area, where soils are fine-textured, silty sandy luvisols. The terrain type is a Glaciofluvial Veneer over Morainal till. The local terrain of the study site is slightly sloped, facing south-southeast. The forest canopy layer was dominated by mature 80-year old trembling aspen with some white spruce both in the overstory and understory.

The area was clear-cut harvested in late November of 2011 during non-frozen soil conditions using tracked feller bunchers and wide tire grapple skidders. The drill pad experiment was started in late January 2012. It was set up with five treatments replicated over six blocks; for each block the total area was 40 x 60 m which corresponds to approximately half the area used for a conventional OSE drilling pad. The experimental blocks were placed in areas that were slightly sloped to allow for the usual cut and fill sides of the pad necessary for accommodating the questions of this experiment. Further site and environmental characteristics correspond to the description in chapter 2.

3.2.2 Treatments

In each block a 20 x 60 m plot was laid out on the upper half of the slope for the FF salvage, and Rollback treatment. The lower half of the pad was laid out into three 20 x 20 m plots each assigned to a different protection treatment. In these plots the original forest floor was not stripped off and three treatments (freezing

(FR), geotextile (GT) and no special barrier (NB)) were used to protect and delineate it from the fill material during the leveling (filling) of the pad. A fifth plot was selected adjacent to the area as an untreated, but harvested Control. I staked out three transects perpendicular to the slope in each of the 20 x 20 m plots; each had four sample points 4 m apart.

The application of the forest floor protection and the delineation treatments are described in more detail in chapter 2. Briefly, for the FR treatment, water was applied with a water truck and hand sprayed on the treatment plot resulting in a 12-17 cm layer of compacted and hard frozen snow-ice mix. In the GT treatment a tough woven plastic mat was rolled out on the 20 x 20 m plot, while in the NB treatment the forest floor did not receive any special treatment to delineate it from the subsoil fill; however at the time of construction all areas had a 33 cm of snow cover.

The upslope portion of the pad (20 x 60 m) received the Rollback treatment where the surface soil was salvaged to a depth of about 15 cm using a $D6R_{xw}$ caterpillar bulldozer and stockpiled. The construction of the pad is described in more detail in the previous chapter.

After lying idle for about three weeks, the level pads were deconstructed to uncover the original forest floor beneath the subsoil and the entire upper slope (Rollback plot) was re-contoured with the subsoil using a back hoe (Komatsu PC200) and a bulldozer. The salvaged FF material was rough dumped back onto the re-contoured upper slope at a similar depth to the salvage and care was taken to minimize the machine traffic over the FF.

3.2.3 Measurements

Measurements of edaphic factors and disturbance were carried out as described in detail in chapter 2. They included bulk density, cover of slash and subsoil residue, as well as categorical evaluations (yes/no) of wheel rutting and forest floor disturbance (gouging) in each of the 12 subplots within each treatment plot. All vegetation assessments were made in these same subplots, too.

Vegetation sampling was carried out in 360 subplots between the end of August and mid-September of 2012. The percent ground cover of all vascular plant species occupying each subplot was estimated. All estimates were done by the same observer and estimates were 'calibrated' by training with cardboard pieces representing values from 1%, 5% and 10% of the 1 m^2 plot. Cover was estimated for seven cover classes: <1% (cover), 1–3, 3-5, 5–10, 10–25, 25–50, 50–75 and >75%. Because of the heights of vegetation and overlapping leaf area, total cover (sum of all cover values in a plot) could be greater than 100%.

All plants were identified to species level except for a late-developing grass and willow (*Salix*) spp. Finally, a walk through was used in every 20 x 20 m treatment plot to identify species that were not present inside the subplots. This knowledge was incorporated into the species richness per treatment plot. Nomenclature and associated authorities follow Moss (1994).

In 2013 soil samples were collected in the Rollback, Control and NB treatments to assess if there were differences in nutrients and nutrient availability, which could influence plant growth. After removing the loose litter, three bulk samples from the top 10 cm of the mineral soil were randomly collected in each 20 × 20 m treatment plot. Samples were combined in the field. After homogenising and sieving with a 1.4mm mesh the samples were air dried, weighed and subsampled to prepare it for chemical analysis. After ball grinding, they were sent to the Natural Resources Analytical Laboratory (NRAL) at the University of Alberta. The retained soil was oven dried to calculate the difference in moisture content. NRAL performed analysis for available P and N, as well as total P using colorimetric determination. For nitrate the diazo coupling method was used, whereas for ammonium the modified Berthelot method was used. Available K was determined by atomic absorption spectrophotometry. Total P was analysed using acid digestion. Analysis of total N and C was carried out using a Shimadzu TOC-V Total Organic Carbon Analyzer.

3.2.4 Data analysis

Species richness was assessed based on the number of plant species found within each 20 x 20 m treatment plot and frequency of species occurrence was calculated as the percentage of 1 m^2 subplots that contained at least one specimen of a plant within a treatment plot.

Cover classes for the estimated plant covers within each subplot were converted to midpoint values (%) prior to computing averages (Macdonald and Fenniak 2007) and deriving relative species cover, diversity, and evenness. Relative species cover was calculated as the percentage contribution of each species to the total cover in each treatment (see Appendix). Species diversity was expressed using the Shannon-Wiener index ($H' = -\sum p_i \ln p_i$) where p_i is the proportion of the total community cover represented by the $_i$th species and the natural log of p_i (Shannon and Weaver 1949). It was used because of its universal application and robustness to sample size (Peltzer et al. 2000). Evenness was calculated as species equitability ($J = H'/H'max$) which is the ratio of observed diversity [H'] to the maximum possible diversity of a community with the same species richness [H'max] (Pielou 1969).

Plants were also categorized into functional groups of trees, shrubs, forbs or graminoids. Further, species were separated into native and non-native species to the region and their life history of either annual/biannual or perennial (Plants database - USDA 2013). However, both the native and life history status did not yield significant differences in response to my treatments and are not presented. The graminoid cover, as well as some single species cover data needed to be log transformed to meet the assumptions of ANOVA.

Categorical disturbance data for wheel rutting and LFH gouging were averaged per treatment to obtain the percentage of subplots with disturbance present (n= 6 per treatment). The effect of the subsoil thickness and bulk density on total plant cover was analysed using data from the subplot level, but only on the fill side of the drill pad, which corresponds with the protected forest floor (NB), as well as the Control (n=86).

Total plant cover, functional group cover, single species cover, frequency, richness, evenness, diversity, soil nutrients and disturbance/edaphic factors per treatment were averaged for each of the six replicate blocks before running ANOVAS in Statistical Analysis System (SAS 9.2, Cary, North Carolina, USA). For each variable, two one-way ANOVAS were carried out to compare among the three main treatments (Rollback, NB and Control) and among the three forest floor protection treatments (NB, GT and FR).

Single species cover was also used in Non-metric multidimensional scaling (NMDS) analysis to produce two ordinations of plant community structure among the three main treatments, as well as the three forest floor protection treatments. They were run in R (R 3.0.2 Vienna, Austria) with 999 permutations. Simple linear regression analysis was used to assess the impact of edaphic factors and disturbance parameters (see Chapter 2 for details) on total plant cover and species richness. For regression analyses of LFH gouging, subsoil residues and bulk density, I excluded the Rollback treatment, because the effects of these variables were not applicable in the mixed-up Rollback soil. For significant regressions it was then tested if all functional groups were influenced to the same degree. I also tested whether tree cover (aspen dominated) influenced the cover of other functional groups, but there was no significant effect.

3.3 Results

3.3.1 Comparison of Rollback, NB and harvested Control

The plot of the NMDS ordination clearly shows a spatial separation between the Rollback and the NB, as well as the Control treatment. The distances between treatments indicate substantial differences in community structure (Figure 3-1A). The species which most drove the difference in Rollback was *Vicia* a*mericana*.

Muhl. Further, the NB treatment is less densely clustered than the Control. The variation for the minimum stress configuration (0.16) at the given 2 dimensions amounted to an R^2 of 0.92.

At the end of the first growing season in 2012, average total ground cover of the lesser vegetation (excluding trees) was 4.6% in the Rollback, which was much lower than 28.4% in the Control and 30.7% in the NB treatment ($p <0.001$); Control and NB were not different ($p = 0.601$) (Table 3-1). The same response was detected when separated by the functional groups of shrubs, forbs, graminoids and trees, where cover was much lower in Rollback compared to the Control and NB (all $p <0.04$; Table 3-1), and the cover of each functional group was not different between the Control and NB treatments. The ratio of total plant cover among the functional groups (shrub:forb:graminoid:tree) was higher in the Rollback 1:10:1:1, while in the NB it was 1:2:1:2 and 1:3:1:3 in the Control treatment.

The species with the greatest cover in the Rollback treatment was *V. americana* (1.3%), which represented 26% of the treatment's total plant cover and had twice the cover of any of the other treatments ($p <0.001$). *Lathyrus ochroleucus* Hook. had the second highest cover (0.9%) and represented 19% of the Rollback treatment's total plant cover, but occurred in similar amounts in the NB and Control treatments (Table 3-2). *Epilobium angustifolium* L. was lower in the Rollback treatment (0.8%) compared to the NB and Control treatments ($p <0.021$). In both treatments *E. angustifolium* had the highest cover of any non-tree species (Table 3-2) representing 18% of the Control's total plant cover and 13% in the No Barrier treatment. Similarly, the cover of *Rosa acicularis* Lindl. was much lower in the Rollback (0.4%) compared the NB treatment ($p = 0.004$), where it had very high cover (5.2%). Yet, *R. acicularis* still represented 8.3% of the Rollback treatment's total plant cover.

The same trend was observed for *Cornus canadensis* L., which only had trace cover in the Rollback, yet the third highest cover (3.9%) in the No Barrier treatment. The cover of *C. canadensis* was lower compared to the NB and Control treatments (p <0.001). Many other species such as *Aralia nudicaulis* L., *Linnaea borealis* L., *Lycopodium annotinum* L., *Mitella nuda* L., *P. palmatus*, *Rubus idaeus* L., *Rubus pubescens* Raf., *Vaccinium myrtilloides* Michx. and *Viburnum edule* (Michx.) Raf. had only trace cover in the Rollback, whereas they performed better in the other treatments (Table 3-2).

Frequency (number of subplots occupied by a species) of *Geranium bicknellii* (98.6%), and *V. americana* (80.6%) was higher in the Rollback than in the Control and NB treatment (both p < 0.006; Table 3-4). The frequency of *L. ochroleucus* in the Rollback (91.7%) tended to be higher than in the Control (68.1%), but also followed a trend similar to the NB (81.9%) (p = 0.061). *E. angustifolium*, *R. idaeus*, *R. pubescens* and *Viola renifolia* had similar frequency in all three treatments (all p > 0.301). *Cornus canadensis* occurred only in 4.2% of the Rollback plots, which was much lower compared to 94.4% in the No Barrier and 98.6% in the Control treatment (p < 0.001). Other species that had lower frequency in the Rollback compared to the NB and Control treatment were *L. borealis* (p < 0.001), *L. annotinum* (p = 0.072), *Maianthemum canadensis* Desf. (p = 0.005), *M. nuda* (p = 0.004), *Trientalis borealis* Raf. (p = 0.011), and *Vaccinium vitis-idaea* (p = 0.037; Table 3-4). All above had similar cover in the Control and NB treatments (p >0.219) except for *Lycopodium obscurum*, which was more frequently found in the Control (p = 0.048). Other species that were missing in the Rollback, but present in the other two treatments were *Equisetum arvense* L., *Galium boreale* L. and *Ledum groenlandicum.*

Although not measured, observations of plant growth after the second growing season indicate an increase in total ground cover across all treatments, yet most notable in the Rollback treatment. Here, *V. americana* and *L. ochroleucus* expanded rapidly, covering most other species including a great majority of the short aspen suckers. Also, *Trifolium* and *Melilotus* spp. had expanded notably in size and abundance.

There were 19 different species found after the first growing season in the Rollback, which constituted much lower richness compared to 28 in each of the Control and NB treatment ($p < 0.001$) (Table 3-3). All species found in the Rollback were also present in the other two treatments, except for *Melilotus officinalis* (see Appendix). Forb and shrub richness were lower in the Rollback compared to the Control and NB treatments (both $p < 0.029$). However, richness of graminoids was not different among the three ($p = 0.751$). Mean species richness across the three treatments was higher in forbs compared to shrubs and graminoids ($p < 0.001$).

According to the Shannon-Wiener index, lesser vegetation in the Rollback treatment was similar in diversity when compared to the Control or NB treatment (Table 3-3). Pielou evenness index did not differ among the three treatments (Table 3-3).

3.3.2 Comparison of forest floor protection treatments

NMDS ordination among the forest floor protection treatments resulted in a greater spread of NB plots compared to the Freezing and the Geotextile treatment. The GT plots were clustered closest together (Figure 3-1B). The variation for the minimum stress configuration (0.26) at the given 2 dimensions amounted to an R^2 of 0.65.

Total vegetation cover was not different among the three protection treatments ($p = 0.668$) and ranged from 30.2% in the FR to 34.7% in the GT treatment (Table 3-1). A great majority of single plant species were very similar in cover (Table 3-2) and their frequency (Table 3-4) among the three forest floor protection treatments. However, there were some species exclusively found in the NB treatment, but only in trace amounts, which included *Amelanchier alnifolia* Nutt., *Chenopodium album* L. and *Galium triflorum* Michx. Species absent in NB treatment, but present in the FR and GT treatments included *Hieracium umbellatum* Michx., *Lonicera involucrata* (Richards.) Banks, *Melilotus officinalis* (L.) Lam., *Trifolium hybridum* L. and *T. pratense* L. Species richness (27) was not different among the three treatments ($p = 0.755$; Table 3-3). There were also no differences in the scores for Shannon-Wiener or Pielou evenness index among the three.

3.3.3 Role of edaphic factors

All contents of soil nutrients were similar among the Rollback, NB and Control treatment (multiple $p > 0.268$; Table 3-5), however total phosphorus tended to be higher in the Rollback than in the Control ($p = 0.054$).

Total plant cover was lower in soil with higher bulk density ($p < 0.001$, $R^2 = 0.188$; Figure 3-2) and wheel rutting ($p = 0.002$; $R^2 = 0.304$; Table 3-6). When splitting it up into life forms, the negative influence of soil bulk density on vegetation cover was strongest in forbs ($p = 0.018$; $R^2 = 0.103$) and graminoids ($p = 0.024$; $R^2 = 0.095$), but not so in shrubs ($p = 0.090$). Total plant cover was positively influenced by slash cover ($p = 0.026$; $R^2 = 0.165$), but not influenced by LFH gouging ($p = 0.489$), subsoil residues ($p = 0.459$) or subsoil thickness ($p = 0.169$; Table 3-6).

Similarly, species richness was reduced by rutting ($p = 0.048$; $R^2 = 0.133$), but not by soil bulk density ($p = 0.177$). Species richness was positively influenced by slash cover ($p = 0.002$; $R^2 = 0.302$) and slightly reduced by subsoil thickness ($p = 0.008$; $R^2 = 0.033$). Species richness was not related to LFH gouging ($p = 0.990$) and subsoil residues ($p = 0.426$) (Table 3-7).

3.4 Discussion

Vegetation response in the Rollback treatment was very different from the recovery in the forest floor protection treatment (NB) and the harvested Control. Total plant cover was only about one sixth and species richness was two thirds of the Control and NB treatments. In the first year 95% of the Rollback area remained barren soil and species assessments indicate a low number of plant species establishing, which had relatively high contribution to relative species cover. The majority of them were early successional forbs which normally establish on disturbed sites after logging and/or burning and have high light requirements. This may suggest that in the first year forbs establish more successfully than shrubs on heavily disturbed industrial sites, which would be the opposite response of natural systems, where aboveground disturbance such as fire typically causes a shift from herbaceous to shrub species (Purdon et al. 2004). Species like *E. angustifolium*, *Mertensia paniculata* (Ait.) G. Don*, V. renifolia, Rubus spp.* and *R. acicularis* might have succeeded in the Rollback, because they are early colonizers of newly-disturbed habitats, with their exposed mineral soil and ample light (Agriculture Canada 2014). *E. angustifolium* and *R. acicularis* could have benefitted from their deep rooting behaviour, which makes them less vulnerable to disturbance (Purdon et al. 2004) and from the fact that their reproduction is stimulated by rhizome cutting and wounding (FEIS - USDA 2014). This would also correspond with the aggressive handling of FF material during the salvage process. Overall, the Rollback treatment represents a very unusual disturbance, because soil salvage moves and dilutes the bud bank, which does not have an analogy in nature. Many understory species found in the NB and Control were completely eliminated in the Rollback treatment, probably due to the change in horizontal soil structure, and deep burial of propagules (Koch et al. 1996). In fact, Mackenzie and Naeth (2010) estimate the loss of emergents in LFH mineral soil mix to be 95% compared to undisturbed LFH.

The understory species which regenerate from shallow roots would likely have been compromised by the salvage process, due to abscission or crushing, which further decreased species diversity. When comparing the response of the two *Vaccinuium* spp. we saw higher frequency of *V. myrtilloides*, but no V. *vitis-idaea* in the Rollback, which suggests that deeper roots of *V. myrtilloides* survived the soil mixing. Also, the lack of an intact organic layer reduces water retention (Gupta and Larson 1979), so the absence of bog cranberry (*V. vitis-idaea*) in Rollback plots may indicate that soil conditions could have been too dry for such a hydrophilic species to emerge. Dilution or loss of forest floor, which would hold the majority of propagules, was likely the main reason for poor regeneration performance in the Rollback treatment. Species such as Labrador tea which is normally present in a harvested stand, may have failed to regenerate, because they need organic matter, (*L. groenlandicum)*, (FEIS - USDA 2013).

The overwhelming frequency of the seedbank species *Geranium bicknellii* in the Rollback treatment is another indicator for intense disturbance. Since *G. bicknellii* seed endures a long time in the propagule bank, soil moving and mixing helped it to germinate. Similarly, fireweed (*E. angustifolium*) may have regenerated from airborne or buried seed, too (FEIS-USDA 2014). This suggests that species which can regenerate from either seed or rhizomes may be more flexible than highly adapted clonal species requiring either shade or wildfire disturbance. Differences in community structure among Rollback and the other two treatments were mainly driven by *V. americana*, which recovered very well in the Rollback, although it is not clear if from seed or rhizomes *but V. americana* is known to spread vegetatively from creeping rhizomes (FEIS - USDA 2013). It may have a long lasting impact on community development, as it was overgrowing and shading other vegetation in the second year of assessment. The other nitrogen fixing, ranking species that was frequently found in the Rollback, *was L. ochroleucus,* but this species is not considered to be a good competitor (Smreciu et al. 2013).

In comparison, NB and Control treatments had higher cover of both early and late successional species. Plants that are adapted to conditions in intact forest understories (Lieffers 1995) or which have been classified as understory obligates (Craig and Macdonald 2009) were found not only in the Control, but also in the forest floor protection (NB) treatments, including *Cornus canadensis, M. nuda, L. borealis* and *P. asarifolia*. Species such as *V. edule*, *A. nudicaulis* and *R. acicularis* were also frequently found in both treatments and can be associated with a more mature aspen forest (Lieffers et al. 1993, Macdonald and

Fenniak 2007). It is very likely that some disturbance such as LFH gouging in the protected NB treatment created microsites for early successional species, which sprouted vigorously because of the overall forest floor intactness and higher propagule survival. The comparably thin forest floor layer can contain about 73% of all species in the propagule bank (Mackenzie 2013). Additionally, forest floor protection, as well as the Control treatment provided shade and sheltered conditions for true understory species, as the aspen quickly regenerated in these treatments.

Therefore, the understory vegetation found in the NB and Control treatments resembles a more diverse and more typical composition of a young natural aspen stand of the central mixedwood subregion than the Rollback treatment. However, the re-establishing stand might not necessarily have the same species proportions as in the pre-disturbance plant community (Strong 2004). Differences among NB and Control were minimal, but may become more visible in future years. Since the Control did not have LFH gouging it likely had fewer microsites for ruderal species such as *Chenopodium album* or seed bank species such as *Corydalis sempervirens* to establish. On the other hand it retained more slash, which could benefit nutrient cycling in future years.

The understory vegetation in the three forest floor protection treatments did not vary greatly in response to different delineation methods. All treatments retained a fairly intact forest floor, so the only nuances I could detect are likely attributable to LFH gouging, which provided some regeneration microsites. Therefore, the NB may have had *C. album, Galium boreale, G. triflorum* and *Taraxacum officinale.* However, it was rather interesting that clover was found in FR and GT, but not in the NB treatment. This could be attributable to higher foot traffic on these sites and movement of seeds stuck to boots. Slight differences among the three forest floor protection treatments were visible shortly after reclamation of the GT treatment, which had retained significant plant cover over the winter. The GT might have had the best survival of plants, especially shallow rooted and creeping species, as its surface was not scraped, because the textile was simply pulled back in the final stages of removing the subsoil to uncover the forest floor.

Overall, the use of subsoil as a buffer over the forest floor worked well and did not seem to influence vegetation recovery, even without extra delineation (NB). Only in subplots with very thick application (> 2 m) the increases in soil bulk density lead to reduced plant cover. Since wheel rutting showed similarly strong effects on plant cover, I assume that soil compaction occurring from machine traffic prior to forest floor protection is more damaging to the propagule bank than subsoil loading. Soil compaction reduces air-filled porosity, which is hypothesized to restrict soil aeration, change soil morphology and water retention (Startsev and McNabb 2009). Maintaining an aerobic soil environment requires sufficient air-filled pore space to allow soil gas exchange with the atmosphere, while changes in any one of these factors can shift the balance for normally aerobic sites to one that is anaerobic (Startsev et al. 1998). This could have implications for propagule viability, germination and root growth. Mechanical impedance, soil water loss and poor aerations increases with bulk density and decrease root growth in seedling plants (Eavis 1972).

As most of the surface of the Rollback treatment remained barren after a full growing season, it poses a higher risk of erosion compared to Control and forest floor protection treatments and might require further monitoring. Apart from erosion, little ground cover in the Rollback treatment may also increase the likelihood of wind-blown exotic species invading (Hobbs and Huenneke 1992). In conclusion, salvage and rollback is not the optimal reclamation technique for OSE drilling pads, if there is a possibility to leave the original forest floor undisturbed and therefore obtain greater plant recovery. Forest floor protection in places that do not require leveling can help reduce the loss of FF material, viable propagules and increase understory plant regeneration.

3.4.1 Management implications

My study shows that forest floor protection provides an opportunity for rapid recovery of many boreal plant species, with high total cover compared to the current approach of complete FF salvage and rollback. These findings could have implications for all OSE sites in the boreal landscape, since understory restoration is not confined to mixedwood or aspen dominated stands. The benefits of forest floor protection are likely also applicable to other upland forest types and could be attained without a change in methodology.

The salvage and Rollback operations in my study may have been superior to most operational reclamation (see Appendix) because the stripping of the organic layer and topsoil layers was done in one pass rather than stripping layer by layer. This likely reduced the overall damage to roots and rhizomes. Furthermore, in these pads the topsoil was carefully stockpiled immediately adjacent to the site and stored only briefly.

Since there were no major differences among the three forest floor protection treatments, the least work-intensive technique using no barrier or special techniques for delineation of subsoil from the forest floor may be favorable to use in the future, provided that there is snow on the ground and that operators are well-trained. During re-contouring of the natural grade on site, the final dumping of the organic and topsoil mix should be done in a single pass and left rough, thereby enabling seeds to remain in place longer than on a smooth surface. This also improves water infiltration and nutrient retention. Therefore, no further earthwork to compact or smooth the re-contoured drilling pad should be carried out.

3.5 References

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Tables

Table 3-1. Mean cover (%) of lesser vegetation (all except trees) in relation to treatments.

Data are further organised by functional groups. Means (± S.E.) with different letters indicate statistically significant differences (α=0.05). None of the ANOVAS for forest floor protection treatments returned significant results and are not presented.

	Control	Rollback	No Barrier	Freezing	Geotextile
Total	28.4_{A} (1.2)	4.6_{B} (0.2)	30.7_{A} (1.3)	30.2 (1.0)	34.7 (2.1)
By life forms:					
Shrubs	5.5_{A} (1.5)	0.4_{B} (0.1)	8.2_{A} (1.7)	5.6 (0.9)	6.0 (1.3)
Forbs	16.6_{A} (2.6)	4.0_{B} (0.5)	17.5_{A} (2.6)	18.3 (3.6)	21.1 (2.4)
Graminoids	6.3_{A} (1.5)	0.2_{B} (0.1)	5.1_{A} (1.1)	6.3 3.0)	7.5 (1.2)

Table 3-2. Species cover (%) per treatment in relation to recovery treatments.

Means with different letters indicate statistically significant differences (α=0.05). None of the ANOVAS for forest floor protection treatments returned significant results and are not presented. Species with less than 0.1% cover in every treatment are excluded. Nomenclature follows Moss (1994).

	Control	Rollback	No Barrier	Freezing	Geotextile
Aralia nudicaulis	0.4	<0.1	<0.1	0.2	0.2
Betula papyrifera	<0.1	0	<0.1	0.2	0
Calamagrostis canadensis	4.6_{A}	0.1_{B}	2.1_{AB}	2.7	5.8
Cornus canadensis	2.9_{A}	0_{B}	3.9_{A}	3.3	4.0
Elymus innovatus	1.7_{A}	0_{B}	3.0_{A}	3.6	1.7
Epilobium angustifolium	7.9_{A}	0.8_{B}	6.6_{A}	7.3	8.0
Fragaria virginiana	0.1	<0.1	0.3	<0.1	0.1
Galium boreale	<0.1	0	0.1	0	0
Geranium bicknellii	<0.1	0.7	0.7	0.4	0.2
Lathyrus ochroleucus	1.3	0.9	1.7	2.4	2.4
Ledum groenlandicum	0.1	0	0.5	0.1	0.2
Linnaea borealis	0.5	0	0.4	0.3	0.8

Lonicera involucrata	<0.1	0	0	0.1	0
Lycopodium annotinum	0.3	0	0.3	0.1	0.2
Maianthemum canadense	0.1	<0.1	0.1	0.1	0.1
Mertensia paniculata	0.5	0.1	1.4	0.9	0.9
Mitella nuda	0.2	<0.1	0.2	0.1	0.3
Petasites palmatus	1.0	<0.1	0.7	1.9	1.6
Picea glauca	0.5	<0.1	<0.1	0.1	<0.1
Populus balsamifera	<0.1	<0.1	0.1	<0.1	<0.1
Populus tremuloides	$13.6_{\mathbf{A}}$	$0.3_{\mathbf{B}}$	$18.7_{\mathbf{A}}$	15.5	16.1
Pyrola asarifolia	0.1	<0.1	<0.1	<0.1	<0.1
Rosa acicularis	$3.8_{\mathbf{AB}}$	$0.4_{\mathbf{B}}$	$5.2_{\mathbf{A}}$	4.4	3.6
Rubus idaeus	0.4	<0.1	0.5	0.1	0.1
Rubus pubescens	0.6	<0.1	0.2	0.6	1.0
Salix sp.	0.5	<0.1	<0.1	<0.1	0.1
Symphyotrichum ciliolatum	0.4	0.1	0.2	0.3	0.2
Trientalis borealis	0.1	<0.1	0.2	0.1	0.1
Trifolium pratense	0	0	0	<0.1	0.2
Vaccinium myrtilloides	0.5	<0.1	0.5	0.6	1.0
Vaccinium vitis-idaea	0.1	0	0.1	<0.1	0.1
Viburnum edule	$0.7_{\mathbf{AB}}$	$<0.1_{\mathbf{B}}$	$1.4_{\mathbf{A}}$	0.3	0.8
Vicia americana	$0.3_{\mathbf{B}}$	$1.3_{\mathbf{A}}$	$0.2_{\mathbf{B}}$	0.1	0.7
Viola renifolia	0.1	<0.1	0.1	0.1	0.2

Table 3-3. Species diversity and evenness calculated from mean vegetation cover in relation to recovery treatments.

Means (± S.E.) with different letters indicate statistically significant differences (α=0.05). None of the ANOVAS for forest floor protection treatments returned significant results and multiple comparisons are not presented.

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Species richness	$28_{\mathbf{A}}$ (1.1)	$19_{\mathbf{B}}$ (0.7)	$27.7_{\mathbf{A}}$ (1.2)	27.3 (1.3)	27.2 (1.6)
Shannon diversity	2.0 (0.1)	1.9 (0.1)	2.1 (0.1)	2.1 (0.1)	2.1 (0.1)
Pielou evenness	0.6 (<0.1)	0.7 (<0.1)	0.6 (<0.1)	0.6 (<0.1)	0.6 (<0.1)

Table 3-4. Frequency (%) of common plant species in relation to recovery treatments.

Means (± S.E.) with different letters indicate statistically significant differences (α=0.05). None of the ANOVAS for forest floor protection treatments returned significant results and are not presented. Nomenclature follows Moss (1994).

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Aralia nudicaulis	24 (13)	4 (3)	7 (3)	17 (12)	21 (7)
Betula papyrifera	0	0	0	1 (1)	0
Calamagrostis canadensis	53_{A} (11)	17_{B} (4)	35_{AB} (9)	38 (8)	46 (13)
Cornus canadensis	99_{A} (1)	4_{B} (3)	94_{A} (3)	94 (3)	93 (4)
Elymus innovatus	36_{AB} (13)	17_{B} (4)	58_{A} (10)	50 (10)	33 (9)
Epilobium angustifolium	82 (7)	75 (8)	71 (12)	74 (14)	83 (9)
Equisetum arvense	1 (1)	0	1 (1)	4 (3)	1 (1)
Fragaria virginiana	7 (6)	4 (3)	13 (9)	1 (1)	4 (3)
Galium boreale	3 (2)	0	3 (3)	0	0
Geranium bicknellii	39_{B} (10)	99_{A} (1)	50_{B} (6)	35 (7)	42 (7)
Lathyrus ochroleucus	68 (8)	92 (2)	82 (9)	85 (5)	85 (5)
Ledum groenlandicum	6 (3)	0	17 (8)	15 (8)	18 (10)
Linnaea borealis	47_{A} (7)	0_{B}	51_{A} (7)	57 (6)	58 (5)
Lonicera involucrata	0	0	0	1 (1)	0
Lycopodium annotinum	25_{A} (8)	0_{B}	25_{A} (11)	25 (9)	29 (6)
Lycopodium obscurum	11 (5)	0	1 (1)	0	10 (5)
Maianthemum canadense	54_{A} (10)	1_{B} (1)	39_{A} (12)	50 (11)	46 (10)
Melilotus officinalis	0	1 (1)	0	1 (1)	1 (1)
Mertensia paniculata	39 (12)	46 (14)	44 (15)	42 (14)	29 (12)
Mitella nuda	35_{A} (11)	1_{B} (1)	40_{A} (14)	38 (11)	42 (12)
Petasites palmatus	56_{A} (11)	17_{B} (7)	56_{A} (13)	64 (12)	69 (6)
Picea glauca	3 (2)	0	1 (1)	1 (1)	0
Populus balsamifera	3 (2)	1 (1)	7 (3)	3 (3)	1 (1)
Populus tremuloides	94_{A} (4)	54_{B} (8)	94_{A} (3)	100 (<1)	96 (3)
Pyrola asarifolia	18 (5	4 (3)	8 (3)	4 (2)	7 (3)
Ribes triste	0	0	1 (1)	0	1 (1)

Rosa acicularis	54 (16)	60 (8)	68 (13)	63 (13)	67 (10)
Rubus idaeus	24 (5)	10 (4)	21 (7)	7 (4)	8 (4)
Rubus pubescens	18 (11)	11 (5)	10 (6)	15 (5)	8 (8)
Salix sp.	3 (2)	0	0	1 (1)	1 (1)
Symphyotrichum ciliolatum	11 (7)	10 (5)	13 (8)	17 (5)	11 (4)
Taraxacum officinale	1 (1)	0	0	0	0
Trientalis borealis	$64_{\mathbf{A}}$ (9)	$25_{\mathbf{B}}$ (10)	$58_{\mathbf{A}}$ (9)	56 (13)	67 (10)
Trifolium hybridum	1 (1)	0	0	0	0
Trifolium pratense	0	0	0	0	2.8 (2.8)
Vaccinium myrtilloides	29 (14)	18 (9)	35 (16)	32 (16)	36 (16)
Vaccinium vitis-idaea	$28_{\mathbf{A}}$ (7)	$0_{\mathbf{B}}$	$25_{\mathbf{A}}$ (11)	22 (11)	40 (13)
Viburnum edule	$36_{\mathbf{A}}$ (6)	$4_{\mathbf{B}}$ (3)	$44_{\mathbf{A}}$ (8)	38 (10)	39 (4)
Vicia americana	$14_{\mathbf{B}}$ (5)	$81_{\mathbf{A}}$ (7)	$31_{\mathbf{B}}$ (12)	26 (7)	28 (13)
Viola renifolia	43 (9)	28 (7)	43 (4)	42 (6)	54 (7)

Table 3-5.Mean soil nutrient content (± S.E.) in relation to recovery treatments.

None of the ANOVAS returned significant results and are not presented.

	Control	**Rollback**	**No Barrier**
PO4-P (mg/kg)	7.7 (0.8)	11.9 (1.8)	11.0 (2.4)
NH4-N (mg/kg)	3.2 (1.1)	2.3 (0.1)	2.1 (0.3)
NO3-N (mg/kg)	1.6 (0.2)	2.1 (0.3)	1.7 (0.3)
K (mg/kg)	92.3 (11.8)	96.6 (5.9)	376.2 (267.7)
TN (wt%)	1.08 (0.27)	1.49 (0.16)	1.51 (0.37)
TP (mg/Kg)	77.3 (9.1)	148.1 (13.3)	124.2 (35.6)
TOC (mg/kg)	417.5 (85.4)	605.2 (64.5)	616.5 (140.2)

Table 3-6. Linear regression analyses for plant cover in relation to edaphic factors.

Data were from averaged treatment plots, except for subsoil thickness (subplots).

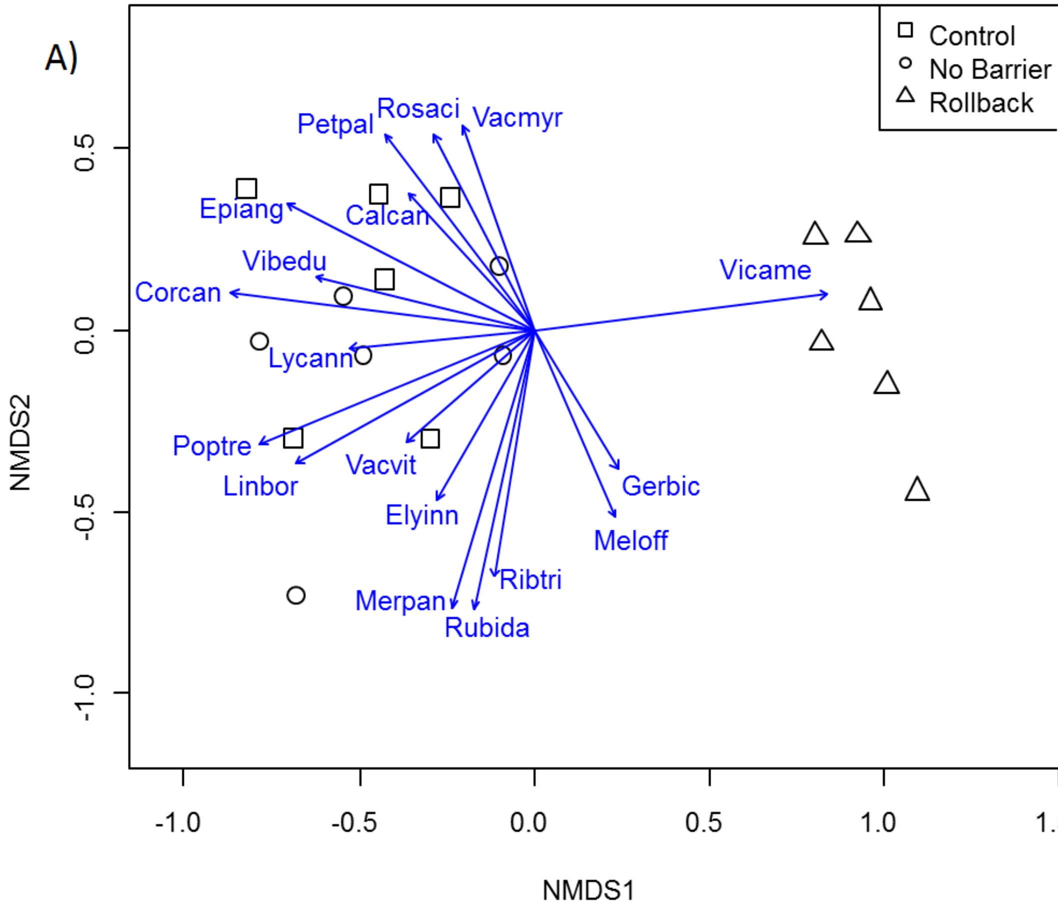
	n	p	R^2	equation
Bulk Density	86	<0.001	0.188	y = -55.645x + 121.28
LFH gouging	24	0.489	0.022	y = 6.9398x + 28.936
Rutting	30	0.002	0.304	y = -31.111x + 37.223
Slash cover	30	0.026	0.165	y = 0.4522x + 14.531
Subsoil residues	24	0.459	0.025	y = -0.1595x + 32.248
Subsoil thickness	86	0.169	0.009	y = -0.0557x + 37.443

Table 3-7. Linear regression analyses for species richness in relation to edaphic factors.

Data were from averaged treatment plots, except for subsoil thickness (subplots).

	n	p	R^2	equation
LFH gouging	24	0.990	0.000	y = 0.0464x + 27.528
Rutting	30	0.048	0.133	y = -6.9664x + 28.407
Slash cover	30	0.002	0.302	y = 0.2072x + 20.702
Subsoil residues	24	0.426	0.029	y = -0.0608x + 28.01
Subsoil thickness	86	0.008	0.033	y = -0.0183x + 13.467

Figures


A)
Control
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Rollback
Petpal
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Calcan
Vibedu
Corcan
Vicame
Lycann
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Vacvit
Elyinn
Gerbic
Meloff
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Merpan
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NMDS2
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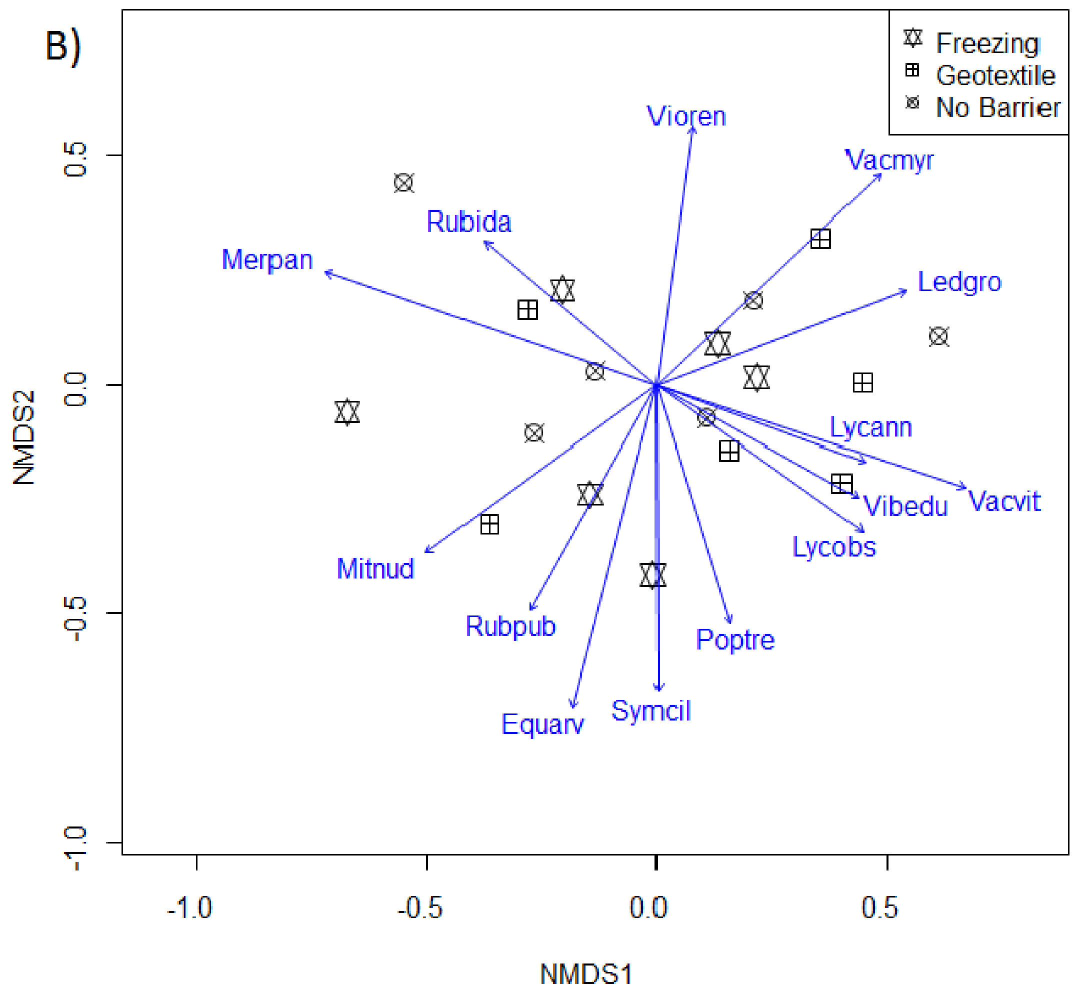

Figure 3-1. Non-metric multidimensional scaling (NMDS) analysis of plant community structure among the A) three main and B) three forest floor protection treatments.

Ordination of treatment plots is most affected by species with longer arrows.

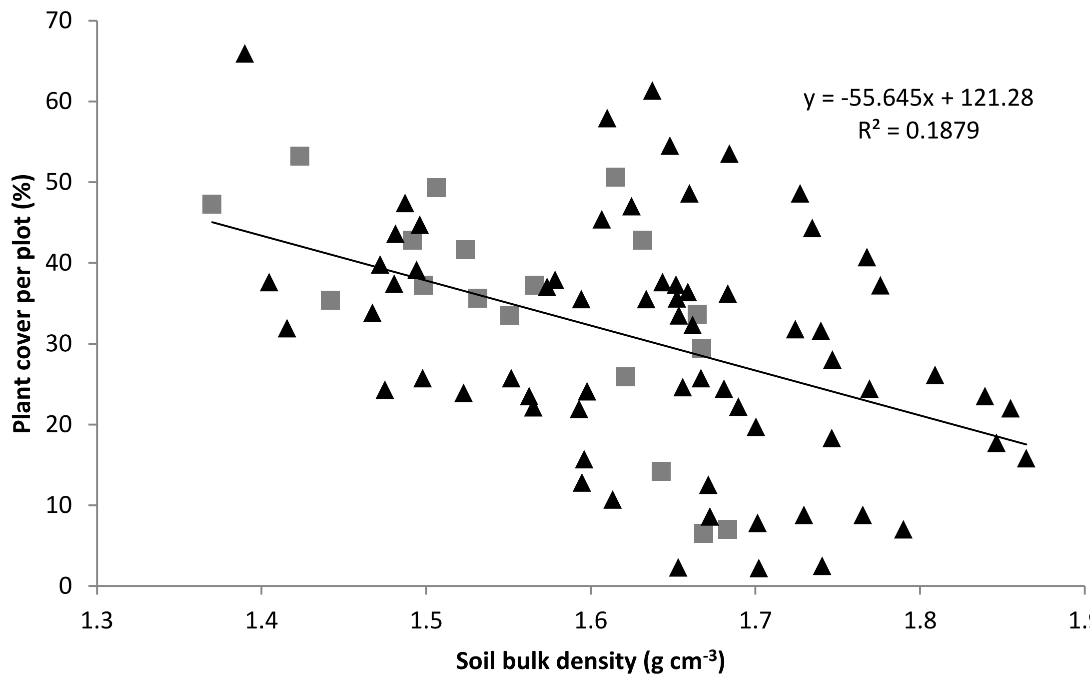

Figure 3-2. Lesser vegetation cover in relation to soil bulk density in the Control and No Barrier treatment.

Black data points (triangles) represent subplots in the NB treatment and grey data points (cubes) represent subplots in the Control treatment (n=86).

Chapter 4. Summary and study impact

4.1 Study summary

The goal of this project was to investigate the acceleration of forest restoration on temporary drilling pads in boreal upland sites by taking advantage of the clonal regeneration potential of trembling aspen (*Populus tremuloides*) and associated understory plants from roots and rhizomes. I wished to test if it is better to keep the propagule bank in place compared to removal, storage and replacement. Therefore, I examined techniques for protecting the original forest floor (covering with subsoil) and compared it to and the current standard of stripping off the forest floor and placing it back on the site after re-contouring (Rollback), as well as operational clear-cut logging (Control). Further, approaches using geotextile cloth or water application to freeze the forest floor were tested to delineate subsoil from forest floor. After reclamation and soil placement, I assessed the extent of surface disturbance, woody debris, soil temperature, soil bulk density, as well as the aspen regeneration and understory plant cover and richness.

Aspen suckers were tallest, had the highest density and had better survival in the system that protected the forest floor compared to the standard Rollback treatment. In the protected sites, as well as the delineated original forest floor I detected little impact of soil compaction and found only moderate soil surface disturbance with no detrimental effect on the aspen regeneration. In the first year of assessment, there were more than 10 times as many aspen suckers in the No Barrier (NB) forest floor protection plots and these were at least three times as tall as in the Rollback plots, which is the current approach for reclaiming the entire pad. Further, the density of aspen suckers on the forest floor protection exceeded the density of the Control by ~ 30,000 stems ha^{-1}. Both trends continued on in the second year of assessment.

Total understory plant cover in the Rollback was only about one sixth and species richness was two thirds of the Control and NB treatments. In the first year 95% of the Rollback area remained barren soil and species assessments indicate a low number of plant species establishing, which had relatively high contribution to relative species cover. Many understory species found in the NB and Control were completely eliminated in the Rollback treatment, probably due to the change in horizontal soil structure, and deep burial of propagules (Koch et al. 1996). Dilution of forest floor, which would hold the majority of propagules, was likely the main reason for poor regeneration performance in the Rollback treatment. In fact, Mackenzie and Naeth (2010) estimate the loss of emergents in LFH mineral soil mix to be 95% compared to undisturbed LFH. It is likely that some disturbance such as LFH gouging in the protected NB treatment created microsites for early successional species, which sprouted vigorously because of the overall forest floor intactness and higher propagule survival. Therefore, the understory vegetation found in the NB and Control treatments resembles a more diverse and more typical composition of a natural aspen stand of the central mixedwood subregion than the Rollback treatment.

It is clear that protection of forest floor during the winter construction of OSE pads allows for a rapid recovery of aspen forests comparable to forest regeneration following clearcut logging. However, overall vegetation recovery in the three forest floor protection treatments did not vary greatly in response to different delineation methods. All of these treatments retained a fairly intact forest floor, so the only detectable nuances are likely attributable to LFH gouging. The results also indicate an adverse effect of soil salvage and Rollback on vegetation recovery compared to the harvested, as well as the forest floor protected treatment. In fact, the simple protection treatment without delineation (No Barrier) was very similar to the Control in terms of its plant community and even surpassed it in the density and leader height of aspen suckers. This proves that forest floor protection was beneficial in maintaining the aspen root system alive, both during site leveling and trafficking, whereas it was heavily compromised during the soil salvage process. This also applies to other plant propagules, since the great majority of plant species from the Control were found in the forest floor protection treatment, too.

It is useful to remember that the ecology of boreal forest regeneration is linked to stand replacing fires, which often take out the aboveground plant organs, but leave roots and rhizomes in place. Many plants of the boreal have therefore developed vegetative regeneration strategies. Once we can protect the vegetative propagules in the forest floor, surface disturbance such scraping from a back hoe might not have detrimental effects. In terms of aspen regeneration LFH scraping (gouging) increased suckering, which might be related to temperature increases and hormonal stimulation as a result of wounding (Perala 1990, Bulmer et al. 1998). An edaphic factor that will be important to monitor is soil bulk density, as it reduced understory plant cover and is known to negatively affect aspen growth (Landhäusser et al. 2003). Since the Rollback treatment was not different in its soil nutrient levels compared to Control or forest floor protection treatment, poor regeneration is likely driven by propagule mortality due to heavy fragmentation as observed in the field and/or deep burial due to heavy admixing.

The results from this study provide evidence for the benefits of forest floor protection and clearly suggest a change to the current OSE drilling pad approach. Especially the reduced need for human intervention, be it seeding or planting, is an enormous improvement, as ecosystem processes will initiate and maintain stable plant communities which are themselves more resilient to environmental stresses.

4.1.1 Limitations

Although replicated six times, all sites were in close proximity to each other which limits statistical inferences to the study area. It would be desirable to disperse test sites over a greater area, but this was not economically feasible and should be achieved through sampling future operational sites.

The study design confined the results of subsoil thickness, however it would have been interesting to look more carefully at possible compaction effects on slope positions with very little subsoil thickness, respectively 0-40cm depth. This might yield results of subsoil with insufficient thickness to act as a machine-traffic buffer (whereas in my study it clearly worked and I concentrated on the compaction effect of the subsoil itself on original forest floor). This study also did not specifically measure salvage or application depth of FF material, although I advised operators to salvage a predetermined depth (20cm) which was based on soil pit assessments and included the zone of major lateral aspen roots.

Also, soil temperature should have been measured throughout spring, because later thawing in the freezing treatment or plots with greater slash loading could have interfered with both germination and sprouting.

Lastly, the interpretation of understory vegetation recovery is only based on the assessment of first year recovery data. It is likely that cover will increase, whereas richness might decrease in subsequent growth periods. This trend was only observed in the second year, yet it would be desirable to monitor future plant species composition and species invasion, especially in the Rollback. An assessment of bryophyte and lichen recovery would have rounded out the dataset for biodiversity.

4.2 Application for reclamation

Forest floor protection should be used in OSE reclamation wherever terrain slope permits, because successful natural regeneration which recovers desirable native plants will obviate a long chain of re-vegetation practices such as tree nursery care, transportation, seeding and planting. In fact, most species in the forest floor propagule bank are currently not commercially available (Naeth et al.

2013), so it is only advantageous in order to recreate a “locally common boreal forest, integrated with the surrounding area… both in its appearance and ecological function” (Cumulative Environmental Management Association 2006). In regards to understory plant regeneration, the forest floor protection approach is not limited to aspen dominated stands, as the benefits of protecting the bud bank are also very applicable to the majority of boreal understory species.

To initiate this approach as early as possible I recommend revising harvesting techniques and attitude towards forest floor protection on these very small cutting units. Machine traffic from skidders, and the skid-turning of feller bunchers is especially damaging to roots and soil and the planners should consider this in the layout of entry roads, skidding directs and decking of wood. Backing-up of bunchers and skidders should be done if it can avoid turns. In order to minimize machine traffic on future protection areas, construction consultants must clearly communicate to harvest crews that lower slope position of the pad are of significant importance to forest floor protection and require special attention. Access roads should be placed to connect the pad on the future cut side, rather than on the lower forest floor protection site. If trees are allotted to be hauled away rather than using them in reclamation, the log deck should not be placed on top of the forest floor protection areas. Another option to reduce the impact from harvesting, specifically compaction, is to use many track-equipped machines, while keeping the amount of turning to a minimum. Distributing unmerchantable slash into areas of machine traffic can further aid to prevent compaction (David et al. 2001), while treetops of serotonous species can additionally increase seed availability on the disturbed site. Optimally, harvesting should occur in frozen conditions, since it minimizes the impact on soil bulk density (Bates et al. 1993) and also protects roots close to the surface from wounding (Renkema et al. 2009). Contractors, such as logging companies must be involved and instructed to reduce machine traffic on future protection sites. Supervisors have to accept further time investment for more site specific meetings to address local terrain considerations (optimal placement of cut and fill areas) and soil conditions.

Since many OSE pads are drilled each winter, which may be in close proximity to each other, the next step will be to consider trucking in subsoil in order to protect the forest floor on more level sites or expand the amount of protection on sloped sites. This way less FF material will have to be cut in order to level the lease. If subsoil application from adjacent pads or borrow pits will be implemented, additional planning will be required to effectively manage the supply chain. Commitment to educate consultants, foremen and operators about the benefits of forest floor protection and increase motivation to skillfully work around such vital but thin layer of soil is needed.

Alternatively, snow could be used to level and build the pad (Osko and Glasgow 2010) or possibly the pad could be produced in several stepped layers. Since my results had the forest floor delineated by 30 cm of snow on the ground, I recommend to make snow if necessary or to freeze in the forest floor to ease the operators work in finding this layer later on. Where FF salvage is inevitable, direct transfer of FF onto a nearby already-recontoured drill pad may reduce the storage impact, loss of propagules (Fair 2012) and improve vegetation re-establishment (Mackenzie and Naeth 2010, Wachowski 2012). Direct placement may yield more than 60% of the species from pre-disturbance state returning in the first year (Fair 2012).

Salvage depth of the FF must be adjusted to onsite soil conditions and should be determined based on assessment of forest floor and aspen rooting depth by digging several soil pits. Sufficient surface soil should be salvaged to include all LFH, A and upper B mineral soil, but avoid heavy clay (Bt). This should include the zone of lateral roots to minimise propagule damage. Salvage depth must not exceed 40cm to avoid excess propagule dilution.

Operationally, salvaging only the upper most soil is not cost effective in most ecosites, and admixing mineral soil may enhance reclamation material by improving soil physical and chemical properties (Naeth et al. 2013). The amount of mineral soil acceptable or ideal is not known, yet greater salvage depth will significantly increase dilution of the propagule bank (Tacey and Glossop 1980, Iverson and Wali 1982, Rokich et al. 2000).

Placement depth should be determined in relation to the amount of soil material available. It may be spread as thin as 10 cm and still provide a deep enough rooting medium, as well as sufficient water and nutrient holding capacity to facilitate plant establishment (Naeth et al. 2013). Most seeds and vegetative propagules will not be buried too deeply to germinate or sprout and emerge. If stored, FF should only be stockpiled for short time, because conditions inside the pile will ultimately promote decomposition, anaerobic conditions and in situ germination that can lead to propagule death, especially in warm and moist condition (Rokich et al. 2000). Stockpiling FF material with a high percentage (50%) of mulched woody debris in small stockpiles or windrows for a short period of time (< 2 months) can substantially reduce native plant establishment (Naeth et al. 2013). FF material should not be stockpiled where it could be driven over, spread out, mixed or permanently buried.

After drilling operation is finished, operators recontouring the pad to natural grade must be aware of where the forest floor layer is and the need to minimize its disturbance. They should be able to detect the transition between subsoil and forest floor either by snow or observations of the litter and slash material in this narrow zone. On the other hand, they have to make sure to remove as much subsoil as possible, even if they leave a few gouges in the forest floor. In this study track hoes were used, which have better depth control than dozers and do not have to drive over the forest floor. Further, with their large clean-up buckets they were able to pick up and deposit the subsoil upslope. On operational drilling pads I observed that if lower positions are not reclaimed to allow appropriate drainage of surface water they are prone to flooding killing much of the mesic vegetation.

When re-placing the subsoil upslope, it is important to minimize the compaction of the subsoil. Many bulldozer operators compact such areas as a standard operation and this behaviour must be reversed. Further, after spreading of salvaged FF materials as the final step in reclamation, surface smoothing and compacting (treading-in) the surface soil should be avoided, too. Plant establishment is normally enhanced on rough versus smooth surfaces (Naeth et al. 2013), because greater roughness enables seeds to remain in place longer than on a smooth surfaces, which enables them to imbibe moisture for a longer time and provided a site for retaining nutrients (Johnson and Fryer 1992). Trees available for reclamation can be distributed as whole logs rather than chipped or mulched debris, as mulch can be detrimental to soil thermal conditions, the C:N ratio and plant recruitment (ASRD 2007).

To increase the amount of forest floor protection and make full use of its ability to quickly restore tree and understory cover I suggest, that if possible to place drilling pads on sites with uniform slopes. Sites with patchy switchbacks of elevation are difficult to plan for and implement forest floor protection in an effective manner. Since I placed great emphasis on aspen and their roots system for reclamation, it would also be beneficial to try selecting leases according to their tree composition. However, one will have to consider that forest floor protection may not yield expected results in old aspen stands that are in the dieback and breakup phase (Frey et al. 2004).

4.2.1 Costs considerations

Cost savings with forest floor protection could be achieved by reducing propagule disturbance, which will result in overall lower cost and less time to achieve recovery of OSE sites. In fact, Osko and Glasgow (2010) state that the costs of building what they call low disturbance pads are lower than in a standard cut and fill operation. From my observations and sampling of older OSE drill pads, which were built using only FF salvage, I found that many pads had no natural recovery. They will ultimately need to be replanted in order grow any vegetation, which would bring along extra cost in buying tree stock and hiring planting crews. Planting shock and associated mortality may result in not meeting reclamation criteria. Since the equipment needed to carry out forest floor protection will be no different than the usual reclamation crew, no extra planning effort or hiring will be necessary compared to contracting tree planting crews. Further, natural recovery via forest floor protection will add value to biodiversity and restore ecosystem functions beyond price, as well as time savings to earn a reclamation certificate.

4.3 Future research needs

In general, future investigations could explore the role of forest floor protection in other upland forest types to evaluate specifically the success of vegetative understory restoration.

More research is needed to investigate the possibilities of revegetating both new and old rollback sites. Since lateral aspen roots from adjacent stands may extend for more than 30 m into an open area (Strong and La Roi 1983a,b) such as an exploration pad, they could be useful for reclaiming old drilling pads. One may consider hydraulic root excavation (see DesRochers and Lieffers 2001) to test if aspen trees on the edge actually grew roots into the reclaimed drill pad. If so, ripping at the edges to initiate suckering could be tested.

On newly developed drilling pads, stockpile conditions such as soil moisture and temperature inside the pile, as well as close to the surface should be compared to understand if such factors possibly influence propagule depletion. Determining the exact cause of loss in seed viability would help determine more feasible methods for constructing stockpiles that maintain seed viability (MacKenzie 2013). Further, measuring root fragmentation would have been an interesting variable to look at in my study, because common sense suggests that roots in the Rollback treatment were severely fragmented due to the soil stripping. On rollback sites soil moisture should also be monitored throughout the growing period, in order to study if soil mixing affected water holding capacity.

Secondly, the suggested stimulative effect of smoke water (smoke dissolved in water) on germination of seeds in salvaged soil may help to make better use of the diluted propagule bank. Such application to the reclaimed soils may also enhance re-establishment of indigenous plant species in a way similar to the role of smoke in the ecosystem after wildfire disturbance (Anyia and Easterbrook 2005, Mackenzie 2013).

Finally, the importance of careful logging procedures on OSE drilling pads should be investigated further. Identifying the specific impacts of machine traffic during site harvesting could be helpful in explaining poor regeneration in relation to soil compaction. Experiments to address protection measures during the logging of stands in non-frozen conditions should be carried out.

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Appendices

Table A1. Mean soil moisture content (%) in 10cm depth among selected recovery treatments. Means (± StDev) with different letters indicate statistically significant differences (α=0.05).

Volumetric soil moisture content	Control	Rollback	No Barrier
Mean	$10.3_{\mathbf{b}}$ (1.7)	$18.5_{\mathbf{a}}$ (3.0)	$10.6_{\mathbf{b}}$ (1.7)
Maximum	$13.0_{\mathbf{b}}$ (1.0)	$29.1_{\mathbf{a}}$ (4.3)	$13.1_{\mathbf{b}}$ (1.5)
Minimum	$5.5_{\mathbf{b}}$ (2.2)	$11.2_{\mathbf{a}}$ (3.0)	$6.6_{\mathbf{b}}$ (1.9)

Table A2. Comparison of mean subsoil loading and traffic associated compaction (± StDev) among slope positions in FF protection sites.

Slope position (m)	Subsoil loading (cm)	Compaction (cm)	Compaction factor (%)
- 4	73.8 (16.1)	7.7 (2.8)	10.4
- 8	95.0 (23.8)	8.0 (3.1)	8.4
- 12	112.1 (31.8)	8.1 (2.5)	7.2
- 16	124.6 (48.0)	8.9 (3.6)	7.1
Total mean		**8.2 (3.0)**	**8.3**

Table A3. Complete species listing and presence in relation to recovery treatments.

Species	Control	Rollback	No Barrier	Freezing	Geotextile
Actaea rubra	x		x		
Amelanchier alnifolia			x		
Aralia nudicaulis	x	x	x	x	x
Betula papyrifera	x		x	x	
Calamagrostis canadensis	x	x	x	x	x
Chenopodium album			x		
Cornus canadensis	x	x	x	x	x
Corydalis sempervirens			x	x	x
Elymus innovatus	x	x	x	x	x
Epilobium angustifolium	x	x	x	x	x
Equisetum arvense	x		x	x	x
Fragaria virginiana	x	x	x	x	x

Galium boreale	x		x		
Galium triflorum			x		
Geranium bicknellii	x	x	x	x	x
Hieracium umbellatum	x			x	
Hylocomium splendens	x		x	x	x
Lathyrus ochroleucus	x	x	x	x	x
Ledum groenlandicum	x	x	x	x	x
Linnaea borealis	x		x	x	x
Lonicera involucrata	x			x	
Lycopodium annotinum	x		x	x	x
Lycopodium obscurum	x		x	x	x
Maianthemum canadense	x	x	x	x	x
Melilotus officinalis		x		x	x
Mertensia paniculata	x	x	x	x	x
Mitella nuda	x	x	x	x	x
Petasites palmatus	x	x	x	x	x
Picea glauca	x	x	x	x	x
Pleurozium schreberi	x		x	x	x
Populus balsamifera	x	x	x	x	x
Populus tremuloides	x	x	x	x	x
Pyrola asarifolia	x	x	x	x	x
Ribes oxyacanthoides			x		x
Ribes triste			x	x	x
Rosa acicularis	x	x	x	x	x
Rubus idaeus	x	x	x	x	x
Rubus pubescens	x	x	x	x	x
Salix sp.	x	x	x	x	x
Sanionia uncinata			x		x
Symphyotrichum ciliolatum	x	x	x	x	x
Taraxacum officinale	x		x		
Trientalis borealis	x	x	x	x	x
Trifolium hybridum	x				
Trifolium pratense				x	x
Vaccinium myrtilloides	x	x	x	x	x
Vaccinium vitis-idaea	x		x	x	x
Viburnum edule	x	x	x	x	x
Vicia americana	x	x	x	x	x
Viola renifolia	x	x	x	x	x

Table A4. Projected ground cover of sampled vegetation by cover classes in relation to recovery treatments.

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Forbs	4	2	4	4	4
Graminoids	3	p	3	3	3
Shrubs	3	p	3	3	3
Trees	4	p	4	4	4

Table A5. Cover classes adapted from Daubenmire (1959) and Braun-Blanquet (1932) with conversion to midpoint values (%).

Daubenmire Reference	Cover class	Range of cover (%)	Midpoint value (%)
5 & 6	7	75-100	87.5
4	6	50-75	62.5
3	5	25-50	37.5
2	4	10-25	17.5
2	3	5-10	7.5
1	2	3-5	4.0
1	1	1-3	2.0
1	p	<1	0.1

Table A6. Composition (%) of vegetation cover according to life history.

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Annuals/Biennials	0.05	0.07	0.05	0.07	0.07
Perennials	0.95	0.93	0.95	0.93	0.93

Table A7. Composition (%) of vegetation cover according to original distribution.

	Control	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Invasives	0.000	0.001	0.000	0.000	0.003
Natives	1.000	0.999	1.000	1.000	0.997

Table A8. Species relative cover (composition) per treatment.

Species	**Control**	**Rollback**	**No Barrier**	**Freezing**	**Geotextile**
Actaea rubra	<0.1	<0.1	<0.1	<0.1	<0.1
Amelanchier alnifolia	<0.1	<0.1	<0.1	<0.1	<0.1
Aralia nudicaulis	1.0	0.6	0.1	0.4	0.4
Betula papyrifera	<0.1	<0.1	<0.1	0.5	<0.1
Calamagrostis canadensis	10.6	3.0	4.2	5.9	11.3
Chenopodium album	<0.1	<0.1	<0.1	<0.1	<0.1
Cornus canadensis	6.6	0.1	7.8	7.2	7.8
Corydalis sempervirens	<0.1	<0.1	<0.1	<0.1	<0.1
Elymus innovatus	4.0	0.9	6.0	7.8	3.4
Epilobium angustifolium	18.4	16.2	13.4	15.8	15.7
Equisetum arvense	<0.1	<0.1	<0.1	<0.1	<0.1
Fragaria virginiana	0.1	0.6	0.7	0.1	0.1
Galium boreale	<0.1	<0.1	0.2	<0.1	<0.1
Galium triflorum	<0.1	<0.1	<0.1	<0.1	<0.1
Geranium bicknellii	0.1	14.6	1.3	0.8	0.4
Hieracium umbellatum	<0.1	<0.1	<0.1	<0.1	<0.1
Hylocomium splendens	<0.1	<0.1	<0.1	0.1	0.1
Lathyrus ochroleucus	3.0	18.7	3.4	5.2	4.7
Ledum groenlandicum	0.2	<0.1	0.9	0.1	0.5
Linnaea borealis	1.1	<0.1	0.9	0.8	1.6
Lonicera involucrata	<0.1	<0.1	<0.1	0.1	<0.1
Lycopodium annotinum	0.6	<0.1	0.6	0.1	0.3
Lycopodium obscurum	0.1	<0.1	0.1	<0.1	0.1
Maianthemum canadense	0.1	<0.1	0.1	0.3	0.1
Melilotus officinalis	<0.1	<0.1	<0.1	<0.1	<0.1
Mertensia paniculata	1.3	1.5	2.8	2.0	1.8
Mitella nuda	0.4	<0.1	0.4	0.3	0.5
Petasites palmatus	2.2	0.3	1.4	4.1	3.2
Picea glauca	1.2	<0.1	<0.1	0.1	<0.1
Pleurozium schreberi	<0.1	<0.1	<0.1	<0.1	0.1
Populus balsamifera	<0.1	<0.1	0.3	0.1	0.1
Populus tremuloides	31.6	5.5	37.7	33.6	31.6
Pyrola asarifolia	0.2	0.1	0.1	0.1	0.1
Ribes oxyacanthoides	<0.1	<0.1	<0.1	<0.1	<0.1
Ribes triste	<0.1	<0.1	0.1	<0.1	0.1
Rosa acicularis	8.8	8.3	10.5	9.5	7.2
Rubus idaeus	0.9	0.2	1.0	0.3	0.2
Rubus pubescens	1.3	0.2	0.3	1.4	1.9

Salix sp.	1.2	<0.1	<0.1	0.1	0.1
Sanionia uncinata	<0.1	<0.1	<0.1	<0.1	<0.1
Sonchus sp.	<0.1	<0.1	<0.1	<0.1	<0.1
Symphyotrichum ciliolatum	0.9	1.3	0.5	0.7	0.5
Taraxacum officinale	<0.1	<0.1	<0.1	<0.1	<0.1
Trientalis borealis	0.2	0.5	0.4	0.3	0.2
Trifolium hybridum	<0.1	<0.1	<0.1	<0.1	<0.1
Trifolium pratense	<0.1	<0.1	<0.1	<0.1	0.3
Vaccinium myrtilloides	1.1	0.4	1.1	1.2	2.0
Vaccinium vitis-idaea	0.2	<0.1	0.2	0.1	0.3
Viburnum edule	1.5	0.1	2.7	0.7	1.6
Vicia americana	0.7	26.2	0.4	0.3	1.3
Viola renifolia	0.2	0.6	0.2	0.1	0.4

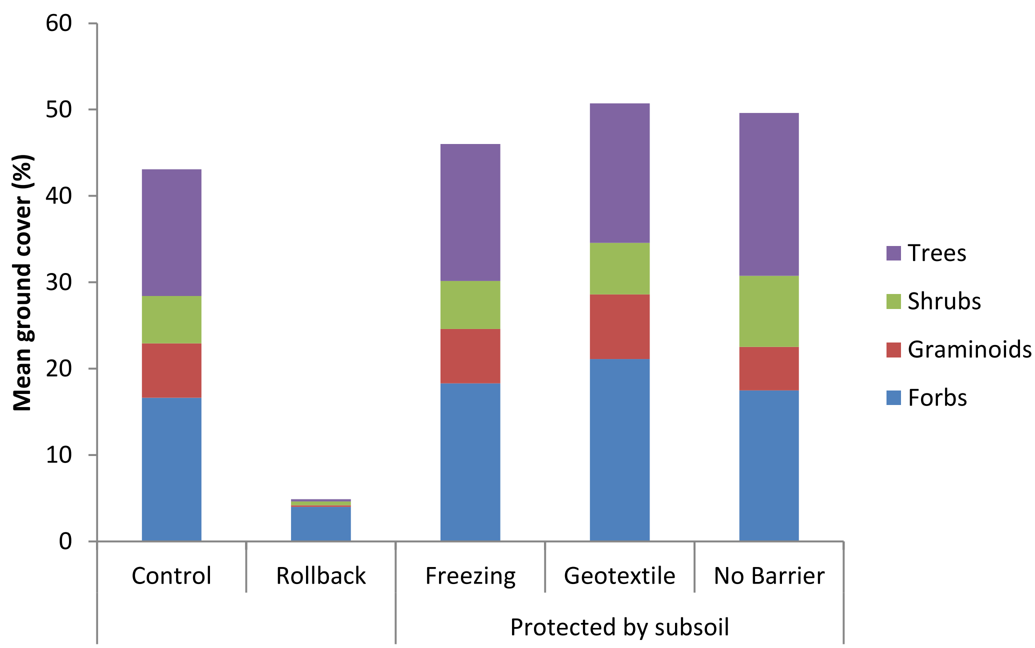

Figure A1. Mean cover of functional groups in relation to recovery treatments. Stacked columns were derived from cover class midpoints.

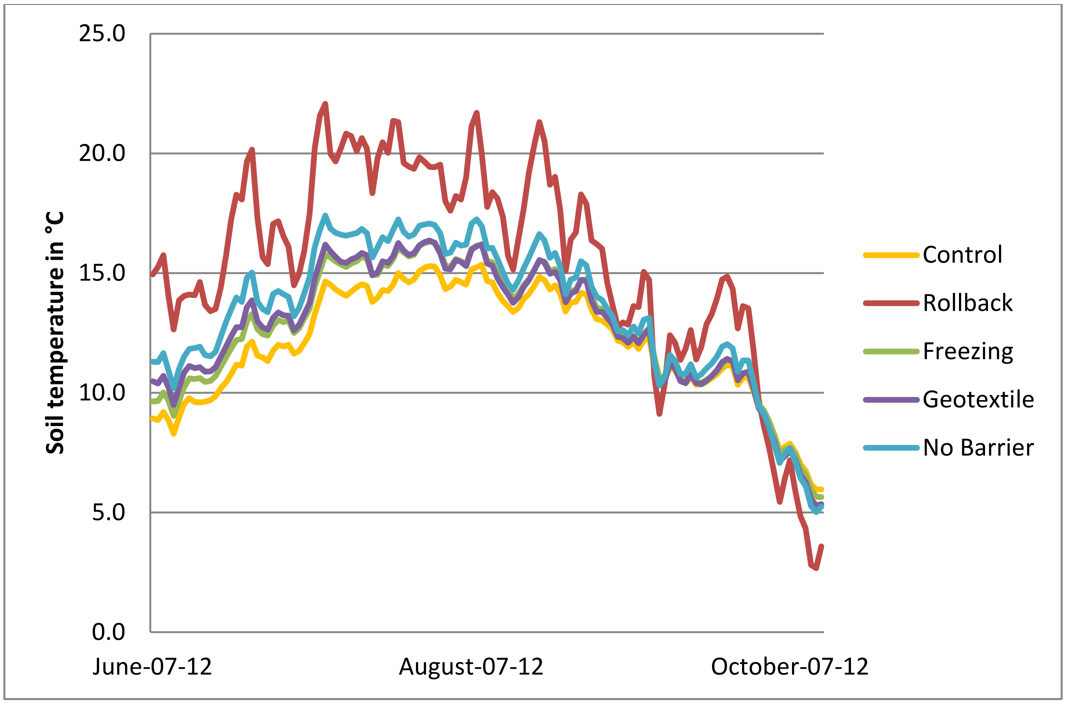

Figure A2. Mean daily soil temperature by treatment at a depth of 10 cm below surface.

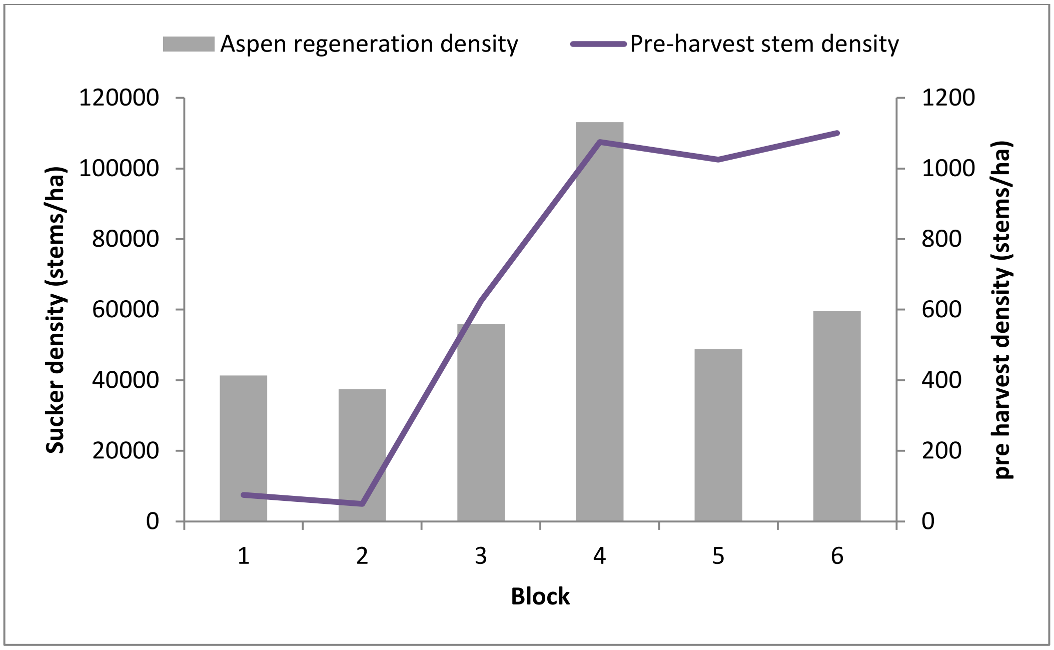

Figure A3. Mean sucker density and pre-harvest stem density in the Control treatment split by blocks.

Operational data

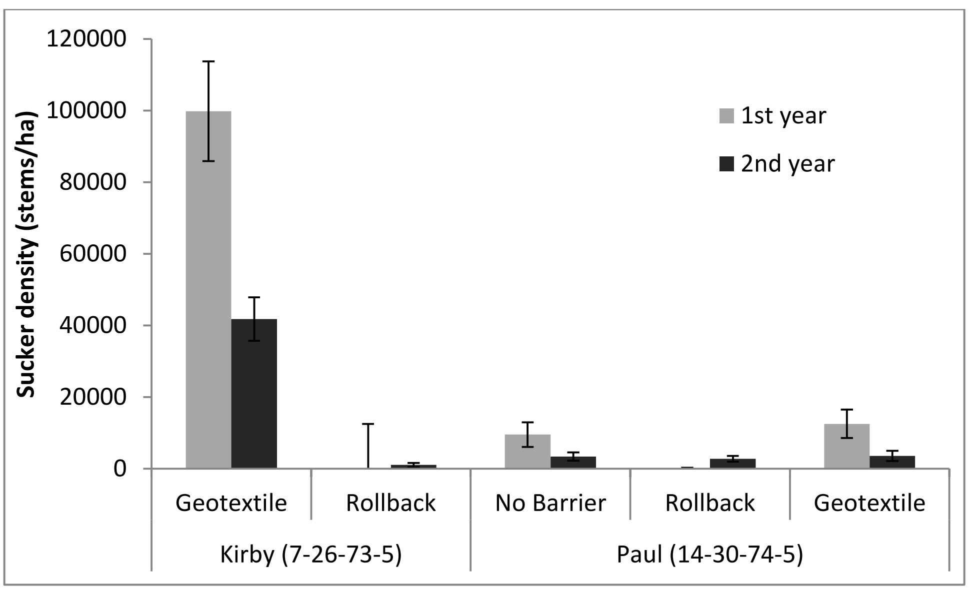

Figure A4. Mean sucker density (based upon 10 m^2 plots) in relation to different recovery treatments on two drilling sites over two growing seasons.

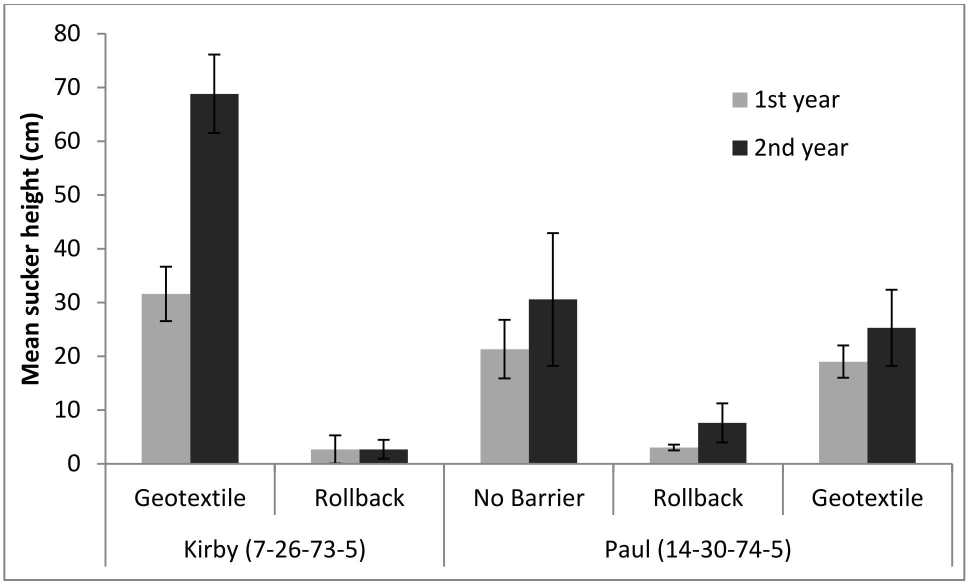

Figure A5. Mean sucker height (based upon 1 m^2 plots) in relation to different recovery treatments on two drilling sites over two growing seasons.

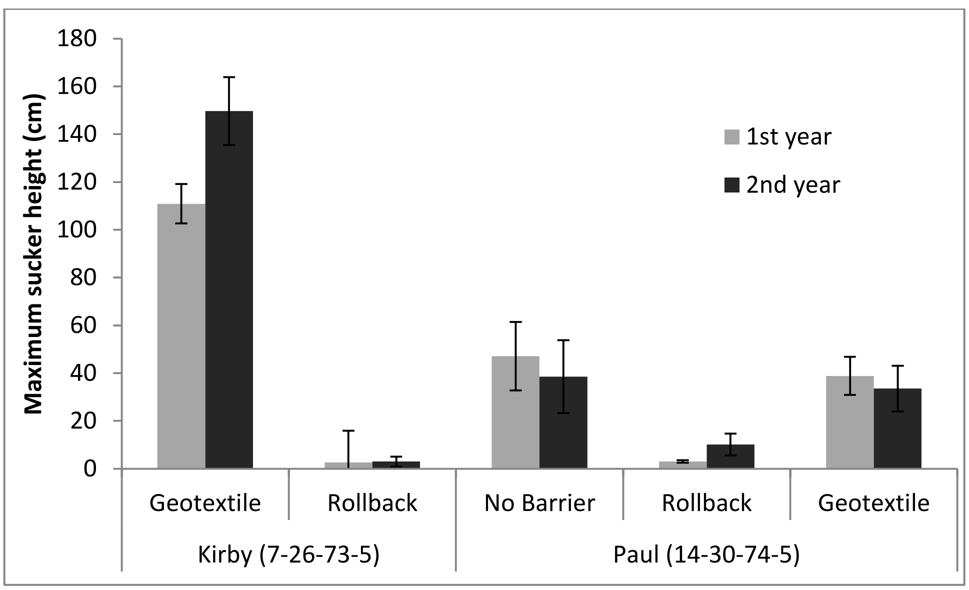

Figure A6. Maximum sucker height (based upon 10 m^2 plots) in relation to different recovery treatments on two drilling sites over two growing seasons.